People-oriented comfort control and energy saving by tracking the building users' position and electrical appliance use
taking the human in the control loop of building systems

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People-oriented comfort control and energy saving by tracking the building users’ position and electrical appliance use

_Taking the human in the control loop of building systems_

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Finally, I hope that this report encourages sustainable developments, where the human is central in the built environment!

Eindhoven, June 2012

Rik Maaijen
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 focuses 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.

This thesis presents a new HVAC control strategy based on the actual demand of the individual users. Therefore indoor localization of the individual building user is needed, where energy for comfort is only deployed on those positions where needed. Thereby it is looked for the most important parameter (e.g. human actions and building parameters) on building comfort and energy performances. The objective of this control strategy is to reduce the energy demand, while maintaining thermal comfort of the individual building occupant.

Theory

The user occupancy in indoor environments is a stochastic process, which makes it hard or even impossible to predict the presence and locations of the building users. In addition, the building user influences his environment passively by his metabolism and use of electrical appliances and actively by changing his environment to restore his individual comfort (e.g. thermostat control).

With the availability of building user information, demand-driven building systems operations can be implemented for optimizing the individual comfort level and energy usage. The control objective is to lower the comfort demands in unoccupied zones, respond to dynamic heat load on a timely manner and operation of the HVAC systems based on the individual preferences. To cope with the individual differences and meet these control objectives, individual controlled (HVAC) comfort systems show high potential. For good operation of these systems accurate building user information is needed. Using low cost wireless sensor networks show high potential.

Case study I: building user analysis

Short measurements on a floor in one of the offices of Royal Haskoning were performed, to look at the most critical parameter for the building energy performance (chapter 3). When applying the measurement results in a building simulation it was showed that the influence of the user on building performances is much higher than the building parameters (e.g. Rc value, g-value). The most important parameter on building energy performances was the internal heat gains of electrical appliances used by the building user. Since the user and his individual comfort are the main objectives of the applied energy the user is the most important parameter to focus on. To investigate how building users' use their building by measuring their position and look at the use of electrical appliances, these parameters were measured on the same case study floor.

Case study II: user position and appliance load

The position of eighteen employees was monitored for a period of six weeks using RFID technology, together with the electrical appliance use at the workplaces. When present, the user is on average 64% of that time on his workplace. More than 75% of the occupants have a most common workplace, despite there are flex office workplaces. When reflecting the results on a floor map, occupancy hotspots can be recognized, where 50% of the spots on the floor are less than 30% of the time occupied compared with the most occupied spot. The use of electrical appliances seems to correlate with the occupancy rate when looking at floor level (0.4 < r² < 0.8).
There is a clear relation between the occupancy rate and appliance load on workplace level. Where the occupancy rate fluctuates strongly from time to time, the electrical load is relatively state resulting in a low correlation coefficient ($0.1 < r^2 < 0.6$).

User comfort and energy saving potential

The energy use and comfort level was looked into for the actual situation and when applying the human in the loop approach on room and workplace level, where it was assumed that local individual controlled comfort systems is present. A simulation, using a whole-building model programmed in the MATLAB HAMBase environment, was performed to calculate the energy saving potential and parameters indicating the comfort level (chapter 5). The study showed an increase of the energy demand (13% for heating, 20% for cooling) and a decrease of the comfort level (25% in winter period based on PMV) compared with the design assumptions. The case study showed an energy saving potential of 30% for heating compared to the actual energy demand by decreasing the set point of the indoor temperature to 19.5°C and taking into account local radiant heating.
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1. Introduction

1.1 Background

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 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.

1.1.1 Energy performances built environment

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.

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].

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 to nationally and internationally 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.

1.1.2 Comfort of the building user

Where people spend more than 80% of their time in buildings and the occupants' satisfaction and productivity is strongly related to the comfort level of the building user, it is important to address this comfort level of the building users.

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.

These parameters are included in the traditionally calculation method of human thermal comfort, based on the Predictive Mean Vote (PMV) comfort index developed by Fanger [Fanger, 1972]. This model is the standard for comfort prediction, where it also has been adopted in the ISO 7730 standard [ISO 7730, 1994]. However, individual differences are not taken into account [Zhang et al., 2010] and therefore the comfort prediction by the PMV model is only valid for a large population and is based on the average office worker who does not exist.
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’.

1.1.3 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 (Figure 1-1) [Mahdavi, 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.

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 1-1. 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 hypothesis 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].
1.2 Research objective

The research is divided into two main objectives to test the hypothesis that when addressing the actual need for comfort, this can simultaneously lead to reduction of the energy.

1. To look at how building occupants use their building, in order to find the parameters to enhance the personal comfort of the individual user;
2. Secondly to assess how a better comfort for the user at same time also can lead to a reduction of the energy consumption for climatization.

Thereby, the energy savings can be obtained in two ways, namely 1) room conditioning is only applied when the building user is present, and 2) avoid energy wasting by the control actions of the building user to improve his perceived individual comfort.

1.3 Research questions

The background description and research objective are translated into the following research question, which can be divided into sub questions:

- Is it possible to simultaneously deploy individual comfort and reduce the building energy demand, by locating the position of the user inside a case study office building?

Sub questions:
1. What are the demands for building control to obtain energy savings with respect to the individual comfort demand?
2. What are the most critical parameters (i.e. user actions and building parameters) for the building energy performance?
3. From literature the "user location" is indicated as an important parameter, through a "case study" this is further analysed together with the most critical parameter.
4. Estimate the potential energy saving by focus more on the individual comfort.
   - Is there a difference on energy performance when controlling the HVAC system on room or individual level?

1.4 Methodology

The research is executed by the following phases and steps as presented in Figure 1-3. The positions of the research questions are also indicated. Below, the different phases are shortly explained and the report outline is given.
In the literature survey, the manner how user actions are taken into account in current building design, his influences on the building energy performances and the position of the user were the central point of interest. First it is clarified why it is important to have information about the building user in the control objective (§2.1). Before looking closer at the user position and movement (§2.3), the research fields of user actions are shortly described and discussed (§2.2). With the special focus on the human position in buildings, the requirements and available techniques for detecting the human position (§2.4) are closer looked into. Finally a description is given of the case study floor in §2.5.

Case study 1: building user analysis

The first case study was to determine and validate if the user influences are the most important factors on building performances. For the case study a floor of one of the offices of Royal Haskoning, a Dutch engineering company, was used. On this floor the control of user actions were analysed to gain insight of their magnitude and to determine the most important user action on building energy (§3.1). The magnitude of these user actions were calculated by hand formulas in §3.2. To validate these hand calculations, to look into the influence of thermostat control and to compare these values with the building parameters the floor is modelled using VABI Elements (§3.3). The results are discussed and evaluated in §3.4.

Case study 2: user position and appliance load

This phase concerns a measurement period of six weeks on the same floor of case study 1 where the user position and most important user action on building energy performance (use of electrical appliances) were measured to gather data to be evaluated. First a method and the RFID system of the user position measurement is introduced (§4.1). Hereafter the measurement results of the experiments are presented in (§4.2 and finally the results are discussed in §4.3.

User comfort and energy saving potential

To determine the energy saving potential with the human in the loop approach, the information from the measurement were applied in a whole building model (§5.2) programmed in the MATLAB HAMBase environment. This environment was used because it was easily possible to apply the measured databases for occupancy and electrical appliances to the building model and as the measured data were already available within MATLAB. The different case studies are presented in §5.1. The simulation results and in more detail when local heating is applied are presented in respectively §5.3 and 5.4.
2. **Background on the building user**

This chapter gives a description of user presence and his actions in the built environment, to gain insight of how people actually use their building, how they interact with building services systems and the indoor environmental conditions. The hypothesis is that buildings are not occupied for a large percentage of time, where the individual comfort level can be optimized when focusing on the individual. First the control objective of this hypothesis is explained in more detail, to gain more insight in the possible advantages of people-oriented energy control. Secondly the user actions are described in more detail in §2.2 where in particular attention has been paid to user occupancy §2.3.1 and techniques to know the user position §2.3.2. A brief description of the case study building is given in §2.4. The application of this theory within the case studies is discussed in §2.5.

2.1 **Control objective**

Current building systems generally operate according to fixed schedules and maximum occupancy assumptions. Typically, operational settings are dictated according to assumed occupied and unoccupied periods of the day (e.g. 9 AM to 6 PM) and minimal or do not consider when buildings are partly occupied.

With the availability of building user information, the following demand-driven building systems operations can be implemented for optimizing the comfort level and energy usage [Li et al., 2012]:

- **Lower temperature demands in unoccupied areas.** Zhang [Zhang et al., 2009] concluded that building energy reductions can be obtained when temperature was lower in winter period and higher in summer period;
- **Maintaining lower ventilation rates in unoccupied areas;** leading to less ventilation losses and building energy needed;
- **Supplying airflow based on occupancy;** two researches [Yang et al., 2011; Sun et al., 2011] looked at dynamic airflows based on the CO₂ concentrations. Applying these strategies savings could be achieved of 15% to 56% found by Sun on the ventilation energy;
- **Responding to dynamic heat loads on a timely manner;** if a change of the occupancy is detected in real time, associated changes of internal heat loads can be calculated, HVAC systems can respond to these changes immediately, before the temperature varies to an extent that is detectable by thermostats;
- **Operating HVAC systems based on occupant preferences;** by knowing the identity of occupants, HVAC systems can adjust and maintain set points to ensure individual occupant comfort;
- **Learning energy consumption patterns;** if the systems are able to profile the pattern for both the occupant, and workplace or room, it can proactively operate for optimum energy consumption.

**Control structure**

To achieve the previous described demand-driven building systems operations a different type of control for building systems is needed. The different approaches can roughly be classified into the following categories: (i) conventional methods; (ii) computational Intelligence techniques; (iii) agent-based intelligent control systems.

(i) Classical controllers where introduced to minimize the energy consumption. In this conventional method Proportional-Integrate-Derivative (PID) controllers where introduced. Later on, predictive techniques where added, including a model for future disturbances (e.g. solar gains, presence of humans, etc.);

(ii) In the decade of the 1990s intelligent methods where applied in the control systems. Intelligent controllers, optimized by the use of algorithms where developed (e.g. neural, fuzzy, etc.) for the control of the subsystems of intelligent buildings;
The goal of obtaining comfort conditions and simultaneously energy conservation in a building is solved by the development of intelligent systems. Dournis proposed the use of an intelligent supervisor that coordinates the optimal cooperation of the local controllers-agents [Dournis et al., 2009]. Hereby, total control is achieved, occupants' preferences are satisfied, conflicts are avoided and energy consumption is conditionally minimized.

![Block diagram of the controlled system, the controllers-agents, and the intelligent coordinator](Dournis et al., 2009)

To involve the human factor in the control system, it is required to real-time measure and monitor the building users' position. The proposed solution is by using sensor data of (wireless) sensor networks [Klein et al., 2012]. This data provides the input to intelligent control systems for optimal comfort and minimal energy consumption.

### 2.2 Building user comfort and actions

**Human comfort in office buildings**

The main goal of building services systems is to provide comfort to the building occupant. The comfort of building occupant is determined by different factors, for example the thermal comfort, visual comfort and indoor air quality. Here only thermal comfort is closer looked into, where it has a direct energy demand of building systems.

Thermal comfort has been defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as “the condition of the mind in which satisfaction is expressed with the thermal environment” [ASHRAE, 2004]. Calculations of human thermal comfort have been based on the empirical Predictive Mean Vote (PMV) model of Fanger [Fanger, 1972]. The comfort prediction by the PMV model is only valid for an average population and individual differences are not taken into account. Because thermal sensations are different among people even in the same environment [Hwang and Cheng, 2007] no absolute standard for thermal comfort can be derived [Havenith, 1985]. People differ in their need for a certain thermal environment as a result of differences in:

- Age [Oeffelen, 2007];
- Difference in gender [Karjalainen, 2007; Choi et al., 2010];
- Metabolic rate [Havenith et al., 2002];
- Clothing resistance [De Carli et al., 2007];
- Body [Zhang et al., 2001; Savastona, 2009];

**Behavioural research fields**

When occupants of residences and work environments act upon discomfort, their main goal is removal of the source of the annoyance. In other words, it is the action of the occupants, in response to discomforting environmental stimuli, in an attempt to restore their comfort [Oseland, 1998; Halidi et al., 2010].

Parys divided the research towards user actions on building performance into six fields, shown in Figure 2-2 [Parys et al., 2011. This division gives a clear division where:
it only includes actions that change the indoor environment and thus the buildings' energy demand;
- this overview makes the importance of the user presence clearly visible, where user actions are only possible when the user is present;
- other adaptive actions like adjusting clothing, having a drink or changing the activity level, better known as personal or intermediate actions, are not included because they do not have a direct influence on the building energy performance.

Figure 2-2 Different behavioural research fields within buildings, modified from [Parys et al., 2011]

The topology with user presence as the covering research field towards user actions is also shown in Figure 2-3. This figure clarifies the relation of the user actions with building energy demand. Where each human being emits heat and pollutants, he directly changes the indoor environment when he is present. In addition, the interaction with electrical appliances as well as the use of artificial lighting increases the internal heat gains and the consumption of electricity. Actions that directly influence the building energy performances are the deployment of shading devices, opening and closing of windows and lighting operation. From this figure it can be clearly concluded that the user and his actions affects the energy consumption for the building’s HVAC unit [Daum and Morel, 2010].

The following can be improved in this relation between the user and the building:
- The thermostat control by the occupant is missing, which also affect the energy consumption and indoor environment;
- Additionally, there are relations between the different user actions, e.g. lowering of blinds could result in turning on the artificial lighting;
- It takes occupancy as a number, meaning it does not include which individual is at what position.

Figure 2-3 Occupancy as leading research field, which sequential influence the control of the user actions research fields. These user actions sequentially influence the building energy demand, modified from [Page et al., 2008]

In both the overview of Parys and Page there is no distinction between the passive influences and active actions. Passively the user influences the building energy demand where he does not change his metabolism and use of electrical appliances on purpose for his comfort level. Control
of shading devices, lighting utilities, opening of windows and the thermostat are the active actions where the occupant tries to influence his comfort level.

