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Smart grid building energy management

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Smart Grid Building energy management

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Smart Grid Building energy management

Master Thesis Building Services

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Tom Thomassen

Abstract

Buildings take a fair share of the available power, whereas in the future is expected that a greater share will be generated by more distributed renewable source. This will lead to fluctuation in the availability of power. The Smart Grid intends to match these fluctuations between sources and users. Buildings can play a role in the operation of the Smart Grid to adapt their power consumption pattern in order to optimize the performance of the grid.

The goal of this study is to identify the possibilities for adapting the consumption patterns of Dutch office building to participate in the Smart Grid, with respect for thermal comfort and Indoor Air Quality related to the productivity of occupants in these buildings.

The focus in this study will be on the expect main consumers of power of a contemporary office building. These are the HVAC system, with especially the use of the chiller, and power needed for lighting the building.

Case study 1 Case Study Building

This study is aiming on current office building which have high potential for improvements with new BEMS, for the experiments a typical office building is selected. Before starting the experiments, the building is analysed and prepared for the experiments. Measurements of reference operation is used to identify aberrations in the building operation, the results of the test serve as reference for the experiments.

Already adopted energy management scenarios like night ventilation can be clearly seen in the energy use profiles. The running scenarios determine which energy management adaptions have significant potential.

Case study 2 Energy management scenarios

Energy management scenarios reducing building systems energy as service to the Smart Grid are experimented by measurements and simulations.

Shifting the operation of the chiller is one of these energy management scenarios. The comfort temperature in the rooms and system temperatures have been measured. The initial and shifted operation have been simulated together with the corresponding comfort temperatures and energy use.

Adapting the chiller operation as a service to the grid, by shifting the time of active operation with a power of 14 kW, is feasible in 64% of the total operation time while maintaining a somewhat acceptable indoor climate of class C. After the shifting event increased active chiller operation will be needed to regain the comfort class B and has to be taken into account for Demand Response.

For energy management of chiller operation the outside temperature has a dominant role and is a good indicator for the prediction of chiller behaviour. Outside temperatures above 28 degrees Celsius will cause the chiller to run continuous on full capacity and shifting operation in this case will cause an unacceptable indoor comfort.

Reducing the airflow of the constant volume air handling unit system is the second energy management scenario. The initial and reduced airflow is measured together with the corresponding CO_2 concentrations and energy use.

Air-flow reduction can be used as a service to the grid or energy efficiency measure, with a power of 2 kW. Beside the direct energy use reduction of the air handling unit fans the cooling demand reduces with 22%. Reduction of the airflow can be used almost during the entire year maintaining acceptable CO_2 concentrations and thermal comfort class B. Except for the days full cooling capacity is needed the comfort decreases to class C. The behaviour of airflow reduction in the winter period however has to be investigated in future research.

In case of full cooling need the airflow reduction is only acceptable when the thermal comfort may decrease to comfort class C.

Artificial lighting reduction is an experiment to identify the possibility of reduction of artificial lighting based on the illumination of natural light. Light intensity entering the window and on the workers desk is measured for a south and north orientated room.

Artificial lighting use reduction shows potential for energy efficiency measure with a power of 2 to 4 kW for 36% of the office hours a year, however further research is needed. Based on the natural lighting entering the room maintaining a 500 Lux or higher on the desk.

With the reduction of artificial lighting use the simulation show the indoor thermal climate improves.

Index

Acronyms and definitions

AHU	Air Handling Unit
ATL	Adaptive Temperature Limits
BAS	Building Automation Systems
BEMS	Building Energy Management System
BMS	Building Management System
DSM	Demand Side Management
DSO	Distributed System Operators
DR	Demand Response
EC	Energy Conservation
EE	Energy Efficiency
EU	The European Union
GEMS	Grid Energy Management System
HVAC	Heating Ventilation Air Conditioning
IAQ	Indoor Air Quality
ICT	Information and Communications Technology
LC	Load Control
LS	Load Shifting
MG	Micro Grids
NG	Nano Grid
PI	Performance Indicators
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
SG	Smart Grid
SR	Spinning Reserve
TC	Thermal Comfort
TSO	Transmission System Operators
VC	Visual Comfort
µCHP	micro Combined Heat and Power plant

1 Introduction

1.1 Background

Energy use and CO_2 production increased over the last centuries [Energie-Nederland and Netbeheer_Nederland, 2011; EIA, 2012] and seems to accelerate during the last decades [MacKay, 2009].

The upward trend in energy demand will continue in the future as a result of; growth in population, electrification of almost everything, increased demand for building services and comfort levels, together with the rise in time spent inside buildings. [Dril and Elzenga, 2005; Pérez-Lombard et al., 2008; MacKay, 2009]

Electricity is seen as one of the most efficient transportable and convertible energy carriers and production of electrical energy counts for 40% of worlds primary energy use. For the production of the world's electrical energy 80% of the used resources are non-renewables (gas, coal, liquid, and nuclear) [EIA, 2012]. The same study indicates for the Netherlands, alike most of Europe, the built environment accounts for nearly 40% of the total primary energy use.

Awareness throughout the entire world started major changes in vision, ambition, goals, and targets.

The European Union (EU) wants to realise a carbon emission reduction of 80-95% by 2050. For the short term (2020) agreements, the Netherlands has stated that the requirements of 20% less CO_2-production, 14% renewable energy, utilization of the potential for energy savings should be obtained [Boersma et al., 2012]. Direct effects are the increase of sustainable generated electricity, increase in use of renewable energy sources, and the increase of sustainability in the built environment. All these changes influence the way we manage and operate our energy systems.

The electrical power grid of today has some challenges which have to be dealt with in the near future in order to facilitate it is services in future grid operation.