Where the user influences the indoor environment and resulting energy demand, knowledge of user actions is crucial for accurate prediction of building performance (energy use, indoor climate) and effective operation of building service systems [Mahdavi, 2009].

Before looking closer at user location as most important factor to focus on, a short description of the current view towards user presence and user actions is presented.

A. Occupancy

The occupancy in buildings varies from day to day and from time to time. Different information sources show averaged profiles for occupancy (Figure 2-4 and Figure 2-5). Looking at those figures, there are some similarities between those profiles (e.g. time of occupancy, lower occupancy during break), but at the same time there are major differences between those figures where the fraction of full occupancy is up to 1 according to the EN 15232 but only up to 0.4 according to the measurements of Nobe [Nobe et al., 2002].

This means that user presence is seen as a standard profile, which is the same from day to day. Also the major difference with a maximal occupancy rate between 40% and 100% are not looked into. Since the user is the most important factor in the building, as concluded from §2.1 and Figure 2-3, these profiles do not meet the sophisticated level as required.

B. Shading device deployment

Shading devices play a central role in the heat gains of a building and therefore on its energy performance, but also on the thermal and visual comfort of the building occupant. Commonly the influence on the internal heat gains and resulting building energy performances are investigated using building simulation models, where the effect is depending on the orientation, season, window area and properties and application of sun shading. Daum and Morel [Daum and Morel, 2010] proved the importance of intelligent blind control, by achieving energy savings up to 40% on building energy demand.

C. Operable windows

Window deployment can significantly influence building energy and comfort performances [Mahdavi et al., 2008-2]. It was observed that indoor conditions describe opening actions, but closing actions tend to be better described by outdoor conditions [Hald et al., 2009]. No research could be found looking at the influence of opening windows on the building energy performances. In the commonly building simulations window opening simplified or not taken into account.
D. Artificial lighting
Artificial lighting influences both the electrical use and the internal heat gains. Mahdavi found that energy savings up to 30% can be achieved, when lighting is only switched on when needed [Mahdavi et al., 2009]. The internal heat gains as set by the NEN 2916 [NEN 2916, 2004] is between 6 and 12 W/m².

E. Electrical appliances
Electrical appliances in offices can either operate independently of the user’s presence (for instance the coffee machine), or are directly driven by the occupancy (for instance a computer or a screen). Parys concluded that the operation of office equipment is obviously not driven by indoor environmental quality motives [Parys et al., 2011]. Therefore it is more logical to link the ratio of internal heat gains over the nominal power of office equipment to the occupancy rate.

The internal heat gains as set by the NEN 2916 [NEN 2916, 2004] is 8-12 W/m².

F. Thermostat control
The influence of thermostat control on building energy performances depends on the building variables, where no general assumptions can be made regarding increase or decrease of the energy demand. Incorrect use of individual temperature control (e.g. over-adjusting or misconceptions) may result in energy wasting behaviour and thermal discomfort [Vastamäki et al., 2005; Karjalainen et al., 2007].

2.3 Building user presence
Since the user presence is important to the hypothesis that energy can be saved when adjusting the conditioning to the occupancy, the building user presence is looked into. In §2.3.1 it is looked for the more advanced approaches to describe building occupancy, where in §2.3.2 techniques are described for real-time localization of the building occupant.

2.3.1 Description of building user occupancy
To get a better understanding of the occupancy, Mahdavi extracted behavioural trends and patterns for groups of building occupants from long-term observational data from different buildings [Mahdavi et al., 2009]. Figure 2-6 shows that there are considerable differences of the mean occupancy at workplace for the different building types. Looking closer at a profile obtained from observations in an insurance office, a standard deviation up to 15% is visible.

Although these figures give a better representation of the building occupancy than Figure 2-4 and Figure 2-5 in §2.2, a lot of information is missing, e.g.:
• Variation of occupancy from time to time;
Where are the people inside the building, since concentrations could exist on some spots where other positions are not occupied;

- Individual preferences cannot be applied where it is not known which individual is at what position in the building.

To overcome the first two missing points, a more dynamic approach is presented.

**Dynamic approach**

The commonly used dynamic approach of considering occupant presence is by using so-called "diversity profiles". The profiles may depend on the type of building and sometimes even on the type of occupants. Wang [Wang et al., 2005] tried to understand, and be able to predict, the transient nature of occupancy during nominally occupied periods. Wang examines the statistical properties of occupancy in single person offices of a large office building in San Francisco.

Figure 2-8 shows the distribution of hourly occupied time as function of time of day.

![Figure 2-8 Distribution of hourly occupied time over 24-h of day for an office in San Francisco (Wang et al., 2005)](image)

This figure indicates that from 8.00 to 17.00 h 75% of the workers are more than 25 minutes at their workplace hourly, except 12.00 to 13.00 h giving a more reliable vision on occupancy.

A closer look towards user presence is by looking how many times the building occupant departs from and arrives at his workplace. Figure 2-9 demonstrates that the occupant, when present, mostly walks five or six times a day from his workplace. Figure 2-10 shows the distribution of the length of the occupancy interval. It appears that shorter occupancy intervals occur more frequently than the longer intervals.

![Figure 2-9 Distribution of the number of occupied to vacant event for an office in a day, modified from (Wang et al., 2005)](image)

![Figure 2-10 Probability distribution of the occupancy interval for an office, modified from (Wang et al., 2005)](image)
Both the research of Wang [Wang et al., 2005] and Page [Page et al., 2008] looked at the probability of the vacancy interval. Figure 2-11 and Figure 2-12 show similarities, where the probability of short vacancy is the highest and lower for the longer vacancy intervals.

These probability functions can be used as input for building simulation models, and are better describe the deterministic occupancy behaviour of the individual building occupant. The weakness of probability profiles lies in the repetition of one or possibly two profiles and the fact that the resulting profile represents the behaviour of all the occupants of a building. "The latter simplification reduces the variety of patterns of occupancy particular to each person by replacing it with an averaged behaviour. The former simplification neglects the temporal variations, such as seasonal habits, differences in behaviour between weekdays (that appear in monitored data) and atypical behaviours (early departures from the zone, weeks of intense presence and of total absence, unpredicted presence on weekends in the case of office buildings—events that all appear in monitored data)" [Page et al., 2008]. Above that the individual is still not recognized, where preferences cannot be applied for individual comfort.

Despite all effort, no current model is capable of describing the individual human position in buildings. This was also acknowledged by Mahdavi [Mahdavi et al., 2009], who concluded that different researches tried to describe the human position and its actions by a model. From all the models he investigated it turned out that interactions with buildings' environmental systems are difficult or even impossible to predict at the level of an individual person. User presence is a complete stochastic and random process, where even the next state of presence cannot be described by the previous.

For optimal building operation real-time information about the building user is needed. With the user position as central point of interest techniques for indoor localization will be discussed in the next paragraph.

2.3.2 Building user position

When it is needed to know the position of the building user this paragraph looks closer at the demands of the indoor localization system and describes the current available techniques for detection. Building occupancy is not only determined by the user position. The notion of occupancy measurement should include information about the (i) space, (ii) occupants and (iii) time span. The quality of information provided by different types of sensors varies widely and can be thought of as the resolution of the sensor. The spatial resolution (i) of occupancy is easily defined in terms of building structures, e.g. floors and rooms. Occupant resolution (ii) is more ambiguous, where four levels are defined:

- **Occupancy** – a zone has at least one person in it;
- **Count** – how many people are in a zone;
- **Identify** – who they are;
- **Activity** – what they are doing.
In addition to spatial and occupant resolution, there is temporal resolution (iii), which refers to the smallest time span in which changes in spatial and occupant resolution can be reported by a given sensor. Generally, as measured resolution increases the space becomes smaller, the occupant become more defined, and the information is available more quickly. For instance, a low resolution sensor might indicate that a building was occupied by one or more unidentified people in the last hour. A high resolution sensor might indicate that a specific room was occupied by three identified people in the last minute [Melfi et al., 2011].

For the set control objective with the user central in the control of building systems it is most important to detect the user on workplace level (i), identify the individual (ii) within a timespan of minutes (iii) because of the inertia of the building systems in this order of magnitude. Figure 2-13 overviews the occupancy resolutions.

![Figure 2-13 Occupancy resolution with the accuracy of the temporal, occupant and spatial resolution, modified from [Melfi et al., 2011]](image)

The commonly known Global Positioning System (GPS) is well-known of obtaining locations in outdoor areas. GPS is able to track positions within a few meters, identify in even a few seconds. However, this technique cannot be utilized in indoor environments as buildings, because of its reliance on satellite visibility leading to no usable data [Li et al., 2012]. Therefore an indoor occupancy detection system needs to be used. The indoor occupancy detection systems can be categorized as individualized and non-individualized systems, based on whether every individual in a spatial area is detected, tracked and identified or not. Since identification of the individual is important for applying individual preferences to the building occupant for more comfort, the non-individualized systems do not show much potential for this building application. The non-individualized systems, passive infrared, IT infrastructures, vision-based, are short discussed in appendix B. The available individualized techniques are presented.

**WLAN**

Woo investigated the application of Wi-Fi-based indoor positioning system for labor at construction sites, and thereby showed an accuracy of 5 m. of error [Woo et al., 2011]. Though it is possible to detect the individual, this error is possibly too high for application in office buildings.

To get a more accurate WLAN locating system, some learning of the system is needed. Therefore a database needs to be generated with reference sample points, which are carefully selected. At a reference point the Receives Signal Strengths (RSS) of all the access points are measured. The characteristic features of all the RSS for that reference point are recorded in a database. This process is repeated for all the points of interest. For localization the RSS at every place are measures by the mobile node of the user. The measurements are compared with the database using an appropriate search/matching algorithm. The outcome is the likeliest location of the user. This process results in a positioning estimate with an accuracy of 1 to 2 m under optimal conditions [Khoury & Kamat, 2009]. The architecture is shown in Figure 2-14.
Figure 2-14 Architecture of the WLAN individual positioning where a WiFi enabled device receives different signals of WiFi access points, where thereafter the position can be calculated and reflected on the floor map, modified from [Khoury & Kamat, 2009]

Indoor GPS

As in satellite based GPS, transmitters send a one-way signal to the receiver allowing an unlimited number of receivers to independently calculate positions. For the calculation triangulation [1] is used, where the angles are measures to known locations. With two known locations of transmitters, the absolute position can be determined (Figure 2-15).

Results of an experiments conducted by Khoury [Khoury et al., 2009] indicated that the Indoor GPS tracking system consistently achieved a positioning uncertainty that fluctuated between 1 and 2 cm. Though, this system has one major disadvantage, where the indoor GPS needs a line of sight for positions tracking. The receiver needs to have a direct link to two of the receivers.

Image of Indoor GPS transmitter (left) and receiver (middle) and the triangulation approach (right)

RFID

Radio frequency identification (RFID) is an effective technology for indoor localizations [Li et al., 2012]. A RFID based occupancy detection system consists of readers, antennae, tracking and reference tags at a frequency of 915 MHz, and a server. The tracking tags are worn by the occupants to denote occupants’ locations, and reference tags are deployed in the environment to provide references for location estimation with their own known locations. The readers in the room receive data of both the tracking and reference tags. After that the server retrieves data from the readers, and performs location calculations based on the signal strength.

Tests with a dynamic environment a zone level detection rate was found of 76%. This percentage was probably lowered because of the small zones (ca. 3x3 m.).

Comparison of indoor localization techniques

The different techniques for detection of the human position are valued on how it functions and can be realized as projected by the Kesselring method. By applying this method singularities are made visible, whereas that in the normal choice tables a bar diagrams only could be retrieved with much effort [Zeiler et al., 2007]. The functioning criteria are based on the occupancy resolution divided into occupant, temporal and spatial resolution, as stated by [Melfi et al., 2011].

---

1 Triangulation is the process of determining the location of a point by measuring angles to it from known points at either end of a fixed baseline.
These criteria are important to meet the control objective of demand-driven building systems. The realization criteria are: flexibility, reliability, costs, line of sight, implementation, and adaptability. For both the functioning and realization, a weigh factor is added to the score. Figure 2-16 shows the s-diagram with the different scores of the techniques, based on the Kesselring method in appendix C.

Regarding the different techniques, the following can be concluded:

- No-individualized occupancy detection systems are more often easy to deploy and scalable. However, they score on average less high than the individualized occupancy detection systems. Additionally, these systems can hardly or not adapt to situations where monitored zones are virtually instead of physically partitioned;
- The score in realization of vision-based positioning systems is negatively affected by line of sight obstructions or light conditions (fluorescent lighting or direct sunlight). The problem with the line of sight is even more for the indoor GPS;
- It is shown that RFID techniques has the highest scores for both the functioning and realization criteria, hence is best applicable for sensing the building occupant for HVAC purposes. It is not known if RFID is able to detect the position on the workplace level.

![S-diagram showing the evaluated functional and realization aspect for the 3 individualized and 3 non-individualized techniques for detection of the user indoor position.](image)

2.4 Description case study building

The presented floor of the case study office is used to capture data from a real situation, without making assumptions for building and user behaviour. The building is the main office of Royal Haskoning, an international engineering company in the north-east of Rotterdam, the Netherlands.
The office building houses various departments of Royal Haskoning, operative in engineering and consultancy. For the case study the third floor of the outbuilding is looked into, where the department building services and building physics are employed. General information regarding the building and the position of the floor is provided in Figure 2-17.

<table>
<thead>
<tr>
<th>Properties floor case study</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of completion</td>
<td>2006</td>
</tr>
<tr>
<td>Floor surface</td>
<td>ca. 500 m²</td>
</tr>
<tr>
<td>HVAC system building</td>
<td>heating: district heating 70°C, capacity : 900 kW</td>
</tr>
<tr>
<td></td>
<td>cooling: air-cooled water chiller 6°C, capacity : 655 kW</td>
</tr>
<tr>
<td>Room conditioning</td>
<td>induction unit, all air</td>
</tr>
<tr>
<td>HVAC control</td>
<td>room level adjustment : +/- 1.5°C</td>
</tr>
<tr>
<td>Employees</td>
<td>ca. 25 persons</td>
</tr>
<tr>
<td>Type of workplace</td>
<td>flexible open office space and cell-office</td>
</tr>
<tr>
<td>Type of work</td>
<td>computer / deskwork, engineering, calculation</td>
</tr>
</tbody>
</table>

On top of the building is the control room, with the HVAC unit. The supply air is preconditioned with a twin coil cylinder and when needed extra heated or cooled. The temperature of the supply air is based on the outside temperature (Figure 2-18). The rooms are conditioned using induction units installed above the ceiling (all-air). Therefore the open office space are equipped with one supply air grid every building pattern and two grids per cell-office and per meeting room. Air is extracted from the conditioned space via the light fixtures. The default set point during the heating season is 22 °C, during cooling season 24 °C is and can manually be adjusted.

This floor was chosen where:
- it has flex office workplaces and to see how the people are moving over the floor and what seats they are sitting on from time to time;
- it is completed in 2006 and can be seen as a high performing office building;
- the surface of 500 m² and 25 employees can be seen as an average office floor space.
2.5 Application of theory to experiments

This paragraph shortly summarizes the most important conclusions as found in literature (§2.1-2.4), and discusses what the theory actually means for this research.

- From §2.1 it was concluded that different advantages leading to energy reductions can be achieved when energy is only applied on the individual needs of the building user. This requires another way of building energy control using more sensors for input of the building services control system [Dournis et al., 2009]. The hypothesis for the case studies is that by focusing on the building user it could result in both energy and comfort optimization;

- To improve the building performances it is needed to focus on the following user actions: deployment of blinds, opening of windows, lighting control, use of electrical appliances and thermostat control [Parys et al., 2011]. Since all this user actions are dependent of the building and the building use, it is needed to look what user actions are the most important parameters to focus on. This is investigated in the first case study, reported in §3.3;

- For optimal functioning of the building services systems, it is needed to understand the random behaviour of the building users
  - Prediction of user presence and actions at the level of an individual person is not possible [Mahdavi et al., 2009];
  - The best applied method at this moment is the application of probability distributions as shown in §2.3.1. Even those probability functions show a lot of errors and are not (yet) applicable for the individual user;
  - Because of this stochastic behaviour it is needed to real-time measure the building users' position. Low costs sensor networks show high potential [Klein et al., 2012];

- Building movement is defined by the occupancy resolution consisting of a spatial, temporal and occupant resolution [Melfi et al., 2011]. This occupant resolution is used in §2.3.2 to as assessment of the functioning of different indoor localization techniques; The best technique to determine the users’ position inside the building is by using RFID technology. This technology as described in §2.3.2, is used to track the position of the individual building users. In §4.1 RFID is used for the experiments;
3. Case study 1: building user analysis

The hypothesis that user influences are the most important factor to focus on in order to improve building energy use is tested. Therefore it is important to look how the building occupants use their building, and to gain insight in the magnitude of these influence. In this first case study first the human influences are determined as described in §3.2, where the impact of these actions on building energy performances are calculated in §3.3 using hand calculations and building model using VABI Elements. The results tell what user action is the most important parameter to focus on to improve building energy performance, as described in the control objective in §2.1. The user analysis is made on the case study floor of Royal Haskoning.

3.1 Building and user analysis

On the case study floor the control of user actions were analysed to gain insight of their magnitude and to determine the most important user action on building energy performance by short measurements and interviews. It was looked into the six behavioural research fields as described by Parys [Parys et al., 2011], which are schematically shown in Figure 3-1.

![Figure 3-1 Personal actions of the building occupant and the most important parameters influencing the comfort level of the building occupant](image)

The map of the floor with the human influences on building performances are stated in Figure 3-2. Here the user influences are shortly described.

A. Only the cell-offices 3.17, 3.18 and 3.19 have fixed workplaces with employees from another division of the company. The open-plan office accounts for 29 flexible workplaces. In practice, the secretary located in room 3.21 has a fixed occupation. The open-plan offices are separated by closed bookcases with height almost to the ceiling.

B. There are no blinds present in the building, since the designer saw no need for it where the glass has a low solar energy transmittance.

C. Three types of windows can be distinguished, with the following dimensions (including window frame): Type I: 2x1.7m., type II: 1.4x2m., type III: 0.9x2m., an U-value of 1.2 W/m²K and a g-value of 0.3. Only type I and type II have the ability to be opened, with an opening area of respectively 0.15 m² and 0.12 m².

- Nine randomly chosen employees where interviewed regarding window opening, answering the following questions:
  
i. What percentage of time you think you open a window in the office during working time?
  
ii. Why do or don’t you open the windows?

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Figure 3-2 Case study floor overview with the different zone types and the workplaces, and user influences on building energy performance

D. In the meeting rooms, open-plan offices and cell offices high efficiency fluorescent lighting is applied of the type TL-5 (49W) in reflector luminaires. In the corridors downlight luminaires are installed with fluorescent pl-lamps. In the cell-offices and the meeting rooms the lighting is controlled manually, while in the other zones the lighting is switched on and off centrally.

- The lighting operation where derived from observations during a week.

E. Most of the employees work on a laptop. Sometimes in addition a bigger screen is used instead or next to the screen of the laptop itself. There are two coffee machines located in a pantry between the lounge and meeting room 3.12. One printer is located in the corridor.

- To determine the internal heat gains produced by the electrical appliances, short measurements of different interesting spots (flexible desk, CAD desk, coffee machines and printer) where conducted for validation of the calculated values. For these measurements the Voltcraft energy Monitor 3000 was used, which monitored the energy use for one week in November 2011.
F. As described in §2.4 the temperature in controlled on room level.
   > Also nine randomly chosen employees were interviewed regarding thermostat control, answering the following questions:
     i. Do you sometimes change the set point of the thermostat during summer or winter period?
     ii. If yes, how often do you change it and do you raise or reduce the set point?

Initial temperature measurements are made to:
- verify whether the temperature fluctuates during the day and if temperature differences can be found between different zones on the floor;
- look if different temperatures are possible if some spots needs to be conditioned when there is someone present on that spot;
- use the temperature differences to validate the building model.

The results are shown in Figure 3-3, were differences are recognized. Arrow A indicates a difference in temperature within one day for the open office up to 3 K. In the meeting room a temperature within a few hours up to 6 K, indicated with arrow B. Arrow C shows that even during minimal fluctuations a temperature difference of 2 K can be observed. In general the temperature around the printer is higher, probably caused by the high internal heat gains of the printer itself.

![Temperature Measurement Chart]

Figure 3-3 Temperature measurement for one week at four different spots on the floor to see whether temperature differences between zones and days can be established. Arrow A indicates differences in temperature within one day of 3K, arrow B indicates that even within 5 hours the temperature fluctuates up to 6K, arrow C indicates that even during the night / weekend a temperature difference of 2K can be recognized.

3.2 Values user actions

Since no blinds are present on the floor, it is not needed to look at the resulting energy demand by deployment of these blinds.

The interviewed employees answered they do not open the windows, except for one employee. The reason for keeping the windows as much closed as possible is because of the noise from the passing highway. The only employee who sometimes does open the window declared he preferred some fresh air from time to time. He only opened the window during the mid-seasons and summer to prevent cold downdraught.

The artificial lighting in the open offices and corridors are centrally operated. The downlights in the corridors are switched on during day and night, where the lighting in the open office is switched on between 8 AM and 8 PM. In the cell offices and meeting rooms the lighting can manually be switched on. From observations it turned out that they are switched on during work time from 8.30 AM to 5 PM. The lighting in meeting rooms is only switched on when present.
The internal heat gains by the electrical appliances can directly be derived from the measurement. As could be expected, the electrical load of the appliances is higher around the CAD workstations (avg 21.7 W/m²) compared to the regular workplaces where the employees work on laptops and sometimes use additional screens (avg 6.1 W/m²). The internal gains of regular workplaces are below the minimum given norm of 8 W/m² and internal load around the CAD workstations are above the given maximum of 12 W/m². With an internal heat load of 176 W per coffee machine and 457 W these appliances have a significant influence on the internal heat gain of appliances.

The temperature set point for the rooms is 22 °C, with the ability of the user to change this set point with +/- 1.5 ºC. The interviewed employees declared that they find it often too cold, where four of the nine floor users indicated they increase the temperature set point more than half of the time.

The results of the first survey as described in §3.1 are summarized in Table 3-1.

<table>
<thead>
<tr>
<th>Inventory</th>
<th>Description</th>
<th>Interview</th>
<th>Measured</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Blinds</td>
<td>No blinds present</td>
<td>*</td>
<td>8/9 votes</td>
<td></td>
</tr>
<tr>
<td>C. Window opening</td>
<td>0% of time (noise of traffic)</td>
<td>*</td>
<td>1/8 votes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0-10% of time</td>
<td>*</td>
<td>0/9 votes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;10% of time</td>
<td>*</td>
<td>0/9 votes</td>
<td></td>
</tr>
<tr>
<td>D. Lighting</td>
<td>Open office centrally switched on</td>
<td></td>
<td>8-20hr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cell office most of work time</td>
<td></td>
<td>6hrs/day</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Meeting room only when meeting</td>
<td></td>
<td>2hrs/day</td>
<td></td>
</tr>
<tr>
<td>E. Appliances</td>
<td>Normal desk work time (avg one week)</td>
<td>*</td>
<td>6.1 W/m²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CAD desk work time (avg one week)</td>
<td>*</td>
<td>21.7 W/m²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coffee machine (avg one week)</td>
<td>*</td>
<td>176 W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Xerox printer (avg during work time)</td>
<td>*</td>
<td>457 W</td>
<td></td>
</tr>
<tr>
<td>F. Thermostat</td>
<td>Set point temperature</td>
<td></td>
<td>+/- 1.5 ºC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>raise temperature</td>
<td>*</td>
<td>4/9 votes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>no action</td>
<td>*</td>
<td>5/9 votes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>reduce temperature</td>
<td>*</td>
<td>0/9 votes</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Results

3.3.1 Hand calculations

The gain insight into the magnitude of user actions on building energy performances, calculations are made using hand calculations. The following formulas are applied, see also chapter Terminology.

B. Shading device deployment:

Although there are no blinds present in the building, it is looked into if it is interesting to look closer towards it in other office buildings. The following numbers for calculation could be applied:

\[ Q_{Solar, diff+dir} = 1,000 \text{ W/m}^2 \]
\[ \sin(45°) = 0.71 \]
\[ g = 30 \% \]
\[ \text{Time} = 1,500 \text{ hrs of sun in NL (knmi.nl)} \]
\[ \text{Device closed} = 40 \% \text{ when sun shines} \]

\[ P_{Solar} = \frac{Q_{Solar, diff+dir} \sin(\alpha) g A_{glass}}{A_{room}} \text{ [W/m}^2\text{]} \]  

3.1

C. Window opening [Heiselberg et al., 2001]:

An average wind speed of 3 Bft is assumed, which is in a range of 3.4 – 5.4 m/s. Window opening of 5% is assumed, corresponding with data found by Mahdavi [Mahdavi et al., 2008-2].
\[ \Delta T = 10 \, ^\circ C \]
Time : 52 hrs opened (1 hour/week)
Amount : 50 % opened of all windows
Type I : 0.15 m\(^2\) area for airflow when opened (3.17)
Type II : 0.12 m\(^2\) area for airflow when opened (3.20)

\[ P_{\text{window}} = \frac{Q_{\text{air}} \rho c \Delta T}{A_{\text{room}}} \, [W/m^2] \] \hspace{1cm} 3.2
\[ Q_{\text{air}} = C_d A \sqrt{\frac{2 \Delta p}{\rho_0}} \frac{m^3}{s} \] \hspace{1cm} 3.3
\[ \Delta p = \frac{1}{2} \rho_0 v_{\text{air}}^2 \, [Pa] \] \hspace{1cm} 3.4

D. Artificial lighting:
Turned on : 70 % of working time, room 3.17
: 100 % of working time, room 3.20

\[ P_{\text{elect,light}} = \frac{P_{\text{electric,light}}}{A_{\text{room}}} \, [W/m^2] \] \hspace{1cm} 3.5
Additional when cooling is needed:

\[ P_{\text{cooling}} = \frac{P_{\text{app}}}{\eta} \, [W/m^2] \] \hspace{1cm} 3.6

E. Electrical appliances:
The electrical load is also calculated, to be compared with the measurements later on.
Power : 90 W per laptop; 150 W per screen
Presence : 70 % of working time room 3.17
: 60 % of working time room 3.20

\[ P_{\text{elec,app}} = \frac{(P_{\text{laptop}} + P_{\text{printer}} + P_{\text{other}})}{A_{\text{room}}} \, [W/m^2] \] \hspace{1cm} 3.7
Additional when cooling is needed, see equation 3.6.

F. Thermostat control
The influence of changing the temperature in the building is hard or even impossible to calculate by hand formulas. To get insight in the magnitude the building is simulated using VABI Elements later on.

Results
The results of the power calculated influence of the C. window opening, D. artificial lighting and E. electrical appliances are shown in Figure 3-4. When windows are opened they have a major influence on the energy demand (>400 W/m\(^2\), 3Bft). Since the windows are almost always closed because of the traffic noise, the energy influence per year is much lower compared with the other behavioural research fields. The corrected value where the value is multiplied with time is shown in Figure 3-5. Here it is shown that the electrical appliances use have the biggest influence on building energy performance.
The measured electrical loads for the printer and coffee machines are shown in Figure 3-6, where it is shown that the printer on average used 450 W and the coffee machines used circa 150 W during this week. Most of this energy is converted into internal heat gains. This means that these appliances have a major impact on the internal heat gains, where in practice 8 – 12 W/m² is assumed as internal heat gains by electrical appliances. Figure 3-7 compares the results of the calculations with the measured values at the office desk. However, the electrical energy use for the CAD desk is three times higher than for the office desk, resulting in significant differences in internal heat gains between different spots in the building.
3.3.2 VABI Elements simulation

The most important input parameters of the model and the three dimensional building in VABI Elements is shown in Figure 3-8.