Challenges in the near future are:

1. Changes in central generation capacity, such as the shutdown of nuclear plans and increase of large scale offshore wind parks, require an increase of transport capacity over long distances. [Netbeheer_Nederland, 2011]
2. Increasing power transport (export and import) between European countries request interconnectivity capacity. Large generation and demand mismatch, price per power difference, are reasons import and export increases. [Netbeheer_Nederland, 2011; Netbeheer_Nederland, 2013]
3. Increasing distributed renewable power generation capacity request local interconnectivity capacity. [Netbeheer_Nederland, 2011; Netbeheer_Nederland, 2013]
4. The existing distribution grid largely has been built in the 60's 70's and 80's, the relatively old components are in dire need for replacement and many may not be operational at desired capacity. [Hoevenagel and Korpel, 2008]

Choices made now have also to deal with the expected changes and challenges in the future to ensure or even improve the reliability and availability of the power grid.

Changes in the built environment are the developments towards less energy consuming buildings and equipment. Together with this the increase of renewable generated energy in forms of heat and electricity.

The local generated energy can be in mismatch between demand and supply resulting in the desired increase of buffer capacity [Saputro et al., 2012]. Mostly in the situation of heat, storage is less of a problem compared to electrical energy. In most cases, the surplus in electrical generated energy is fed back to the grid which the building is connected to.

This development introduces a new challenge for the grid, namely, possible changing energy flow direction at lower grid levels due to the feed in of renewable generated electrical energy [Slootweg et al., 2011].

Current grid management maintains balance by increasing or decreasing centralised power generation based on demand side behaviour or requirements. With the expected increase of renewable generated energy in the total generated energy mix, which has stochastic behaviour, the management of the grid has to change in the future.

Slootweg [Slootweg et al., 2011] states the increase of decentralised active loads, compared to the passive loads connected to the grid can be a solution for futures grid management. Active loads are loads which can participate in the energy management and possible react on grid requests or economic stimulations. Examples of active loads are; micro Combined Heat and Power (µCHP), Electrical-vehicles, heat pumps, and others. Active loads can request or in some cases even deliver energy to the grid and schedule their demand or even change their characteristics online.

In order to compensate an active load there has to be an economic compensation. A classic example of economic stimulation is the double tariff structure, evoking households to shift their energy use to economic stimulated period which is the most convenient period for the grid. For now the more flexible tariff structures are still in experimental phase.

The mix of connected active and passive loads will keep changing in future even as the mix of electricity generators.

The Smart Grid (SG) is required to be the solution to all mentioned possible challenges managing electrical energy production, distribution, buffering, and consumption matching supply and demand making use of the available system flexibilities [Slootweg et al., 2011].

Grids management, control, voltage management, power quality, and the need to modify the system security will change due to all mentioned developments. New policies and contracting with flexible tariff structures are possibilities which are being investigated. [Taskforce Intelligente Netten, 2011; Innovatietafel Smart Grids, 2012].

The SG incorporates current physical electrical grid infrastructure integrated with Information and Communications Technology (ICT) in grid components, and a communication network to enable energy management. [Wang et al., 2011] The real ‘Smartness’ of the SG is integration of multiple functionalities to guarantee properties including; reliability, availability, stability, controllability, and security, and at the same time realise overall system optimisation. Functionalities boil down to energy management making use of the flexibilities of all grid connected. The purpose of the energy management measures should be to compensate surpluses and deficits in the network. Flexibility is the degree to which the pattern of consumption and generation can be influenced. In a system of

systems view this will lead to a better balanced and controlled network at all levels [Dave et al., 2011; Lo and Ansari, 2011; Lopes et al., 2011; Acevedo and Molinas, 2012].
The biggest change as a result of transformation to SG will be the requirement of active participation of end users in grid management [Hommelberg et al., 2010; Slootweg et al., 2011].

Nowadays the common end-users of the distribution network are barely integrated into the distribution networks management, whilst larger end-users (the industry) already participate in the management of transport or distribution network [Hommelberg et al., 2010].

The distribution grid in the future can be seen as multiple Micro Grids (MG) connected to each other and connected to the transmission grid by turning the distribution grid from a passive system into a more active system. In order to cope with future developments active management of the distribution grids is necessary as a way to continued reliable delivery of electricity and facilitation of the integration of distributed generation. This is the driver for development towards Smart Grids. Figure 1 shows the traditional grid and future grid presented by Slootweg et al. [Slootweg et al., 2011].

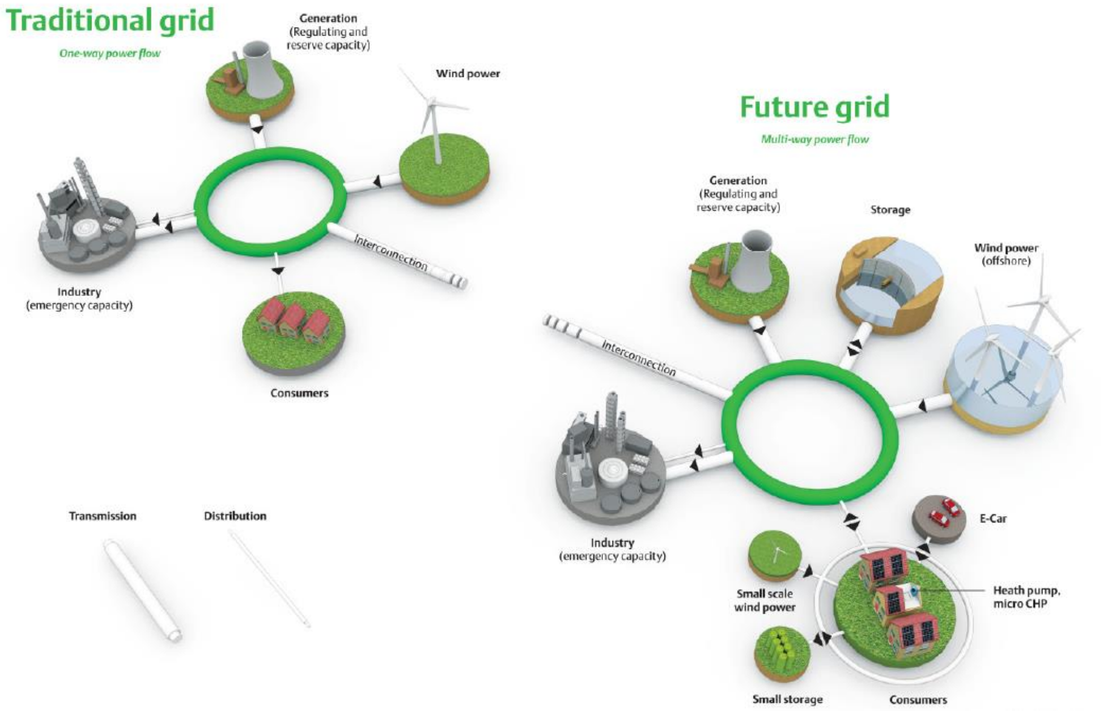


Figure 1: Traditional and future grid [Slootweg et al., 2011].