<table>
<thead>
<tr>
<th>Building parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-value</td>
<td>1.6 W/m²/K</td>
</tr>
<tr>
<td>g-value</td>
<td>0.3</td>
</tr>
<tr>
<td>RC-wall</td>
<td>4.5 m²KW</td>
</tr>
<tr>
<td>RC-floors</td>
<td>1 m²KW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal heat gains</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-value</td>
<td>10 W/m²</td>
</tr>
<tr>
<td>g-value</td>
<td>10 W/m²</td>
</tr>
<tr>
<td>RC-wall</td>
<td>10 W/m²</td>
</tr>
<tr>
<td>A. metabolism</td>
<td>10 W/m²</td>
</tr>
<tr>
<td>D. lighting</td>
<td>10 W/m²</td>
</tr>
<tr>
<td>E. appliance use</td>
<td>10 W/m²</td>
</tr>
<tr>
<td>F. Temperature</td>
<td>22 °C</td>
</tr>
<tr>
<td>F. Overheating</td>
<td>150 hrs.</td>
</tr>
<tr>
<td>Operating time</td>
<td>8-17 hr</td>
</tr>
</tbody>
</table>

Figure 3-8 Most important input parameters and a view on the building model in VABI Elements

The input parameters are changed within a predetermined bandwidth, to look for the impact on the building heating and cooling demand. Since it was said that the windows are almost never opened and from Figure 3-5 is can be concluded that the resulting influence on energy performance is much lower than lighting and appliance use, this value is not calculated. The primary energy demand is calculated for the south oriented cell office 3.17 (Figure 3-9) and the open-office space 3.20 – 3.22 (Figure 3-10). From these results the most critical parameter on building energy performance can be determined.

![Variation on energy demand HVAC system cell office](image)

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>3.2</td>
<td>0.25</td>
<td>3</td>
<td>0.4</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>20.5</td>
</tr>
<tr>
<td>Upper</td>
<td>1.1</td>
<td>0.4</td>
<td>4.5</td>
<td>1.5</td>
<td>20</td>
<td>15</td>
<td>20</td>
<td>23.5</td>
</tr>
<tr>
<td>Reference</td>
<td>1.6</td>
<td>0.3</td>
<td>4.5</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>22</td>
</tr>
</tbody>
</table>

Figure 3-9 Building energy simulation results to determine the sensitive parameters on building energy performance (cell office) with the variation in building parameters shown left and the user influences (right) showing a much bigger deviation in the simulation outcome.
A high variation in the outcome means that the parameter is an interesting research field as it has the biggest influence on building energy performance. For the cell office and the open office space it is clearly shown that the variation for user influences is much higher than building parameters, underlining the importance in the research field towards user behaviour and is in accordance with literature on this subject. In the case study the use of appliances has the biggest deviation in the outcome.

The above changes are static, as the input is a fixed value during the operation hours. As shown in literature especially occupancy rates and the resulting user influences change from day to day and from time to time. Therefore different time schedules are put into the building model. The reference schedule is the schedule as used in the calculations above; from 8-17 hr. By changing the operation schedule it will have an influence on the occupancy rate (metabolism), lighting and electrical appliances. Schedule one and two are simple variations on this schedule. In the third schedule average occupancy profiles derived from a walk-through survey in an engineering centre are applied to the model. The averaged profiles for the occupancy (left) and averaged typical shapes of lighting and equipment loads (right) are shown in Figure 3-11.

![Figure 3-11 Average occupancy profile and average load shapes of lighting and equipment loads from a walk-through survey in an Engineering Center, modified from [Abushakra and Clardown, 2001]s](image-url)

The different time profiles for the internal heat production are implemented into the VABI building model. The results (Table 3-2) indicate a small difference in energy use (± 3%) when the
static time schedule is changed, but a major increase up to 35% when the changing profiles are applied to the model.

Table 3-2 Results of the total energy use for different schedules

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Ref</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Occupancy</td>
<td>8-18hr</td>
<td>8-20hr</td>
<td>8-12hr /13-20hr</td>
</tr>
<tr>
<td>D. Lighting</td>
<td>8-18hr</td>
<td>8-20hr</td>
<td>8-12hr /13-20hr</td>
</tr>
<tr>
<td>E. Appliances use</td>
<td>8-18hr</td>
<td>8-20hr</td>
<td>8-12hr /13-20hr</td>
</tr>
<tr>
<td>Energy use</td>
<td>100%</td>
<td>103%</td>
<td>97%</td>
</tr>
</tbody>
</table>

3.4 Discussion and evaluation

Measurement results

- Via this first case study it was validated that user influences have a much bigger influence on building performances than building parameters. Therefore optimizing the building performances without taking the user into account is not going to be very effective. So it is needed to focus on the user instead of the building parameters. These results are consistent to the finding of Nicol [Nicol, 2007], as discussed in the introduction;
- For the case study building the electrical appliances are shown to have the biggest influence on its energy performances by both the hand calculations and the building energy simulation. Therefore the electrical load is looked into in the next case study.
- In the building simulation the input of the user influences is changed accordingly to the limits of the measurements. The results do not take into account that at one moment there may be the maximum internal heat gains in one side of the room, where at the other side of the room there are (almost) no internal heat gains.
- The overall temperature nearby the printer is higher which is probably caused by the high internal heat gains produced by the printer itself. In cooling period it is suggested to look for a manner to extract this heat locally.
- The metabolism and use of electrical appliances are both no user actions in a response to discomforting environmental stimuli, in an attempt to restore the comfort level as described in literature [Haldi et al., 2010]. Therefore it is suggested to focus more on these passive influences to improve the building performances of this case study, before looking at the active actions.
- Blinds are important instruments for controlling the inside comfort, both thermal and visual. On the one hand, they affect the lighting situation, and on the other, especially in summer, they have a large influence on the heat gains through the window. It is suggested having a closer look towards the influence of blinds in another case study office building.

Evaluation

- From the measurements it was not clear if the internal heat loads are constant or vary during the day. This means that the use of the electrical appliances needs to be logged instead of measured by an integrating measurement device.
- To enhance the objective to make the user central in the control of building service systems, it is important to know his position and to meet the control objective as described in §2.1. Therefore measurements need to be made to look if the individual building user can be localized;
- Since the temperature fluctuates during the day and differs between spots, also the temperature for every room is measured. These temperature values can be used in building energy simulations, as described later on in this rapport.
4. Case study 2: user position and appliance load

From the first case study (§3.3) it was concluded that electrical appliances are the most important user parameter to focus towards the building energy performances. The question remains to what extent it is possible to locate the user inside the building, and what information can be obtained from these measurements.

Second measurements are conducted in the case study building, in a period of six weeks to answer this question. This chapter describes the measurement set-up with the system to track the user position (§4.1), the results of these measurements are presented in (§4.2). Finally these results are discussed and conclusions are drawn. A system to measure the user position was proposed

4.1 Measurement set-up

User position

From literature (§2.3) it was shown that RFID technology has the biggest potential to measure the human position inside buildings. Therefore a wireless sensor network (WSN) based on RFID technique was installed on the case study office floor of Royal Haskoning. The individualized occupancy detection system has the following components: static nodes, mobile nodes, receiver and a (cloud)server for data collection. Where there are differences in the organization of the RFID localization system, a brief description of the applied system is given.

- The static and mobile nodes are physically the same (Figure 4-1). The static nodes are programmed with a known location, and mounted on known spots of interest e.g. between the workplaces, nearby the printer, coffee machine and toilet;
- Mobile nodes are attached to occupants to denote occupants’ locations, meanwhile the static nodes are deployed in the environment to provide references for location estimation with their own known locations;
- Based on signal strength from the surrounding static nodes, the mobile node takes over the location of the closest static node. The location is sent to the receiver which uploads the ID, time and location to the online cloud;
- This sensor network is a completely self-organizing WSN, meaning nodes need no configuration to form a network where nodes can freely enter and leave existing networks. Thereby the operation of the network never depends on particular topologies or on single nodes. The platform of the WSN is modular designed, meaning all other kind of different sensors and communication modules can be connected to the network.

![Figure 4-1 Applied nodes for occupant detection with the important components indicated](image-url)
In total eighteen employees wore a mobile node for six weeks in the winter period from 9 January 2012 till 20 February 2012. The employees were randomly chosen and represent almost 80% of the building occupants working on the case study floor. An example of a static node and two methods for wearing the mobile node during the measurements are shown in Figure 4-3.

The composition of the 18 employees is shown in Table 4-1. After the measured period the employees were asked with what accuracy they think the node worked well. Different reasons for dysfunction are empty battery; forget to wear the node; node seemed not to work; etc. The accuracy of the nodes was weighted to the time the employee said to be present during the
measured period. The average weighted accuracy of the measurements is 85% over the period of 6 weeks. Because two stated that the accuracy was too low by a not proper functioning node there results are skipped out leading to usable data of sixteen employees.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sex</th>
<th>Function</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>Female</td>
<td>Male</td>
<td>Drawer</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>13</td>
<td>2</td>
</tr>
</tbody>
</table>

**Electrical appliance load**

For measuring the electrical use by the appliances, a power logger was installed at every desk and/or group of desks, and on other points of interest (printer, coffee machines). In total fifteen power loggers were installed of the type Voltcraft energy logger 4000. This energy meter logs every minute the power and the active power of the electrical appliances plugged in (Figure 4-4).

![Figure 4-4 Applied Voltcraft energy logger 4000, logging electrical appliance load at the desks](image)

**Temperature set points**

Also the temperature set point was monitored by using the data from the PRIVA building management systems (BMS). Therefore a laptop with PRIVA history was set next the BMS saving data every 6 minutes. This data could later on be used to get more accurate simulation results of the actual energy demand.

**Set-up overview**

Figure 4-5 gives a schematic overview of the measurement set-up in this research. The RFID network is used for detecting the position of the building occupant, with the static nodes mounted on walls and placed on desks, and the mobile node carried by the occupant sending its coordinates to the database. Meanwhile the power logger measured the electrical load. Also the indoor temperature was logged, to be used as input in the building energy simulation. Therefore a computer was installed next to the building management system, able to log the actual temperature and desired temperature.

![Figure 4-5 Schematic representation of the measurement set-up with the mobile node (1) determining his position based on the signal strength from the static nodes (2), where the mobile node updates its position to the server via the receiver (3). The most important user influence on building performance, electrical appliances (4), is measured and the thermostat control (5) to be applied in future building energy simulations](image)
4.2 Results

The measurement results of the case study measurement period of six weeks are presented in this paragraph. By the found data it should be possible to analyse the user location and the actions of the user on most important parameter, electrical appliances.

4.2.1 The building user

Data conversion

The measurements generated an extensive quantity of data. Using MATLAB the data is put into usable information. The data for the building users' position was given in JSON format from the cloud, with a longitude and latitude value and additional a Unix timestamp (given in seconds). An example is shown below.

data.value = "longitude":28.000000,"latitude":8.000000,"provider":"myrianed" 1326266799

A MATLAB function is used which parses the JSON string and returns a cell array with the parsed data. The JSON converter to MATLAB file can be found in appendix D, JSON TO MATLAB. The timestamp is set at 0 at the moment 1/1/2012.

The timestamp is in seconds, but the sequential steps are completely random since there was not a fixed time for passing on the data. Performing matrix operations, known arrays with a fixed time step between the rows are needed. Therefore the data is round off to the closest minute. The accuracy of the measurements is thereby brought back to minutes (see appendix D, KNOWN TIMESTAMP). The data conversion to minutes was not needed for position analysis, e.g. looking for the most common workplaces. All further matrix operations are described in appendix D.

Occupant position

Figure 4-6 shows the mean occupancy level (i.e., presence on the office floor or at workplace) with standard deviation for the case study over the course of a reference day (representing the entire observation period). There can be considerable differences amongst offices, though this occupancy shows a comparable pattern with occupancy patterns found in literature [Mahdavi, 2011]. The mean occupancy level is low where it never exceeds 50%.

It is likely that occupancy patterns vary from one day to another day in a week. Figure 4-7 shows the occupancy level between 7AM and 7PM, with the highest occupancy on Tuesday and the lowest on Thursday.

![Figure 4-6 Mean occupancy level and standard deviation as measured over the six week period as a percentage of maximum occupancy level per person](image1)

![Figure 4-7 Mean occupancy level as measured for the different days in a week as a percentage of the maximum occupancy level per person, 7AM – 7PM](image2)
Where this building user locating system was individualized, more information is obtained from the data. To get a better notion of the movement of the building occupant, it is first needed to look at the occupant positions. The data is transformed into an $m \times n$ matrix, with occupancy time in every zone is plotted against the building occupants using equation 4.1.

$$\text{time at position}_{\text{person } n} = \frac{(\sum_{n=1}^{m} \text{occ}_{n, \text{zone } 1} \ast t_{\text{zone } 1}) + (\sum_{n=1}^{m} \text{occ}_{n, \text{zone } 2} \ast t_{\text{zone } 2}) + \ldots}{\sum_{1}^{m} t_{\text{zone } 1-30}}$$  \hspace{1cm}  \text{4.1}

Figure 4-8 depicts (as circular graph), for the whole measured period the percentage of time the employees were on average at their workplace, or at what other spots when they were not behind their desk. The average time, when present on the floor, an employee is on his workplace is 64%. Meaning that, even when present on the floor, for a large percentage of time the occupant is at another position in the building. Next to the informal (17%) and work-related spots (6%), the other spots (13%) indicate that the building user walked to a colleague, is in the corridor or at the secretariat.

![Diagram showing time at different positions]

The locations of the individuals on the floor are the central point of focus. In fact this gives information about the positions which were most in the need of climatization during the measurements. In Figure 4-9 a boxplot with the percentage of present time at the workplaces is given over the measured period. The plots include the results of all measured employees. It shows that there is a clear difference between the different building users, were the time on the most common workplace varies between 15 and 72% of the time present on the floor. It shows the difference how building users use their flex office. Since this office had flexible workplaces, some change position from time to time. Still though it can be concluded that most office workers have a slightly preferred workplace as 50% of the employees is more than 40% of their time being present on the most common workplace, meaning almost two-thirds or more of the time working on the same workplace.