In offices Building Management Systems (BMS), also known as Building Automation Systems (BAS), control the HVAC systems to facilitate building operation. These BMS evolved over time with the addition of more and more systems, functionalities, and requirements. BMS with energy use reduction during life time as an extra goal, turned into Building Energy Management Systems (BEMS) [Choi et al., 2011] and [Han et al., 2011]. The main goal of the BEMS is to fulfil the occupant comfort requirements while reducing energy consumption during building operations [Yang and Wang, 2011]. The BEMS uses peak shaving and load shifting based on planning to reduce the energy consumption together with energy efficiency improvements of systems equipment and energy management strategies.

The shift towards smart electrical grid cannot ignore connected buildings. This implies active participation of buildings in the grid. Energy management in the Micro Grid depends highly on the energy management inside the buildings, called Nano Grid (NG), belonging to the MG. In this study, with respect to the MG within the SG, the network and electrical energy consuming systems in the building managed by the BEMS are called Nano Grid.

For an optimal SG from a system of systems point of view, the BEMS has to be coupled with the management platform of the grid [Dave et al., 2011]. The control of loads in the building, may also be a resource to the grid using the flexibilities in service of the grid in Demand Side Management (DSM) scenarios as so called Demand Response (DR) or Load Control (LC). [Callaway and Hiskens, 2011] However, these flexibilities remain largely undefined with respect to interactions with the power grid. Also, the development of the SG is still at an early stage and some parameters are yet to be fully defined with respect to interactions with NG.

With the development of a communication platform between the BEMS and Grid Energy Management System (GEMS) both systems get more interconnected and thus more dependant from each other. The present choices made in energy management have the capacity to, affect future choices. [Callaway and Hiskens, 2011]This means goals and functionalities of both coupled energy management systems have the potential to effect each other.

For the built environment nowadays the chance is to prepare for the coming SG. New strategies of energy management, building management, and comfort management have to be developed to anticipate on the coming possible changes on DSM by DR and LC.

This study evaluates the possibilities for adapting the consumption patterns of an office building and the impact of energy management with grid interaction.

1.2 Research objective

Buildings take a fair share of the available power, whereas in the future is expected that a greater share will be generated by more distributed renewable source. This will lead to fluctuation in the availability of power. The Smart Grid intends to match these fluctuations between sources and users. Buildings can play a role in the operation of the Smart Grid to adapt their power consumption pattern in order to optimize the performance of the grid.

The goal of this study is to identify the possibilities for adapting the consumption patterns of Dutch office building to participate in the Smart Grid, with respect for thermal comfort and Indoor Air Quality related to the productivity of occupants in these buildings.

1.3 Research question

The background description and research objective form the central research question which is as follows:

- To which extent can the consumption patterns of current office buildings be adapted with smart energy management to support the Smart Grid, and what are the consequences for the operation of the building regarding thermal comfort, Indoor Air Quality?

The focus in this study will be on the expected main consumers of power of a contemporary office building. These are the HVAC system, with especially the use of the chiller, and power needed for lighting the building.

a) The airflow in a building has to be sufficient for air refreshment and is designed for transportation of full cooling capacity of an office, while in practice full capacity is seldom needed. How can the airflow be adapted to required refreshment based on the actual occupancy?
b) Currently the artificial lighting is a constant consumer of power, the full capacity is used almost the whole year. Is it possible to reduce artificial lighting based on the use of available natural light, and what will be the effects on illuminance and luminous intensity in the office?
c) The chiller is a large consumer, in high summer the full capacity will be needed, for periods were not the full capacity is required, is it possible to shift the operation of the chiller, and what are then the effects on thermal comfort in the building?

With the results of the experiments the questions regarding the flexibility in power consumption can be answered for the main part.

1.4 Research method

The methodology applied during this graduation project is schematically shown in Figure 2. The position of the research questions are also indicated. Below, the different phases are shortly explained.

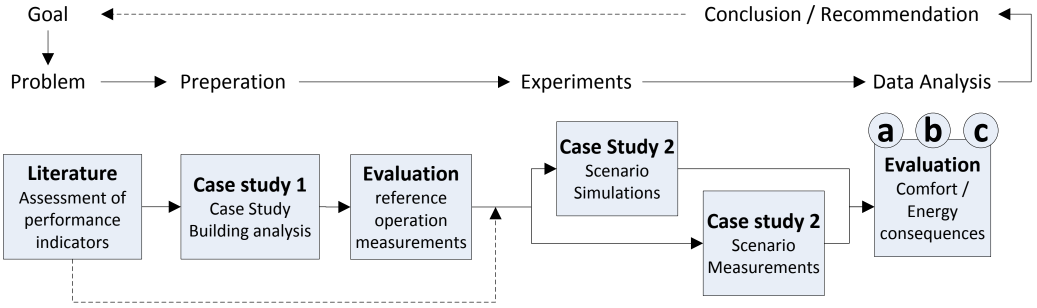


Figure 2: Research methodology.

Performance Indicators
For evaluating the effects of power management on thermal comfort and Indoor Air Quality related to the productivity of occupants, suitable performance indicators have to be selected. With a literature survey indicators are selected (1) on the energy management on the lowest grid level and building, called demand side management, and (2) for thermal comfort, Indoor Air Quality, and productivity of occupants.

Case study 1 Case Study Building
This study is aiming on current office building which have high potential for improvements with new BEMS, for the experiments a typical office building is selected.