In Figure 4-10 the boxplot looks at what position the building users are when they are not at their workplace. The following can be said about the spots:

- The time spend around the informal spots coffee machine and lounge is significant. Meaning that 75% of the building users are more than 2.5% of the time nearby the coffee machine. The dispersion of the lounge is even greater, where 25% of the employees spend more than 8% of their time in the lounge;
- One of the meeting rooms are not often used, where 14 employees only spend 2% or less of the time in this room. There were two exceptions with 5% and 8% of the time in a meeting room. This means that the meeting room is not occupied most of the time, but when it should be noticed that the building occupant intensity is probably high when the room is occupied;
People spend a significant part of their time on the toilet, where 75% of the building users are more than 5% of the time being present in the toilet. These figures give an impression of the time at what position the employees are on the different spots, where the spots in Figure 4-10 are known spots except for the meeting room since there are more meeting rooms.

To look at the partition the results of all employees are first reflected on a floor map, where the occupancy intensity for the 30 measured spots is shown. When reflecting the results in more detail on a floor map (see Figure 4-11), it is possible to detect occupancy hotspots. The colors are as a factor of the most occupied spots. The following can be concluded:

- There are two dark red spots with location 6 and 14 which were mostly occupied. Also the cell office (location 19) was occupied for a relatively high percentage of time.
- Higher occupancy intensity is also at the lounge, coffee machines, toilet and printer as was also shown in Figure 4-10.
- There are also a lot of blue zones visible, indicating low occupancy time compared to the green, yellow and red colored spots;
- High occupied spots are randomly, e.g. no higher occupancy intensity close to windows.

The total occupancy intensity over the measured period is for 14 cells in the grid less than 30% of the most occupied spot and 19 spots were even less than 40% occupied over the measurement period. In the meanwhile all the spots in the building (except for the toilet) received the same amount of ventilation and where kept at the same temperature set point, indicating potential for saving energy.
4.2.2 Use of electrical appliances

Floor level

Since the electrical appliance where shown to have the highest influence on building energy performance, the electricity use of all appliances were measured. Via a regression analysis it was looked into whether there was a correlation between the mean occupancy level and electrical appliance use of workplaces and all appliances which include the printer and coffee machines on the floor of the case study building. From Figure 4-12 the following could be derived regarding the correlation occupancy and appliance use:

- For the values derived over the measured period, there is a clear correlation between the mean occupancy and mean appliance use;
- There is a concentration of points in the marked box A, originating from the fact that this regression analysis is produced from averaged profiles. The deviation should be closer looked into in the marked box A. The concentration of points originates from the fact that this regression analysis is produced from averaged profiles, with an average occupancy between 25% and 45%. However, by taking averaged profiles data is thrown away.
- A higher order polynomial seems to fit better with in this case 5th order indicated with dotted lines. However the regression coefficient is lower with a value of 0.85 for the total appliance use and 0.87 for the appliance use on workplace level.
Linear regression of electrical appliances as a function of occupancy
Averaged day from 7AM - 7PM with timestep of 6 minutes

Where data is thrown away when applying the averaged profiles, the correlation is determined for 5 reference days on floor level. Figure 4-13 shows the linear regression for 5 randomly chosen days. The regression coefficient of the combination of the five reference days is 0.49 (the square of the correlation coefficient) indicating that 49% of the variation in the appliance load on floor level may be explained by the occupancy variable. In other words the confidence level is 49%, which is probably too low when thinking of the importance of internal heat gains by electrical appliances on building energy performances. The regression lines are parallel to a certain extent, which indicate that the appliance load is not completely random and can be assessed by the occupancy on floor level.

Workplace level
Since the interest is on the user and his individual need for comfort, a closer look is made at the workplace level. Figure 4-14 shows the occupancy rate and the load by electrical appliances
for four CAD workplaces in zone 3.22. Figure 4-15 shows the occupancy rate and the load by electrical appliances for four office workplaces in zone 3.20.

- A time step of 5 minutes is used, where it is assumed that it is feasible to switch appliances off or put them into sleep from this period of time;
- A clear gap indicated with the arrows is visible where there are no occupants for a longer period, but where the electrical load does not decrease in graph I, II and III. The occupants were, for example, in a meeting where the electrical load did not drop. Contrary is the increase of occupancy in graph IV, where the electrical load does not change at that moment of time;
- There are relations visible between the occupancy and appliance use in the four examples, where the electrical load sometimes changes accordingly with the occupancy;
- The occupancy at the workplaces is changing very consequently, where the electrical load of the appliances in relatively constant.

![Figure 4-14 Occupancy of 4 CAD workplaces and electrical load, time step = 5 min, date I. 8-2-2012, II. 10-2-2012](image1)

![Figure 4-15 Occupancy of 4 office workplaces and electrical load, time step = 5 min, date III. 24-1-2012, IV. 13-2-2012](image2)

Just like for the floor level, a regression analysis is made for the desk group in the office and CAD workplaces. The correlation coefficient for these random four days, as depicted in Figure 4-16, shows that a very weak correlation exists between the occupancy level and appliance load on workplace level.
From the above figures the following can be derived:

- Although relations are clearly visible between occupancy and appliance load on workplace level, they do not correlate;
- It is not suggested to predict the appliance load based on the occupancy, or vice versa on workplace level;
- When electrical appliances would shut down when someone is not present, there are major possibilities in saving electrical energy and cooling load.

4.3 Discussion on measurement results

General observations

- The applied sensors using RFID for communication seems to be promising technique to be applied in the built environment, were the application of low cost wireless sensors was already acknowledges by [Klein et al., 2012]. Via this indoor localization the building can be divided in zones where a mesh arises from communication by the static nodes. It is not known if the mesh can already be accurate enough to identify exactly at which desk someone is sitting when two desks are next or opposite of each other;
- The average occupancy rate was below 50%, similar to the occupancy profiles found in literature [Mahdavi, 2011]. The low occupancy rate indicated possibilities for energy savings when this energy is focussed around the building user;
- The building users spend on average 64% of their time in the building at their workplace, where they were a significant time (17%) at informal spots like the toilet, lounge and coffee machine in the building. Where 75% of the occupants are more than 5% of their time at the lounge, this is an important spot to focus on;
- Projecting the occupancy time on the floor map, so called hotspots can be distinguished. Half of the spots in the building were less than 30% of the time occupied compared to the most occupied spots, meaning that conditioning of some spots is more needed than other spots on the same floor.

Prediction appliance load by occupancy

From the first case study it was shown in §3.3 that electrical appliances is the user action having the biggest influence on the building energy performance.
Electrical loads on workplace level show relations with the occupancy rate. However, where the occupancy rate fluctuates strongly and the electrical appliance use is relatively stable those two do not correlate. It is suggested to apply smart energy devices, which can be put into sleep mode or turned off when the occupant is not present for a period more than 5 minutes;

Where no previous researches investigated occupancy as explaining variable for the appliance load, the results of this study cannot be compared to literature. Where Parys [Parys et al., 2011] suggested to link the ratio of appliance load to the occupancy rate, it is concluded that this is only limited possible on floor level.
5. User comfort and energy saving potential

5.1 Modelling cases

A model is 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 is 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 are the same, only a change will be in the user profiles. These input variables are explained in more detail.

A. Design input

In the design phase assumptions are made for the different user influences on building performances. The zones of the building model are equal to the rooms of the floor plan. The values are shown in Table 5-1.

Table 5-1 Overview of the input values for the building simulation on workdays

<table>
<thead>
<tr>
<th>Simulation Input</th>
<th>A. Design</th>
<th>B. Actual</th>
<th>C. Room</th>
<th>D. Workplace</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Metabolism</td>
<td>10 W/m² 8-18hr</td>
<td>1.1 Met/hrs</td>
<td>Occ./room*</td>
<td>Occ./zone*</td>
</tr>
<tr>
<td>D. Lighting</td>
<td>10 W/m² 8-18hr</td>
<td>Power/room*</td>
<td>8-20hr</td>
<td>Power/zone*</td>
</tr>
<tr>
<td>E. Appliances</td>
<td>10 W/m² 8-18hr</td>
<td>Power/room*</td>
<td>Power/zone*</td>
<td></td>
</tr>
<tr>
<td>F. Temp. (heating)</td>
<td>22 (8-18hr)</td>
<td>Temp./room*</td>
<td>19 18</td>
<td>18</td>
</tr>
<tr>
<td>F. Temp. (cooling)</td>
<td>24 (8-18hr)</td>
<td>23.5 (8-18hr)</td>
<td>If occ. 23.5 else 25</td>
<td>If occ. 23.5 else 25</td>
</tr>
</tbody>
</table>

* 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 are applied. The occupancy contributes 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, Aₕ=1.8m²), which is standard for office activities such as typing according to ASHRAE (2004). The heat produced by the lighting is the sum of the light fixtures in every room, assumed to be switched on from 8-20hr. The internal heat gains by the appliances are the sum of the measured energy demands in every room. For the heating the measured temperature profiles are used as temperature set point. In the winter a temperature set point of 23.5 °C during working time is assumed.

C. Human in the loop – room level

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

In Figure 5-1, 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 this day the maximum occupancy equals 80%. For the appliances the total heat load is presented. Remarkable point to mention is that even when the occupancy decreases (e.g. during the lunch break at 12.00h), the heat load by appliances does not significantly change.
D. Human in the loop – workplace level

In this case the model is divided into the 30 zones, which are the same as the conducted measurements on the case study floor. The internal heat gains of metabolism, lighting and appliance use are 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 19.5°C 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 is only applied on the workplaces, e.g. no hand heaters are applied in the toilet, nearby printer.

5.2 Simulation model

Building level

A simplified sketch of the simulation model in Simulink is shown in Figure 5-2, in this case D. control on workplace level with 30 zones. In simulation A, B and C the zones of the model correspond to the physical rooms in the building.

Climate data of the measured 6-week winter period is coupled to the whole-building model. The indoor air temperature of the zones is the output of the whole-building model. This information is
used as feedback signal for the control algorithms of the individual zones. A demultiplexer (demux) is used for selecting the data-output from this feedback signal. A multiplexer (mux) is used for combining several data lines into one single signal line. The physical properties as applied in the model are in appendix G.

Zone level
The energy balance of the different zones in the model can be written using the general energy balance, see equation 5.1.

\[ V_c \rho \frac{dT}{dt} = \dot{Q}_{\text{in}}(t) - \dot{Q}_{\text{out}}(t) \]  

(5.1)

It can be assumed that the energy flows into the room constitutes:
- Energy supplied for space heating/conditioning by the central HVAC system \(Q_{\text{basic}}\);
- Energy supplied for personalized conditioning of the occupants, only applied in case D with the human in the loop on workplace level \(Q_{\text{local}}\);
- Direct solar gains \(Q_{\text{sol}}\);
- Internal heat gains from lighting, occupants and appliances.

\[ \dot{Q}_{\text{in}}(t) = Q_{\text{basic}}(t) + \sum Q_{\text{local}}(t) + Q_{\text{sol}}(t) + Q_{\text{light}}(t) + Q_{\text{occ}}(t) + Q_{\text{app}}(t) \]  

(5.2)

The energy outflow of the zone constitutes heat losses from the building envelope towards the external conditions \(Q_{\text{out}}\) and ventilation losses \(Q_{\text{vent}}\). Heat is stored and released by the building construction.

![Diagram of zone control system](image)

**Figure 5-3** Simplified sketch of the zone control in Matlab/Simulink for the actual energy demand (room level) and the individual zones (workplace level). The power provided to the zone consists of the basic heating, the internal heat gains by occupants, appliances and lighting, and in case D the local heating.
About the simulation model the following can be said:
- Each zone has its own control loop for regulating the indoor air temperature (Figure 5-3).
- For the basic room heating ($P_{\text{basic}}$) a proportional control algorithm is applied;
- In the cases 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;

5.3 Results

Energy

The (primary) energy saving potential is calculated according to equation 5.3. The energy needed for the case is divided by the energy needed for the reference situation which is the design situation. The results are presented in Figure 5-4.

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

(5.3)

![Energy saving potential](image)

Figure 5-4 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 is 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 can be obtained compared to the design reference situation. A higher energy reduction is obtained when the temperature is 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 can be obtained.

Comfort

Occupant comfort for the cases B. actual situation and C. control on room level are compared with the designed thermal comfort based on the PMV value. Since there is no model available looking at the individual comfort, this well-known PMV index will be used. From the measurements the temperature is available, where the averaged radiant temperature and relative humidity are determined by the building simulation. For the purpose of this evaluation, all other PMV values were considered to have the fixed values shown in Table 5-2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Clothing (Clo)</th>
<th>Air velocity</th>
<th>Metabolic rate (W/m²)</th>
<th>External work (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1</td>
<td>0.1 m/s</td>
<td>1.2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5-2 Fixed parameter values for PMV calculations
The PMV values are 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 5-5. The room temperature fluctuates during the day around three degrees Celsius and the radiant temperature circa two degrees Celsius. The relative humidity is between 40% and 50% during this working week. The results of the PMV calculations are shown in Figure 5-6. The green area presents the designed values where the PMV should be in between. In the actual situation, the PMV value does 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 is not yet at its desired temperature at 8 AM. For case C the room temperature set point is 19.5°C when no one is present in the room. The PMV values are only counted for when someone is present. It is clearly visible that the PMV value is lower, where 50% of the values are below the comfort boundary. However, this PMV does not take into account the time it takes the 5 - 10 minutes before a building user perceives the change in temperature in slightly cool environments [Wang et al., 2007].

In his research Vissers [Vissers, 2012] showed that by 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 hand with a radiation panel the local- and overall thermal sensation of tested subjects were maintained neutral or slightly higher level. Therefore it is assumed that the PMV is between the boundaries when applying local heating.

Since the proposed control strategy of Vissers shows high potential for improving the comfort level, while reducing the energy use this is closer looked into in § 5.4.

5.4 Energy improvement using local heating

The application of local heating and cooling shows high potential, especially when combining it with the possibilities of indoor localization. Only energy savings by local heating are looked into, since no obvious results could be found for personal cooling.