Reference operation measurement
Before starting the experiments, the building is analysed and prepared for the experiments. Measurements of reference operation is used to identify aberrations in the building operation, the results of the test will serve also as reference for the experiments.

Case study 2 Energy management scenarios
Energy management scenarios reducing building systems energy as service to the Smart Grid will be experimented by measurements and simulations.

Air-flow reduction: An experiment reducing the airflow of the constant volume air handling unit system has been done. The initial and reduced airflow is measured together with the corresponding CO_2 concentrations and energy use. The goal is to identify when and to what extend it is acceptable to reduce the airflow.

Use of natural light: An experiment to identify the possibility of reduction of artificial lighting is based on the illumination of natural light has been done. Light intensity entering the window and on the workers desk is measured for a south and north orientated room. The goal is to identify whether it is acceptable to reduce artificial lighting use based on workplace light intensity.

Shift chiller operation: An experiment shifting the operation of the chiller has been performed. The comfort temperature in the rooms and system temperatures have been measured. The initial and shifted operation have been simulated together with the corresponding comfort temperatures and energy use. The goal is to identify when and to what extend it is acceptable to shift the chiller operation.

1.5 Report outline

The outline of the report is as follows: Chapter 2 Theoretical framework provides the theory of energy management in Micro Grid and Nano Grid called Demand Side management (DSM). First it is clarified what energy management categories belong to DSM, and their dependency on the time and timing, before looking into the most important categories for building energy management in Smart Grid operation. The most important DSM categories are discussed for the experiments.

The relation between productivity of the office worker and the indoor comfort is investigated to provide the range of acceptable indoor climate variations. For the intended experiments with the HVAC system performance indicators are chosen to identify the possible effect on the productivity in buildings.

In Chapter 3 Case Study Building, a description of the case study office building is given, the on-site measurements of performance indicators are explained, and the results of the reference operation measurements are presented. The model setup for simulations of experiments is presented. This chapter ends confirming the HVAC fans, chiller, and lighting as the main power consumers of an office building in the discussion and conclusions section.

The experiments, of energy management scenarios reducing building systems energy as service to the Smart Grid are first described in chapter 4. Before they are evaluated by the measured and simulated performance indicators. Finishing with a comparison of the reference operation results and results of the experiments. Evaluating the influence of experimented energy management scenarios on the indoor environment answering the sub-questions.

Chapter 5 Conclusion, provides the conclusions where the central research question is answered and where discussion points are described together with recommendations for future work.

2 Chapter 2 Theoretical framework

2.1 •Demand Side management
2.2 •Productivity of office workers
2.3 •Conclusions

This chapter contains the theory of energy management in Micro Grid (MG) and Nano Grid (NG)named: Demand Side management (DSM). The different categories and their dependency on the time and timing of DSM are clarified. The most important DSM categories are discussed for the experiments of this study.

The relation between productivity of the office worker and the indoor comfort is investigated to provide the range of acceptable indoor climate. For the intended experiments with the HVAC system performance indicators are chosen to identify the possible effect on the productivity in buildings.

2.1 Demand Side Management

With respect to the Smart Grid (SG) the hypothesis is that the so called Demand Side Management should provide better integration of the demand side.

DSM is defined by [Palensky and Dietrich, 2011] as a portfolio of measures to improve the energy system at the demand side.

[Bruggen, 2012] states demand side management for buildings is as follows:

'All actions 'behind the meter' that relate to changing or modifying energy use including changes to the consumption pattern are called demand side management.'

DSM actually is a term capturing all the energy management possibilities and energy efficiency improvements at the lowest levels of the power grid. In perspective of the SG it is the energy management of the MG and all connected. For the NG this is the energy management of the Building Energy Management System (BEMS) .

[Palensky and Dietrich, 2011]divided the DSM in 5 main categories based on timing as illustrated in Figure 3. The categories are Energy Efficiency (EE) improvements, Load Shifting (LS), Market driven Demand Response (Market DR), Physical Demand Response (Physical DR), and Spinning Reserve (SR).

With respect to this work the categories Market DR and Physical DR are combined under Demand Response (DR).

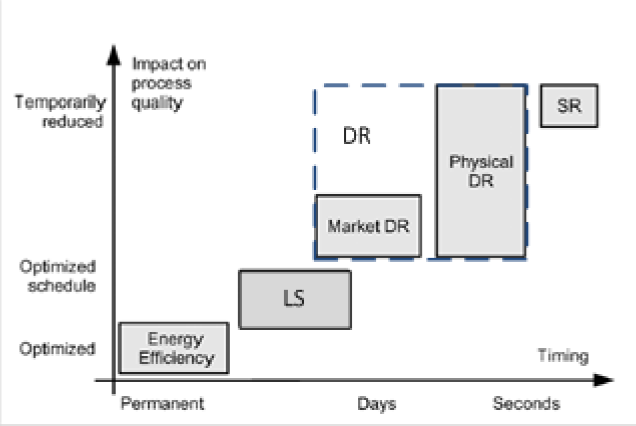


Figure 3: Categories of Demand Side Management, modified from [Palensky and Dietrich, 2011]

Comparing the four categories Energy Efficiency, Load Shifting, Demand Response, and Spinning Reserve, they can be divided in two groups with respect to their behaviour in time. A static group containing; EE, and LS, and a dynamic group containing; DR, and SR.

The later of the groups does not necessary save or reduce energy by influencing the consumption patterns. This can be due to a process needs to 'catch up' after interruption and can cause a 'rebound effect'.

Key driver for DSM is improvement of secure energy delivery with increasing energy efficiency and lowering the carbon footprint of the total energy system.

2.1.1 Energy Efficiency

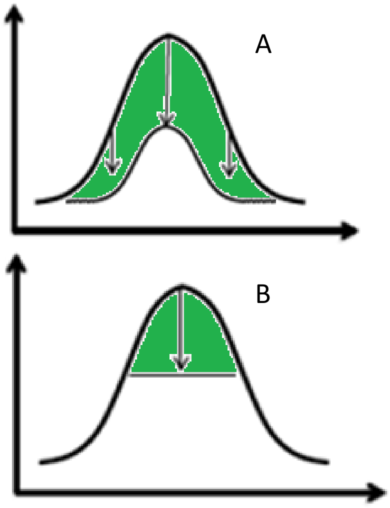


Figure 4: Energy Efficiency as overall improvements (a) or peak shaving (b).

Energy reduction measures at first belong to the optimisation of Energy Efficiency (EE). This can be by installing more energy efficient equipment from NG up to MG. In the NG this can also be building physics related improvements, reducing the heat losses and heat gains for example.

With best energy efficient equipment and an optimal functioning energy management, the energy uses of a building should be the lowest possible while maintaining the desired indoor conditions.

EE of the building and systems can also be improved by Energy Conservation (EC). EC in this case is changing the users behaviour by creating awareness and education, to achieve more efficient energy usage or less unnecessary energy use by user appliances. [Yeh et al., 2009] propose an automated system to reduce unnecessary energy use.

Peak shaving results in lower capacity energy consumption, a lower convenience level is acceptable in this case or the peak in energy consumption was already unnecessary.

With respect to time, EE scenarios are always intended for a long, if not eternal, period of time.

EE scenarios in the building are always providing a 'win-win' situation for the grid and building. EE scenarios reduce the energy needed for building operation and thus less energy has to be transported through the grid the building is connected to.

Ideally seen EE scenarios always improve the total energy system. Weather they are applied in NG (building) or MG (distribution grid).

In this study EE improvements, regarding the split unit set-point and case study building heat gains in stair case, have been identified with the 'zero-measurement' presented in section 3.3.

2.1.2 Load Shifting

Energy management by planning scenarios in advance are called Load Shifting (LS). These scenarios can be called peak shifting, or shifting energy use, and lead to a reduction of the maximum capacity of the original expected energy profile.

For some energy processes the time that the power supply is switched on is not so important. The time can be chosen to be favourable for the overall consumption pattern. It is possible that switching off power supply to a process within an acceptable bandwidth will be at the cost of convenience which is this case is unacceptable.

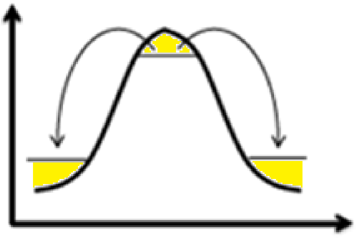


Figure 5: Load Shifting

Peak shifting refers to the flattening-off of peak consumption. Usually this does not result in lower total energy consumption, since a lower convenience level is unacceptable and the energy has to be used before and / or after the original peak. Switching on is either brought forward or delayed to avoid peak situations.

Some LS scenarios can be combined with increasing EE. In this case a less energy consuming system can take over a load, or work towards a better starting condition, of the original intended system. An example regularly used in office buildings is night ventilation. In this scenario the ventilation system intends to pre-cool the building before the operation of installed chillers.

With respect to time, LS scenarios are designed and implemented with corresponding parameter measurements and set-points, long before building operation calls on them.LS scenarios are nowadays common in building operation and optimisation.

2.1.3 Demand Response

Demand response (DR) is lowering or cutting power for a certain amount of time as service for the grid the building is connected to. Usually this does not result in lower total energy consumption, in case a lower convenience level is unacceptable and the energy has to be used before and / or after the DR event. Still it might be possible the convenience level cannot be recovered or it is acceptable to briefly lower the convenience level. [Palensky et al., 2011]

DR shows many similarities in behaviour compared to LS whilst the difference lies in the occurrence and duration. LS is planned longer in advance compared to DR and can have a longer period of time it can be deployed. DR has respective quick response, day to minutes ahead, compared to LS scenarios.

DR reacts on a signal broadcasted by Distributed System Operator (DSO) (for stabilisation of balance in MG) or even Transmission System Operator (TSO) (for stabilisation of balance in a wider grid perspective) whilst LS and improving EE are initiated locally.

These signals might contain a prise (market based DR), request or even command (physical based DR), for load shedding. The signals also need to tell a deadline, whether this is not pre-set, the action should be constrained by. The deadline doesn't have to be instantaneous and can be in some cases a time in future like over one or multiple hours. The time the DR scenario has to be active is either pre-set or the end of the event will be broadcasted by the requester. [Palensky and Dietrich, 2011]

DR means, with an optimal functioning energy management in a building, the reduction of the buildings energy demand for a certain amount of time. And as consequence the possibility of not maintaining the desired indoor conditions, since these could just be achieved with the lowest energy consumption possible.

To counter the problem and maintain indoor conditions the amount of energy used as demand response has to be consumed either before or after the response event. To make sure the indoor conditions are kept within the defined acceptable bandwidth. Which makes the link to the scenarios described in LS. The big difference is the DR event in planned or occurs in a smaller time window compared to the LS scenarios and is not a constant or on regular basis occurring behaviour.

Processes which accept a time delay or have some kind of storage capacity or latency are best suitable for DR. Still the indoor condition fluctuation from before till after the DR event have to be acceptable.

In new to build buildings these requirements can be used while engineering the building and systems making sure the building and her systems can provide this flexibility of providing DR without compromising the indoor conditions.

However, for existing buildings these requirements have not been used while engineering the building and systems thus these buildings possibly do not have this flexibility.

The key in providing the DR is finding the flexibility which does not reduce the productivity, even better increases the productivity.

Possibilities and characteristics for DR will be identified based on the measurements in the test building.

Comparing Market DR with Physical DR, Market DR has the disadvantage of contradictions involving price per power. In case of Instantaneous increase of renewable energy production, the DSO wants the price per power to rice as more energy travels through the grid and system capacity is almost reached. While Energy producers want the price per power to drop, making sure they sell, stimulation other to use, the generated energy. Especially renewable generated energy with stochastic behaviour can cause these situations.

DR for physical grid balancing purposes, is already used in western parts of the power grid in the United States of America. Applications for DR have been limited and used primarily for emergencies and peak shaving. As such, their capabilities are often assessed only for a few select times of the year.

This study evaluates DR as a tool used by energy management in case of power shortage, to manage network congestion, or other ancillary service to the grid. The goal should be making the best use of generation resources and infrastructure.