The (primary) energy saving potential is calculated according to equation 5.4. The energy needed for the case is divided by the energy needed for the reference design situation. The results are presented in Figure 5-7.

$$\text{energy saving} = 1 - \frac{Q_{\text{basic}} + \sum Q_{\text{local case}}}{(Q_{\text{basic}})_{22°C}}$$
The energy saving potential for heating is 17%, as shown in the previous paragraph, when lowering the set point of the indoor air temperature from 22°C to 19.5°C and taking into account personalized heating of 98W per occupant [Vissers, 2012].

Simulation results compared to literature
Zhang also reported the energy savings by expanding the dead-band [2] in which the room temperature is controlled [Zhang et al., 2010]. The annual energy savings, obtained by a numerical study, for different climate zones in the United States are shown in Figure 5-8. The energy use of the local task-ambient conditioning (TAC) system itself is not taken into account. Therefore the energy savings, as found in this research, are less high compared to the graph of [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 22°C to 20°C [Oeffelen et al., 2010], which is about 10% higher as found in this research. However, this research considered real occupancy profiles and energy use for individual local heating, which makes the results more realistic.

---

*Indoor temperature range between thermostat settings for heating and cooling.*
6. Conclusions, discussion and future directions

6.1 Conclusion

The HVAC systems are controlled on building level and room level in which we loosed the building user out of sight. The building service systems are wasting energy by deploying energy on spots where there is no need for energy. This graduation project presented a new strategy, where the user is leading in the control of HVAC systems by locating the user position inside the building. It was assumed that the user has a major importance on building energy control, where it is needed to focus more on the user and its influences and actions on the building. This lead to several research questions (§1.3), to which the following conclusions are drawn:

i. What are the most critical parameters (i.e. user actions and building parameters) for the building energy performance?

Calculations and VABI modeling of short measurements on the case study floor showed that the most critical parameter is the use of electrical appliances, where this has the biggest influence on building energy performance.

The following observations were made:

a. Where major differences of internal heat gains by the appliances load between spots on the floor are measured (e.g. 6~20 W/m² workplaces, 450 W for the printer), it is needed to look if this use can be predicted by the occupancy rate.

b. Occupant information is needed, where (i) the occupant influences are three to four times higher on building energy performances as building parameters (ii) by low occupancy rates the occupant position is needed to send energy only to those spots where needed, for optimization of the energy demand and comfort level.

ii. From literature the “user location” is indicated as an important parameter, through a “case study” this is further analysed.

From measuring the position of 18 building users and the electrical appliance use at the workplaces during six weeks, the following can be derived:

a. With RFID technology it is possible to localize the building user on room level. However, additional measures are needed for detection on workplace level. The identification of the user and time needed are accurate enough;

b. When the user is present, he is on average 64% of the time on this workplace. More than 75% of the occupant have a most common workplace, despite there are flex office workplaces.

c. Position hotspots are recognized, where other spots are often not occupied. A higher position intensity is recognized around the non-workplaces, coffee machine, lounge, toilet and printer.

d. The use of electrical appliances seems to correlate with the occupancy rate when looking at floor level (0.4 < r² < 0.8). There is a clear relation between the occupancy rate and appliance load on workplace level. Where the occupancy rate fluctuates strongly from time to time, the electrical load is relatively state resulting in a low correlation coefficient (0.1 < r² < 0.6).

iii. Estimate the potential energy saving by focus more on the individual comfort.

By applying the ‘human in the loop’ control strategy on individual level energy savings are achieved, where the basic-room air set-point can be lowered and there is locally heated or cooled. It can be assumed that this strategy has potential for increasing the comfort level. For the floor an energy saving potential close to 30% for heating and up to 45% for cooling is obtained compared to the actual energy demand. Regarding the comfort level and energy use the following can be said:
6.2 General discussion

This paragraph looks towards a general discussion of the proposed human in the loop control with the human as leading factor of HVAC systems. The results of the case studies were already discussed in detail at the end of chapter 3 and 4 about respectively the influence of the human on building performances and the human and his position leading in the control of HVAC systems.

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.

Energy reduction and comfort improvement

- Where this research did not look at the comfort level by conditioning when the user is present, the building user comfort level should be looked into. The challenge is that the workplace should be right conditioned before the neutral thermal state 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 [Wang et al., 2007] tested persons by exposing them to a slightly cool environment of 19 °C and warm environment of 28.2 °C. In the situation of the slightly cool environment the testes subjects voted their thermal sensation was cold between 10 and 20 minutes. In the warm environment the subjects voted warm after circa 10 minutes. This means that the building service systems must be capable of conditioning the workplace within 10 minutes, before the building user perceives warm or cold;

- The achieved energy reduction by controlling the temperature on room level was 16% for heating and up to 28% for cooling compared with the actual situation. Klein [Klein et al., 2012] implemented a multi-agent comfort and energy system in a university floor. A reduction of 12% to 17% was achieved. The energy saving is 4-11% lower than found in this research. However, where in the research of Klein the case study floor consisted of 33 rooms, he was able to divide the floor in 17 thermal zones. When the floor could be divided in thermal zones compared with the rooms it is reasonable that he also finds higher energy savings;

- The applied model to calculate the comfort is based on the PMV value. For the actual situation, where an uniform environment is assumed this PMV model could be said to be applicable, where it has the restriction that even with PMV of zero, there is 5% of the building users not satisfied with the environment. For the calculated PMV on room level
there are some points which can be discussed. This PMV does not take into account that it takes some time before cold conditions are perceived. With the possibilities of the user position detection it should be looked into if the room can be feed-forward controlled, so the building systems start with climatization before the occupant enters the room.

‘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 Huizenga [Huizenga et al., 2006] and 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.

**Added value for Royal Haskoning**
This master study conducted in one of the offices of Royal Haskoning, also leads to added values as a consultancy agency. With this research they participate in the newest developments and gain knowledge about the future directions of the control of building services systems.

The focus should be more on the user, where this research helps to ground them in their advice to clients. This approach provides Royal Haskoning knowledge and experience for services: monitoring and realizing indoor climate on user level. The development could lead to financial benefits for all stakeholders by a better performing building, with a higher (end) value, higher productivity and reduction of the energy costs.

By the measurements they gain practical inside in the numbers to be applied for electrical appliances in building simulation.

*Not included in the research*, probably the reason why the building users raise the temperature set point is by the cold radiation from the large area windows. It was measured that the temperature 1-2 m from the glass was on average 0.5 °C colder than at 3-4 m from the glass. Next to this temperature difference, the human skin is most sensitive for radiation. It is suggested to use windows with lower U-values or apply convectors near the windows.

### 6.3 Recommendations and future directions

**General**
This pilot study showed the possibilities for tracking the buildings users’ position inside the building by RFID technology. The obtained results can however only be applied to the case study building. Where the results are promising it is highly recommended to repeat these measurements in different office environments.

- Thereby, the differences between offices should be investigated. In this case a possible important factor is that windows are almost never opened by the traffic noise and blinds are not present. Different buildings could give another view on most important user action research field.
- In addition, it is advisable to investigate how conditioning on building users presence can be applied in existing building HVAC systems. When control algorithms are applied to the existing building control possibly energy can be applied on users’ presence. Thereby the energy savings should be determined to be compared with the simulation model.
- Possible lower energy savings are achieved in real energy consumption by the presence of the user rebound effect. This effect, as described by Hens [Hens et al., 2010], results in a more energy consuming behaviour by the building occupant, since the idea exist that the
building is energy efficient. Possible consequences are a higher temperature set point or light is turned on more often, resulting in higher energy consumption.

Building services control structure
Integrating the building user location and other information of the user actions, should result in another control structure of the building management systems.

- The goal of obtaining comfort conditions and simultaneously energy conservation in a building is solved by the development of intelligent systems. Dournis proposed the use of an agent based structure, with an intelligent coordinator that supervises the optimal cooperation of the local controllers-agents (e.g. thermal controller, lighting controller) [Dournis et al., 2009]. Hereby, total control is achieved, occupants' preferences are satisfied, conflicts are avoided and energy consumption is conditionally minimized.

A comparable agent based structure is also proposed by Klein [Klein et al., 2012] who successfully implemented this control structure at a university floor of ca. 700 m². Where Klein tried to assess the improvement of comfort based on PMV calculations with the temperature as only variable he found a comfort improvement of 5%. In this research he was not able to locate the individuals, where individual differences could not be taken into account on advance. It is suggested to extend this research with comfort assessment in a real building to determine the actual energy savings and estimate the comfort improvement by questionnaires.

- Using many low-cost wireless sensors results in a large amount of data. The received data could contain a lot of noise, e.g. someone walks quickly from and to his workplace to get some literature. The use of large amounts of simple sensors creates a need for temporal pattern mining algorithms to work on such data as described by Salah [Salah et al., 2010]. The problem is that, as concluded before, action patterns depend on multiple factors and cannot be predicted by the previous state since they are stochastic. Secondly, these patterns exist in different time intervals, and the time difference between related events of a single action can have a large variation. Consequently, the interpretation of the real-time data becomes a very challenging task needing state-of-the-art pattern analysis methods.

Include smart control of lighting and appliances in the simulation
In the current energy simulation only energy savings are made changing the temperature set point. It is expected that the energy savings will be higher by inclusion of the following aspects in the simulation:

- Include smart control of lighting, where lighting is only switched on when someone is present in the zone. As Mahdavi already concluded from long-term measurements, electrical energy savings up to 30% can be achieved when lighting is only switched on when needed [Mahdavi et al., 2009]. This will probably lead to energy savings on the building HVAC demand;

- Include smart electrical devices in the simulation, by switching them of or putting them in standby modus when the user is not on his position. In Figure 4-14 and Figure 4-15 in chapter 4 it is shown that even when workplaces are not occupied for a longer period, the electrical load does not decrease. This could lead to both energy reductions on electrical use and HVAC load.

- When positions are not occupied the ventilation rate could be reduced accordingly, which directly influence the heating and cooling demand of building systems. When the position of the user is known it is possible to feed forward control the ventilation rate before the CO₂ level increases.

Improved detection technology
In the nearby future (end of the year 2012) [Sense OS, 2012] it should be possible using SMART phones for detecting the position of the building user. The occupant position can be
determined using the signal strength of Bluetooth, since no RFID sensors are included in the SMART phones. The advantage of using SMART phones for localization is diverse, since:

- Most people already wear a (SMART) phone in their pocket;
- No extra investments needs to be made, since commonly used consumer electronics can be used;
- SMART phones can provide the building management system a lot of information about the building users which could be interpreted by the building management system. Every SMART phone has different sensors available, as shown in Figure 6-1.
  - For example, the position of the user outside the building is known by the GPS sensor in the SMART phone. When the building user arrives at the building his fixed workplace can be conditioned in advance.

Figure 6-1 Available sensors in a SMART phone to be used by the building management system providing information about the user

Another improvement of the individualized location system is integration of the RFID node in the company batch worn by the building occupant. The result is minimal hinder for the building user, where the same information is received by the building management system.
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<table>
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<th>Author(s)</th>
<th>Year</th>
<th>Title</th>
<th>Details</th>
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<tr>
<td>Hoyt, K.H. Lee, H. Zhang, E. Arens, Webster, T.</td>
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Microsoft Office 2010 Professional

Sense MyriaNed

VABI Elements V0.9, 2011, building energy simulation
### Terminology

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>geometrical opening area</td>
<td>[m²]</td>
</tr>
<tr>
<td>A_{glass}</td>
<td>glass area room</td>
<td>[m²]</td>
</tr>
<tr>
<td>A_{room}</td>
<td>area of the room of personal action</td>
<td>[m²]</td>
</tr>
<tr>
<td>c</td>
<td>capacity of incoming air (&lt;=1.000)</td>
<td>[J/kgK]</td>
</tr>
<tr>
<td>C_d</td>
<td>discharge coefficient (between 0.8 and 1.0)</td>
<td>[-]</td>
</tr>
<tr>
<td>g</td>
<td>solar factor glazing (Dutch: ZTA)</td>
<td>[%]</td>
</tr>
<tr>
<td>Δp</td>
<td>pressure difference across the opening</td>
<td>[Pa]</td>
</tr>
<tr>
<td>ΔT_1</td>
<td>temperature difference (in- / outside)</td>
<td>[K]</td>
</tr>
<tr>
<td>ΔT_2</td>
<td>temperature difference (inside / set point)</td>
<td>[K]</td>
</tr>
<tr>
<td>T_{in}</td>
<td>Indoor air temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>Q_{air}</td>
<td>air flow through window opening</td>
<td>[m³/s]</td>
</tr>
<tr>
<td>Q_{solar}</td>
<td>solar irradiation (assumed max. 1,100)</td>
<td>[W/m²]</td>
</tr>
<tr>
<td>v_{air}</td>
<td>air speed (wind)</td>
<td>[m/s]</td>
</tr>
<tr>
<td>V_{room}</td>
<td>volume of the room of personal action</td>
<td>[m³]</td>
</tr>
</tbody>
</table>

### Greek

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>angle of the sun on glazing</td>
<td>[°]</td>
</tr>
<tr>
<td>η</td>
<td>system efficiency H/C</td>
<td>[%]</td>
</tr>
<tr>
<td>ρ_0</td>
<td>density of incoming air (≈ 1.3)</td>
<td>[kg/m³]</td>
</tr>
</tbody>
</table>

### Subscripts

- Min: Minimum
- Max: Maximum
- Mhz: Mega hertz
- Occ: Occupancy
- Sol: Solar
- Vent: Ventilation

### Abbreviations

- ABG: Architectural Bond Graph
- ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers
- BMS: Building management system
- CP: Critical parameter
- CAD: Computer-Aided Design
- ID: Identity
- HVAC: Heating Ventilation Air Conditioning
- PIR: Passive Infrared Sensor
- PMV: Predicted Mean Vote
- PRIVA: Prins and Valk (brand)
- Rfid: Radio frequency identification
- WLAN: Wireless Local Area Network
- WSN: Wireless sensor network
A. Movement of building users per quarter

The position is the most common spot of the building user during the indicated quarter of an hour. During these three quarters the random movement of the building users is visible. Also the fraction of appliance use is shown in the zones as a fraction of the maximum measured appliance load.