2.1.4 Other Demand Side Management categories

Local energy production and energy storage are included in the DSM categories. Since one of the drivers for the SG is the increase of distributed renewable generation, energy storage can provide an optimisation together with DSM.

The categories Spinning Reserve, Energy storage, and Local Energy production are briefly described to clarify the existence and possibilities.

Spinning Reserve

Spinning Reserve (SR) is described by [Palensky and Dietrich, 2011] as primary (active power output directly depends on frequency) and secondary control (restoring frequency and grid state with additional active power).

Nowadays this is mostly done by relative large producers, generators, of electrical power like gas fired power plants, combined heat and power installations, and others.

Relative new are the developments of SR on the demand side of the grid trying to support the traditional providers of ancillary services by imitating their behaviour. This means load reduction in case the frequency drops and load increase in case the frequency rises.

SR scenarios are still in phase of research and, as far as known, only used in experiments and simulations. [Eto et al., 2007; Eto et al., 2012]

Energy storage

Storage of energy can achieve a shift in the consumption pattern. Storing energy can be done in different manners like storing electricity, storing heat or cold. A fundamental difference is that in an electrical storage, surpluses in the network can also be stored, or can also be delivered to the network. [Molderink et al., 2009; Molderink et al., 2010]

Local Energy production

Local energy production can be sustainable energy production and energy production using fossil fuels. The first has the disadvantage it is not ‘on‘ switchable as desired but it is one of the key energy producers in making the energy system more energy efficient. The second has the advantage of switching on when desired for own use or feeding-in to the grid.

Sustainable energy has the highest priority. However sustainable energy production does belong to the smart grid because one of the goals of the smart grid is to facilitate local sustainable energy production. Energy production from fossil fuels can be deployed only when needed. [Molderink et al., 2009; Molderink et al., 2010]

2.1.5 Demand Side Management conclusions

Increasing Energy Efficiency is the first goal for supporting the Smart grid. Load Shifting scenarios imply optimisation of local processes and energy use. With Demand Response a more dynamic behaviour is introduced. In this study we discuss to what degree the pattern of consumption can be influenced, and whether it is useful with a certain amount of constrains for Demand Response.

For each experiment the most important DSM categories are Energy Efficiency, Load Shifting, and Demand Response. The impact of applying a load with one of the three DSM categories on each other has to be evaluated.

Peak shaving and Load Shifting will be used in the experiments regarding the chiller as Demand Response for brief peak reduction. As presented the energy use reduction can lead to a lower convenience level which might not be acceptable. The influence of the energy reduction has to be evaluated with corresponding Performance Indicators.

The Performance Indicators for the Thermal comfort, Indoor Air Quality, and Visual Comfort, used for evaluation of each experiment can be found in section 2.2.

2.2 Productivity comfort and IAQ

Regarding the possible effects of load shifting and peak shaving on the indoor climate Performance Indicators (PI) are needed for the evaluation of the effects on: Thermal Comfort (TC), Indoor Air Quality (IAQ), and Visual Comfort (VC). The grid responses might also have an effect on the productivity of the occupants. Based on literature suitable PI are selected for evaluation of IAQ, TC and VC on the experiments presented in section 3.3 and section 4.

Productivity is influenced by many factors. According to [Roelofsen, 2002] these factors can be divided by working environment related factors and non-working environment related factors. The working environment related factors like job stress and job dissatisfaction are combined in the factor motivation. [Roelofsen, 2002] assumes a certain level of motivation is present and guaranteed before looking into the relation of productivity and the indoor environment. The same study states that the indoor environment has a relatively substantial effect on productivity. And there is a clear relationship between job stress, job dissatisfaction and the indoor environment.

Office buildings are designed to provide the occupants a productive environment. Energy efficiency measures or energy management scenarios may not jeopardise the productivity of the occupants. The link between productivity and the energy management scenarios lies in the indoor climate and related comfort [Ratcliffe and Day, 2003; Steve, 2008].

In overall, the main components of indoor comfort are TC, IAQ, and VC. All of the mentioned comfort components somewhat influence the productivity of an office worker. Indices have been based on comfort rather than on productivity and are based on research done in artificial laboratory environments.

The three aspects of comfort described above do not capture the entire field of comfort, but to rate the buildings performance in terms of comfort they can be assessed.

The link between the indoor comfort and productivity is investigated by literature. With this a level of acceptance can be created for the Demand Response scenarios.

2.2.1 Thermal Comfort

The effect of the Thermal Comfort (TC) on productivity has not been quantified.

TC is influenced by radiant and by air temperatures and air velocity.

[Seppänen et al., 2006a] related the influence of the temperature to the relative productivity of office workers

The optimum temperature is 21,5 degrees Celsius and, an increase to 26 degrees Celsius, or decrease to 17 degrees Celsius, the influence of the temperature on productivity reduction is 5% according to their findings presented in Figure 6.

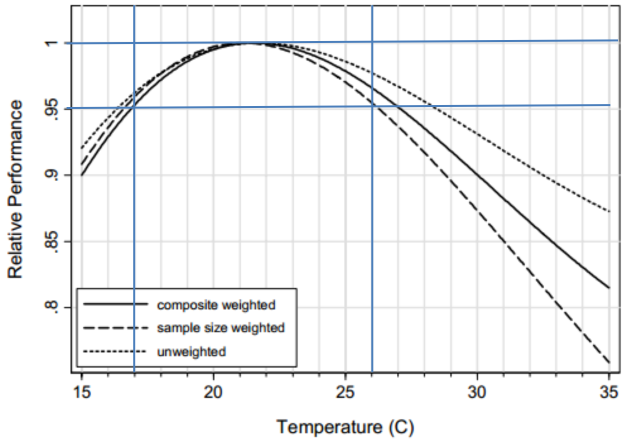


Figure 6: Influence of temperature on relative productivity of office workers, modified from [Seppänen et al., 2006a]

For rating the thermal comfort one of the most accepted methods is the PMV and PPD model of Fanger and ATL-method.

PMV and PPD

The Predicted Mean Vote (PMV) model of P.O. Fanger is used to rate and indicate an acceptable bandwidth taking temperature, radiant temperature, humidity, air velocity, metabolic rate, and clothing into account.

The percentage of a group of people in the same indoor conditions which is dissatisfied with these conditions is given by the Predicted Percentage Dissatisfied (PPD). The PPD is related to the PMV as shown in Figure 7.

PMV predicts the mean thermal sensation vote on a standard scale for a large group of persons, even at PMV=0, still 5% is dissatisfied as can be seen from Figure 7. With this knowledge one knows and accepts the fact that an uniform indoor environment cannot please all occupants. According to the standard NEN-EN ISO 7730 there are three categories presented in Table 3.

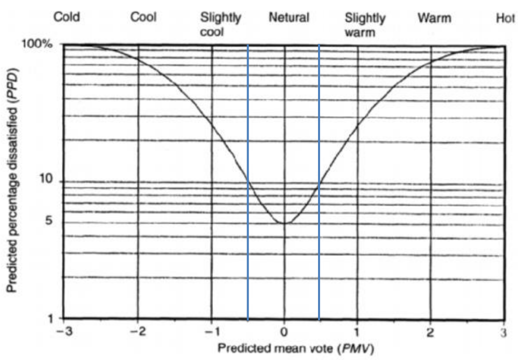


Figure 7: PMV/PPD model of P.O. Fanger.

Table 1: Categories according NEN-EN ISO 7730 [NEN-EN ISO 7730, 2005]

Class	Upper PMV	Lower PMV	Weighted exceeding hours
A	0.2	- 0.2	100
B	0.5	- 0.5	150
C	0.7	- 0.7	250

What is generally accepted for the office situation is facilities with which the PMV value can be kept between –0.5 and 0.5.

Adaptive Temperature Limits

Adaptive Temperature Limits (ATL) method is used to get an impression of the performance of the building and systems. This method takes the physiological, psychological and behaviour adaptations of the human related to the thermal environment in account. Hereby changes the boundary of the comfort classes based in the weighted mean outside temperature. ISSO 74 states the method should only be used to compare the building to design or to simulations with the climate year 1964/65 in case the weighted mean outside temperature is not higher than 22 degrees Celsius. [ISSO, 2010]

For this research only a comparison between the measured and simulated comfort temperatures with current climate year by the ATL-method is necessary.

The comfort temperatures are determined with the measured air temperatures and radiant temperatures.

In the ATL-Chart three classes can be defined, Class A, Class B and Class C. Class A is the bandwidth in which 90% of the occupants accepts the thermal environment (white area in ATL-Chart).

Class B, defined as a ‘good indoor climate’ is the bandwidth in which 80% of the occupants accepts the thermal environment (light coloured area in ATL-Chart).

Class C is the bandwidth in which 65% of the occupants accepts the thermal environment, this class is only used in for temporary accommodation (area between the light and dark coloured areas in the ATL-Chart).

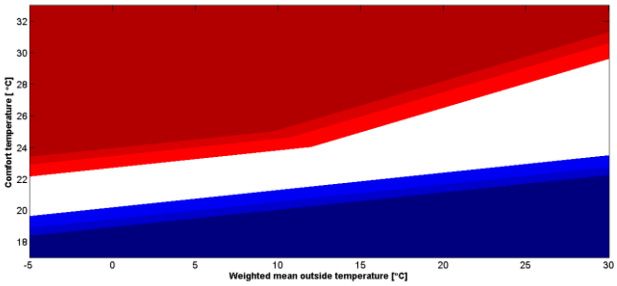


Figure 8: ATL-Chart example.

2.2.2 Indoor Air Quality

Air supply, odour, and pollutants determine the air quality within a building. Reducing indoor air pollution may improve the comfort, health, and productivity of building occupants. Humans pollute the air by their presence and actions and even worsen the odour. The ‘fresh’ outside air supply together with the indoor pollutants form a balance determining the Indoor Air Quality (IAQ).

An indicator for IAQ is CO_2 concentrations since the human is considered the biggest polluter within the office. And the ventilation system is utilized to keep low CO_2 concentrations.

The Dutch ARBO Regulations prescribe a maximum of 800 PPM CO2 concentration as a maximum in offices. [Horsten, 2013]

The ASHRAE states a maximum CO2 concentration of 1000 PPM considering an outside CO2 concentration of 350 PPM. [ASHRAE 62.1, 2007]

[Seppänen et al., 1999] reported that ventilation rates below 10 L/sec per person in all building types were associated with statistically significant worsening in one or more health or perceived IAQ outcomes. They also found that about the risk of SBS symptoms decrease significantly with decreasing carbon dioxide concentrations below 800 ppm.

[Fisk, 2000] mentions studies that have shown that doubling of ventilation rates increases worker task efficiency by some 2%. This is not the same as productivity increasing by 2% but does suggest a significant increase.

[Seppänen et al., 2006b] related outdoor air ventilation rates with relative performance. Their findings are shown in Figure 9. The figures show an increase in relative performance by an increase of outdoor air ventilation. The left figure starts at a ventilation rate of 6 l/s per person outdoor air and the right starts at a ventilation rate 10 l/s per person of outdoor air. Both show the increase in relative performance tends to stop while increasing ventilation rates of outdoor air above 40 l/s per person. This seems logical since at some high ventilation rates the pollution of indoor air equals the outdoor air pollution and the relative performance should stabilise.

Very high ventilation rates however, can bring more noise production of the systems, and droughts can be a risk.