<table>
<thead>
<tr>
<th>Fraction of appliance use</th>
<th>Occupancy per zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>None</td>
</tr>
<tr>
<td>0.9</td>
<td>1</td>
</tr>
<tr>
<td>0.8</td>
<td>2</td>
</tr>
<tr>
<td>0.7</td>
<td>3</td>
</tr>
<tr>
<td>0.6</td>
<td>4</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 0-1 Mean occupants position in quarter of an hour and fraction of electrical appliance load from 10:45 AM to 11:30 AM on a reference day
B. Non-individualized occupant detection

**Passive infrared**

Occupant detection in current buildings is typically accomplished using passive infrared (PIR) and ultrasonic motion detectors [Page et al., 2008]. There are some other drawbacks of this human detecting method:

- The sensor only recognizes two states of presence: occupied or vacant, and can therefore not distinguish whether the zone is multiply occupied or not;
- The recognition of presence or not, is not capable of detecting which individual is at what position and how they move;
- A non-moving occupant at his workplace could considered to be vacant.

To meet those drawbacks, Dong [Dong et al., 2010] proposed a system that collected data through CO₂ detection, acoustic and PIR sensors. The average accuracy became 73% in counting occupants. The dependency on CO₂ is a major disturbance, where it takes time to build up the CO₂ level as a cumulative effect of various factors other than occupancy, such as outdoor air quality, ventilation rate, opened windows.

**IT infrastructures**

Melfi [Melfi et al., 2011] uses existing IT infrastructures to replace and/or supplement traditional dedicated sensors to determine building occupancy. The applied sensing method is largely based on monitoring the MAC and IP addresses in routers and wireless access points, and then correlating these addresses to the occupancy of a building, zone, and/or room. The occupancy was based on the Wi-Fi signal from mobile phones, worn by the occupants. Another indication of occupancy is the use of the computer. In his research Melfi compared the accuracy of PIR, Wi-Fi connection and the PC activity. The accuracy of sensing is shown in Figure 2-2.

<table>
<thead>
<tr>
<th>Device</th>
<th>Accuracy Vacancy</th>
<th>Occupancy</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIR</td>
<td>61%</td>
<td>100%</td>
<td>91%</td>
</tr>
<tr>
<td>PC activity</td>
<td>100%</td>
<td>85%</td>
<td>89%</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>61%</td>
<td>59%</td>
<td>59%</td>
</tr>
</tbody>
</table>

It shows that the overall accuracy of PC activity is accurate to obtain the occupancy. PC activity could therefore give a good estimation whether someone is at his workplace or not, but the main disadvantage is that still the position in the building is not known, even when the occupant is behind his desk. The overall accuracy of the Wi-Fi connection is less high, though it shows some potential. Beneficial compared to the PC activity is that the position of the occupant is known at the level of several rooms. Though, there are two main issues which affect the accuracy as an implicit measure in the count and localization: 1) overlap of access point coverage, and 2) inconsistent Wi-Fi connectivity of mobile phones.

**Vision-based**

Benezeth [Benezeth et al., 2011] proposed a vision-based system based on video analysis, using a static camera. The detection composes of three main steps, where the first step is to change detection using a background model. Since the scene is never completely static, the model is designed to adapt to different environmental changes, e.g. slow variations in lighting conditions, addition or removal of static objects. The second step is by background subtraction to focus only on the moving object. The third step is to detect the nature of the moving objects and it should be looked whether it corresponds to a human or not. The process of human detection is shown in Figure 0-2.
The total accuracy of counting the occupants (number of correctly estimated points divided by the total number of points) found by Benezith is 83%. Benezith suggested that for a more exact localization of the more than one camera must be used to estimate the 3D position of each detected person.

Drawbacks of this system are that the detection process so far is only possible with daylight cameras, where the cameras fail at detecting humans in hot summer days and often suffer from floor reflection. Another disadvantage is that these measurements are not capable of detecting which individual is at what position, besides the fact that in every zone one or more cameras need to be installed.

Figure 0-3 shows the obtained occupancy results (A), with the blue line as actual occupancy profile and the red line as the estimated number of occupants derived from the video tracking in a corridor. The right graph (B) shows the activity characterization of a meeting room. The value of activity is of course dependent on the relative subjectivity of the activity concept. The confidence level of the overall activity of humans turns out to be 91%.
## C. Kesselring assessment

<table>
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<th>Functioning</th>
<th>Non-Individualized</th>
<th>Individualized</th>
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<th></th>
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<td>PIR</td>
<td>IT infra</td>
<td>Vision-based</td>
<td>WLAN</td>
<td>Indoor GPS</td>
<td>RFID</td>
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<td>Factor Max Score Total</td>
<td>Score Total</td>
<td>Score Total</td>
<td>Score Total</td>
<td>Score Total</td>
<td>Score Total</td>
<td>Score Total</td>
<td>Score Total</td>
<td></td>
</tr>
<tr>
<td>Spatial resolution</td>
<td></td>
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<td>56</td>
<td>44</td>
<td>53</td>
<td>33</td>
<td>86</td>
<td></td>
</tr>
</tbody>
</table>
D. MATLAB important M-files

JSON TO MATLAB

filename = ['934.txt'];
data = importdata(filename); %import the file into data
parse=data.textdata %searches for the column with the json data
for j=1:length(parse)
    mat=json2mat(parse{j,1}) %changes json format into matlab matrix
    P(j,1)=data.data(j,1) %time of position
    P(j,2)=mat.longitude %x position of building occupant
    P(j,3)=mat.latitude %y position of building occupant
    P(j,4)=P(j,1)-1325376000 %UNIX TIMESTAMP: set time to 01-01-2012 00:00:00
    %P(j,1)=P(j,1)/3600 %make hourly values of the time
end

function data = p_json(string)
    DATA = P_J__ON(string)
    % This function parses a JSON string and returns a cell array with the
    % parsed data. JSON objects are converted to structures and JSON arrays are
    % converted to cell arrays.
    global pos inStr len esc index_esc len_esc
    pos = 1; len = length(string); inStr = string;
    % String delimiters and escape chars identified to improve speed:
    esc = find(inStr=='"' | inStr=='\'); % comparable to: regexp(inStr, '"\"');
    index_esc = 1; len_esc = length(esc);
    if pos <= len
        switch (next_char)
            case '{'
                data = parse_object;
            case ']['
                data = parse_array;
            otherwise
                error_pos('Outer level structure must be an object or an array');
        end
    end % if

    function object = parse_object
        parse_char('"');
        object = []; %
        if next_char == ',"
            while 1
                str = parseStr;
                if isempty(str)
                    error_pos('Name of value at position %d cannot be empty');
                end
                parse_char('"');
                val = parse_value;
                eval( sprintf( 'object.%s = val', valid_field(str) ) ); %
                if next_char == ','
                    break;
                end
            end
        end
    end
function parse_char(c)
    global pos inStr len
    skip_whitespace;
    if pos > len | inStr(pos) ~= c
        error_pos(sprintf('Expected %c at position %d', c));
    else
        pos = pos + 1;
        skip_whitespace;
    end
end

function c = next_char
    global pos inStr len
    skip_whitespace;
    if pos > len
        c = [];
    else
        c = inStr(pos);
    end
end

function skip_whitespace
    global pos inStr len
    while pos <= len & isspace(inStr(pos))
        pos = pos + 1;
    end
end

function str = parseStr
    global pos inStr len esc index_esc len_esc
    % len, ns = length(inStr), keyboard
    if inStr(pos) == "";
        error_pos('String starting with " expected at position %d');
    else
        pos = pos + 1;
    end
    str = ' ';%index_esc
    while pos <= len
        if index_esc > len_esc

str = [str inStr(pos:len)];
pos = len + 1;
break;
else
str = [str inStr(pos:esc(index_esc)-1)];
pos = esc(index_esc);
end

nstr = length(str); switch inStr(pos)
case ""
pos = pos + 1;
return;
case "\"
if pos+1 > len
error_pos('End of file reached right after escape character');
end
pos = pos + 1;
switch inStr(pos)
case '{' '{' '{' '{' '{' '{' '{'
str(nstr+1) = inStr(pos);
pos = pos + 1;
case [b' ' 'n' 'r' 't']
str(nstr+1) = sprintf(['\' inStr(pos)]);
pos = pos + 1;
case 'u'
if pos+4 > len
error_pos('End of file reached in escaped unicode character');
end
str(nstr+1) = inStr(pos), keyboard
pos = pos + 1;
end
otherwise % should never happen
str(nstr+1) = inStr(pos), keyboard
pos = pos + 5;
end
end
error_pos('End of file while expecting end of inStr');

function num = parse_number
global pos inStr len
[num, one, err, delta] = sscanf(inStr(pos:min(len,pos+20)), '%f', 1);
if ~isempty(err)
error_pos('Error reading number at position %d');
end
pos = pos + delta-1;
end

function val = parse_value
global pos inStr len
true = 1; false = 0;
switch(inStr(pos))
case ""val = parseStr;
return;
case '"val = parse_array;
return;
case ','val = parse_object;
return;
case ['-','0','1','2','3','4','5','6','7','8','9']val = parse_number;
return;
case 't'
    if pos+3 <= len & strcmp(lower(inStr(pos:pos+3)), 'true')
        val = true;
        pos = pos + 4;
        return;
end
case 'f'
    if pos+4 <= len & strcmp(lower(inStr(pos:pos+4)), 'false')
        val = false;
        pos = pos + 5;
        return;
end
case 'n'
    if pos+3 <= len & strcmp(lower(inStr(pos:pos+3)), 'null')
        val = [];
        pos = pos + 4;
        return;
end
end
error_pos('Value expected at position %d');

function error_pos(msg)
global pos instr len
    posShow = max(min([pos-15 pos-1 pos pos+20],len),1);
    if posShow(3) == posShow(2)
        posShow(3:4) = posShow(2)+[0 -1];  % display nothing after
    end
    msg = [sprintf(msg, pos) ': ' ...
            instr(posShow(1):posShow(2)) '<error>' instr(posShow(3):posShow(4)) ];
    error([ 'JSONparser:invalidFormat: ' msg ]);

function str = valid_field(str)
    % From MATLAB docs: field names must begin with a letter, which may be followed by any combination of letters, digits, and underscores.
    % Invalid characters will be converted to underscores, and the prefix "_s_" will be added if first character is not a letter.
    if ~isletter(str(1))
        str = ['_s_' str];
    end
    str(~isletter(str) & ~(0 <= str & str <= 9)) = '_';
end
KNOWN TIMESTAMP

%----write into matrix with known timestamp-----------------------------

day_time=zeros(70560,3); % matrix w. time in min for 7 weeks
for i=1:length(day_time)
    day_time(i,1)=i*60; % assign time in sec to first column
end

for j=1:length(data)
    t=round(data(j,1)/60)*60 % round value to one minute
    row=find(day_time==t) % find row in matrix
    day_time(row,2)=data(j,2) % write x-value to column
    day_time(row,3)=data(j,3) % write y-value to column
end

%----fill values when not received--------------------------------------

time_2=day_time

for i=2:length(day_time)-2
    if day_time(i-1,2)==0 && day_time(i,2)==0 && day_time(i+2,1)==0
        time_2(i,2)=day_time(i-1,2)
        time_2(i,3)=day_time(i-1,3)
    end
end
E. **MyriaNed description**

MyriaNed is the software placed on the receiver to upload the received data to the online cloud. MyriaNed is installed on a netbook using Ubuntu. The online cloud is referred to as CommonSense.

**Netbook Installation**
- The netbook should be located in a central place, and have a wired internet connection as well as power.
- Startup the netbook in Ubuntu (default).
- Login as Username: sense; Password: sensei.
- In Ubuntu, start a terminal (black square icon in top left corner).
- Navigate to Desktop/Royal_Haskoning (cd Desktop/Royal_Haskoning).
- Start SinkHost (. /SinkHost.sh). You will be asked for the above password.
- In SinkHost, fill in your CommonSense username and password (register at http://common.sense-os.nl), tick “Print Items”, “Save Items”, “Upload Items”, set Frame Time to 500000, and click “Start Listening”. If all is well, SinkHost should now start running.
- Note that SinkHost will only start uploading data for a node once it collected a number of samples.

**MyriaNed Installation**
- Nodes marked yellow are to be used as static nodes, pink nodes as mobile nodes.
- All static nodes periodically measure temperature and ambient light.
- They only start participating in the localization algorithm once they have been given a location. To do this, use the netbook: in the bottom of the window, in the Command field, fill in the node id of the static node (this is the number found on the node, but subtract 2000!), fill in “location” for function, and fill in an x, y and z value for specifications. Note that x and y must be between 0 and 255 and that z must be 0. For example: 567 location 0 10 0. Click Give Command to send the command. When the node has received the command, it will briefly switch on its orange led, so make sure you watch for it. To check if it worked, put a mobile node close to the static node, and check in SinkHost if it reports the location you just assigned to the static node. Static nodes will remember their location even if you switch them off.

**MyriaNed at runtime**
- The localization algorithm is quite battery-intensive, and so nodes may drain their batteries. If a node stops blinking its green led, it is either switched off or the battery is dead. Replace the batteries by sticking a pen under the battery and wedging it out. Be sure to use 1.2A, 3.6V, 1/2AA, Lithium Thionyl Chloride batteries, and do NOT attempt to recharge them! (available at www.farnell.com, around 2-3 euro a piece at over 50 pieces, delivered next day).
- The SinkHost program on the netbook may turn unresponsive and stop uploading data. Check regularly whether the data displayed is still recent. If not, switch to the terminal from which you started SinkHost (it will display “Valid message received at * * * * * * times many times). Press ctrl+c to kill the process, then start it again. It should have remembered the correct settings and should start again straight away. However, check the terminal for reports of either “error unauthorized” or “logged in as * * * *”. In the first case, Stop Listening, fill in the password again, and Start Listening. In the second case, all is well.
F. Application of ABG for building modelling

Bond Graph user modelling

Where the user is the subject to focus on in the building environment it is needed to model our building performances with a supportive tool for the inclusion of occupants in the control of the performance of building and HVAC installations [Zeiler et al., 2012]. Where previous models did not succeed to describe the user position in buildings, the recent development regarding bond graph technique can serve as a possibility to both the necessary quantitative and qualitative analysis of the interaction between human, building and building services installations. Tsai and Gero developed Archi Bond Graph (ABG) which provide the ability to not only include HVAC installations, but also the building and the people [Tsai and Gero, 2010]. An example plan drawing and ABG graphical representation are shown in Figure 0-4, showing how a floor plans can be described by ABG.

![Figure 0-4 The space-people system (a) plan drawing and (b) ABG graphical representation [Tsai and Gero, 2010]](image)

Building occupant movement

A closer look is made to the distribution of the positions in time and look if it is possible to describe the user movement in detail by the application of ABG.

Therefore data of one building user is taken during one day. During this day the user most commonly worked in a cell office. The position of this user during the day is shown in Figure 0-5, where the user was not present between 11.33 hr. and 13.49 hr.

![Figure 0-5 Timeline with the position of the building user indicated for a reference day](image)

The used floor plan and spatial description using ABG is shown in Figure 0-6.
Figure 0-6 Part of the building model used for modeling, with the coffee machine, lounge, printer and toilet as special spots included in the model (left) and the spatial system as ABG graphical representation (right).

First the movements of the occupant are drawn in the floor map to have a graphical representation of the movement. What is visible in Figure 0-7 is that 13 of the 20 movements the user stays less than 10 minutes at his position. In these figures the lines of one person moving one day inside the building already gives a disorganized view. The used data is shown in more detail in appendix.

Figure 0-7 Movement of the occupant over the floor in the morning (left) and in the afternoon (right) with the time the occupant is at a certain position given by a dot.

In Table 0-2 the applied data is shown for one person during one day. In the table the time that the occupant enters a certain location is shown, followed by the time the person stayed on this location. The path corresponds with the different access points and locations as described in §4.3.
Table 0-2 Filtered data from one building user during one day, describing its movements and positions

<table>
<thead>
<tr>
<th>Time</th>
<th>Location</th>
<th>Path</th>
<th>Time</th>
<th>Location</th>
<th>Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:32:15</td>
<td>Coffee C1</td>
<td>CR1</td>
<td>11:01:28</td>
<td>16:30:18</td>
<td>Gone</td>
</tr>
<tr>
<td>8:33:45</td>
<td>Lounge C2</td>
<td>CR2, CR4, C5, C6, CR6</td>
<td>11:02:01</td>
<td>Coffee C1</td>
<td>CR6</td>
</tr>
<tr>
<td>8:35:05</td>
<td>Cell office C6</td>
<td>CR6</td>
<td>11:03:45</td>
<td>16:30:18</td>
<td>Gone</td>
</tr>
<tr>
<td>8:42:46</td>
<td>Printer C5</td>
<td>CR6</td>
<td>11:04:21</td>
<td>16:30:18</td>
<td>Gone</td>
</tr>
<tr>
<td>8:43:32</td>
<td>Cell office C6</td>
<td>CR6, C8, C9, C10, C11</td>
<td>11:05:07</td>
<td>16:30:18</td>
<td>Gone</td>
</tr>
<tr>
<td>9:20:15</td>
<td>Toilet C3</td>
<td>CR3, C4, C5, C6, C7, C8</td>
<td>11:06:32</td>
<td>16:30:18</td>
<td>Gone</td>
</tr>
<tr>
<td>9:25:09</td>
<td>Cell office C6</td>
<td>CR6, C8, C9, C10, C11</td>
<td>11:07:07</td>
<td>16:30:18</td>
<td>Gone</td>
</tr>
<tr>
<td>10:42:01</td>
<td>Open office C8</td>
<td>CR8, C9, C10, C11, C12</td>
<td>11:08:32</td>
<td>16:30:18</td>
<td>Gone</td>
</tr>
<tr>
<td>10:44:20</td>
<td>Cell office C6</td>
<td>CR6, C8, C9, C10, C11</td>
<td>11:09:07</td>
<td>16:30:18</td>
<td>Gone</td>
</tr>
<tr>
<td>11:00:02</td>
<td>Coffee C1</td>
<td>CR2, C4, C5, C6, C7, C8</td>
<td>11:10:32</td>
<td>16:30:18</td>
<td>Gone</td>
</tr>
<tr>
<td>11:12:00</td>
<td>Print C5</td>
<td>CR6</td>
<td>11:13:15</td>
<td>16:30:18</td>
<td>Gone</td>
</tr>
</tbody>
</table>

ABG as user modelling approach

In this research a new modelling approach is looked into, where this ABG approach is capable of coupling the user and its actions to the building energy demand.

- Where ABG describe the human movement in detail and very time depending this is not needed, where (i) building users move through the building they mostly of the time do not stay for more than 10 minutes period on another spot then their workplace as indicated by the probability distribution in §2.3 [Wang et al., 2005] and shown in Figure 0-7 in §4.3. (ii) In slightly cool and warm environments it takes more than 10 minutes before the perceives this change in temperature [Wang et al., 2007] (iii) building service systems need time for conditioning what by the building inertia takes up to 15 minutes

- Contrary to the idea found in literature [Tsai and Gero, 2010] this approach does not give a clear representation of the movement and positions of the building user, since the amount of data connections cannot simply be interpreted by the human
### G. HAMBase building properties

The values in Table 0-3 are applied in the building simulation model to determine the energy saving potential. The values are the input of the HAMBase building model.

<table>
<thead>
<tr>
<th>Building Properties</th>
<th>d [m]</th>
<th>λ [W/mK]</th>
<th>R [m²K/W]</th>
<th>p [kg/m³]</th>
<th>Cp [J/kgK]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External wall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brick</td>
<td>0.1</td>
<td>0.6</td>
<td>0.17</td>
<td>1500</td>
<td>840</td>
</tr>
<tr>
<td>Cavity</td>
<td>0.05</td>
<td></td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.15</td>
<td>0.039</td>
<td>3.85</td>
<td>30</td>
<td>840</td>
</tr>
<tr>
<td>Limestone</td>
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<td>1.2</td>
<td>0.18</td>
<td>2000</td>
<td>840</td>
</tr>
<tr>
<td><strong>Internal wall</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plaster</td>
<td>0.013</td>
<td>0.6</td>
<td>0.02</td>
<td>1300</td>
<td>840</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.15</td>
<td>0.039</td>
<td>3.85</td>
<td>30</td>
<td>840</td>
</tr>
<tr>
<td>Plaster</td>
<td>0.013</td>
<td>0.6</td>
<td>0.02</td>
<td>1300</td>
<td>840</td>
</tr>
<tr>
<td><strong>Floors</strong></td>
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<td></td>
</tr>
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<td>Concrete</td>
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<td>1.7</td>
<td>0.12</td>
<td>2400</td>
<td>840</td>
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<tr>
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<td>0.036</td>
<td>2.22</td>
<td>35</td>
<td>1470</td>
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<tr>
<td>Concrete</td>
<td>0.05</td>
<td>1.7</td>
<td>0.03</td>
<td>2400</td>
<td>840</td>
</tr>
<tr>
<td><strong>Glazing</strong></td>
<td>U [W/m²K]</td>
<td>g-value [W/mK]</td>
<td>Cfr. [-]</td>
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<tr>
<td>HR++</td>
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<td>0.3</td>
<td>0.03</td>
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</tbody>
</table>

Re: 0.04 [m³kW]; Ri: 0.13 [m³kW]
H. Privacy statement

1. Project informatie
   Project verantwoordelijke: Rik Maaijen (h.n.maaijen@student.tue.nl)
   Meetperiode: december 2011 – februari 2012
   Betrokken partijen: Royal Haskoning
                       Technische Universiteit Eindhoven

   Binnen de gebouwde omgeving is vraag naar gebouwen met hoge prestaties, zoals een laag energiegebruik en een hoog comfort niveau. Uit diverse onderzoeken is gebleken dat de invloed van de gebruiker toeneemt bij toenemende prestaties van het gebouw.

   Energie dient gestuurd te worden naar plekken waar nodig met als doel een optimaal comfort waarbij er geanticipeerd wordt op het menselijke gedrag. Dit onderzoek is erop gericht om door middel van een analyse en metingen vast te stellen:

   • Welke relevante afwijkingen in patronen van gebruikersgedrag voorkomen;
   • Hoe in het ontwerp beter rekening gehouden kan worden met het gebruikersgedrag (in de praktijk) zodat de energieprestatie van het kantoor verbeterd wordt;
   • Wat is het besparingspotentieel indien energie gericht gestuurd wordt.

   Hiertoe wordt in dit voorbeeldproject met draadloze sensoren de bezetting per zone bepaald. Voor u als gebouwgebruiker betekent dit dat bij aanwezigheid in het kantoor de mobiele node gedragen dient te worden, zodat de bezettingsintensiteit van zones bepaald kan worden.

2. Gegevens drager sensor (nader te noemen: gebouwgebruiker)
   Naam: .................................................  Geslacht: M / V
   Functie: .................................................  Werkuren p. week ........... uur
   Sensor nr. ..................................................

3. Privacy verklaring
   In dit onderzoek zal zorgvuldig worden omgegaan met uw gegevens. De data wordt anoniem behandeld en aan geen ander verstrekt. Hierbij wordt gehouden aan de eisen die de Wet Bescherming Persoonsgegevens stelt.

   Uw gegevens worden niet voor andere doeleinden gebruikt dan vermeld bij 1. Project informatie. De anonimiteit van de deelnemers in de onderzoeksresultaten is te allen tijde gegarandeerd. Mochten de gegevens voor andere doeleinden toegepast worden, wordt dit niet gedaan zonder uw uitdrukkelijke toestemming.

4. Ondertekening
   Hierbij verklaar ik, Rik Maaijen, zorg te dragen voor het hetgeen in punt 3 genoemd.

   Datum .........................  Plaats  .........................
   .........................................................
   .........................................................
   Rik Maaijen  Gebouwgebruiker
I. Posters for informing employees Royal Haskoning (A3 format)

Onderzoek naar de invloed van gebruikersgedrag
op het energiegebruik van kantoorgebouwen
De mens centraal in de aanschuing van klimaatsystemen

Binnen de gebouwde omgeving is vraag naar gebouwen met hoge prestaties, zoals een laag energiegebruik en een hoog comfort niveau. Uit diverse onderzoeken is gebleken dat de invloed van de gebruiker toeneemt bij toenemende prestaties van het gebouw. Er is echter nog maar weinig informatie beschikbaar over het werkelijke gebruikersgedrag. Het feit dat het gebruikersgedrag niet goed bekend is, wordt in deze onderzoeken ook genoemd als een reden voor de ondermaatre prestaties van de gebouweninstallaties. Meer inzicht in het werkelijke gebruikersgedrag en de invloed hiervan op het energiegebruik zal zaken bieden om de gebouwprestaties verder te optimaliseren.

Gebruikersgedrag in de gebouwde omgeving...

Gebruikersgedrag vertonen gebouwen dat hun omgeving te beïnvloeden voor meer comfort. De onderzoekers wenden aan gedrag die de gebouwprestaties beïnvloeden: de aanwezigheid van de gebruiker en de interacties van de gebruiker met zonwering, ramen, verwarming en ventilatie, gebruik elektrische apparatuur en bediening van de thermostaat. De onderzoeksgebieden en de beïnvloedende factoren zijn schematisch weergegeven in de volgende figuur.

Waarop diest gefocust te worden...

Zonder aanwezigheid van de gebruiker hoeven er minimale eisen gesteld te worden aan het binnenklimaat. Daarmee is logischens het aanwezigheid van invloed uiteindelijk te verifiëren op het gebouw. Echter onderzoek in een engineering center leverden zogenaamde bezettingspatronen op, weergegeven in figuur 2.

Voor de 3° verdieping van dit kantoor is via een analyse met VAV2 Elements bepaald wel de invloeden van de gebruiker zijn op de energieprestaties. De gegevens voor vrijgegeven in de input in de gevalen kantoortuin van deze verdieping staan in figuur 3.

Dat tezamen is dat de onderzoeksrelevante gerelateerd aan gebruikersgedrag een veel sterkere invloed hebben om het energiegebruik dan de overige parameters. Vooral de invloed van elektrische apparatuur op de energieprestaties is groot.

Wat hiermee te bereiken...

Energieuik geïntegreerd te worden in praktijken waar mogelijk met als doel een optimal comfort en er diend gecontroleerd te worden bij het menselijke gedrag. Dit onderzoek is erop gericht om door middel van een analyse en metingen vast te stellen:

Welke relevante invloeden in patronen van gebruikersgedrag voorkomen,

Hoe de ontwerp beter in overeenstemming gebracht kan worden met het gebruiksgedrag (en de praktijk) zodat de energieprestaties van het kantoortuin verbeeld wordt.

Metingen op kantoorverdieping

Voor het bepalen van het energie besparingspotentieel en verbeter mogelijkheden in het etalage, wordt er in dit voorbeeldproject met draaikusaarnomen worden de bezettings per zone, het energiegebruik van verschillende apparaten, de temperatuur per zone en de CO2 concentratie gemeten. Dit bekeken het volgende:

Sensitieve (geïntegreerd aan wanden en plafonds) en mobiliteit nodes (geïntegreerd door de geïntegreerd) registreerden de locatie van de gebouwgebruikers (figuur 4),

Deze zette statische nodes bepalen het CO2 gehalte en temperatuur per de diverse zones,

Energiegebruik van elektrische apparatuur wordt bepaald in figuur 4.
Laatste periode metingen kantoor Haskoning!

Sommige van jullie hebben een prachtig kastje bij zich voor lokalisering. De metingen zijn nog in volle gang en zullen lopen tot:

**dinsdag, 20 februari**

Nogmaals bedankt voor de medewerking!

Mochten er vragen en/of opmerkingen zijn betreffende dit onderzoek dan hoor ik dit graag via een e-mail naar h.n.maaijen@student.tue.nl of tel. 06 1496 8281.