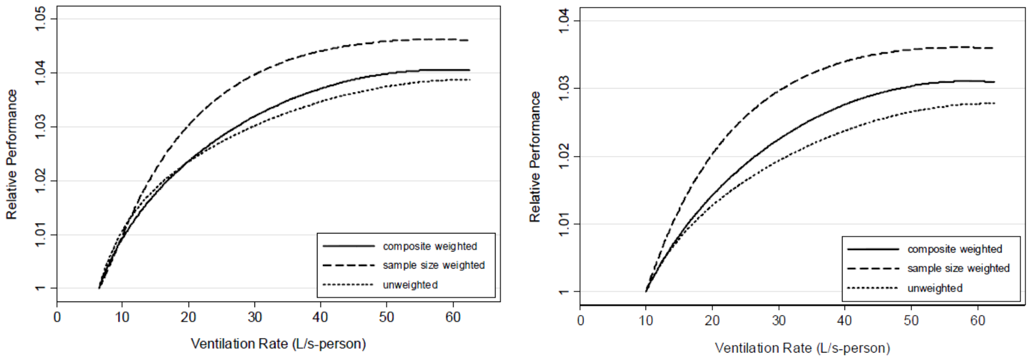


Figure 9: Relative performance in relation to the reference values 6.5 L/s-person (left) and 10 L/s-person (right) versus ventilation rate, modified from [Seppänen et al., 2006b]

2.2.3 Visual Comfort

According to [Linhart and Scartezzini, 2011] visual comfort in office rooms, depends on the horizontal illuminances, distribution of the light on the workplace, and discomfort of glare. The same study states the horizontal illuminances especially on the workplanes must be sufficiently high. The light on the workplane has to be properly distributed e.g. appropriate illuminance uniformities. And discomfort glare e.g. from luminaires or through windows must be avoided to maintain a good visual comfort.

According to [Fisk, 2000] lighting has the theoretical potential to influence performance directly because work performance depends on vision, and indirectly because lighting may direct attention, or influence arousal or motivation.

Occupants prefer a window location which may be due to the preference for natural daylight over artificial or the view out or control over the opening of the window and blinds. [Hartkopf and Loftness, 1999; Leslie, 2003] report a window location is to be one of the main influences on an occupant's degree of satisfaction with the indoor environment with incidences of health complaints reduced by 20-25%.

A daylight factor of 2% gives an illuminance of 1000 Lux for much of the working year but is difficult to achieve for areas much over 6m from the window. Daylight levels nearer the windows can be ten times or more higher and have an effect on the bodies biological clock [Muneer, 2000]. At the same time, of course, windows can cause significant glare problems at times of high outdoor illuminance and particularly direct solar gain.

Productivity is believed to be increased by daylight though the quantitative effect is not known.

'*Given the strong preference for natural light shown by the majority of people, it is difficult to imagine that daylight does not improve productivity provided, of course, that glare is avoided.*' [Hartkopf and Loftness, 1999]

Most standards suggest average horizontal workplace illuminances of 500 Lux. And an uniformity on the working place of 0,7.

2.2.4 Productivity comfort and IAQ conclusions

Productivity is hard to quantify for the total indoor comfort. Thermal comfort, Indoor Air Quality, and visual comfort are all influencing the comfort and it is known in case one of the comfort is insufficient the productivity is jeopardised.

For thermal comfort both the methods, PMV and ATL, asses thermal comfort by the air temperature and radiant temperature. The PMV and PPD method also assesses the air velocity and occupant related parameters. The air velocity is mainly related to the ventilation which also influences the IAQ.

In this study the thermal comfort will be assessed by the air temperature and mean radiant temperature as Performance Indicators. The PMV, PPD, and ATL methods will be used to assess the bandwidth wherein it is acceptable the PIs can fluctuate.

For the PMV, class B according NEN-EN ISO 7730 is used as acceptable boundary and exceeding hours. [NEN-EN ISO 7730, 2005]

With the ATL-method values outside of Class C are considered not acceptable.

For the Air Quality CO_2 will be used as Performance Indicator. Maximum concentrations are described in building code and the level of 800 PPM will be used as upper boundary.

Visual comfort will only be assessed by the level of Illuminance on the workplane / desk. Effects of glare are expected to be cancelled manually by the users actions lowering solar screens or positioning of working place.

2.3 Discussion and conclusions

Increasing Energy Efficiency is the first goal for supporting the Smart grid. Load Shifting scenarios imply optimisation of local processes and energy use. With Demand Response a more dynamic behaviour is introduced. In this study we discuss to what degree the pattern of consumption can be influenced, and whether it is useful with a certain amount of constrains for Demand Response. Whether this Demand Response is Physical or Market based is not important for this study. It is assumed the building receives a signal after which loads should be shed.

This research focuses on the effects of Demand Response and therefore, at first, ignores the possibilities for spinning reserve, energy efficiency or load shifting scenarios.

During the measurements of reference operation opportunities for better Energy Efficiency or Load Shifting will be reported. Spinning Reserve scenarios are not in the scope of this work.

In case the case study building already has a few management scenarios for Load Shifting it is expected to find them and their influence on the energy profile during the evaluation of the reference operation.

For each experiment the most important DSM categories are Energy Efficiency, Load Shifting, and Demand Response. The impact of applying a load with one of the three DSM categories on each other has to be evaluated.

Productivity is hard to quantify for the indoor comfort. Thermal comfort, IAQ, and visual comfort are all influencing the indoor comfort and it is known in case one of the comfort is insufficient the productivity is jeopardised.

Thermal comfort in this study will be assessed by the air temperature and mean radiant temperature as Performance Indicators. The PMV, PPD, and ATL methods will be used to assess the bandwidth wherein it is acceptable the PIs can fluctuate.

For the Air Quality CO_2 will be used as Performance Indicator. Maximum concentrations are described in building code and will be used as upper boundary.

Visual comfort will only be assessed by the level of Illuminance on the workplane / desk. Effects of glare are expected to be cancelled manually by the users actions lowering solar screens or positioning of working place.

3 Chapter 3 Case Study Building

- 3.1 Case study building
- 3.2 Measurement setup
- 3.3 Zero measurements
- 3.4 VABI Elements model
- 3.5 Discussion and conclusions

For doing the experiments with the expected main electricity consumers in an office; HVAC fans, chiller, and lighting a typical office building for the Netherlands has been selected.

[Bak, 2013] sorted the current office stock in the Netherlands by size into five categories (Figure 10). The selected case study building belongs to the category representing 23% of total office building stock in 2011.

The building selected for this study is the office building of Kropman Breda. It is a building of medium size, the key values are given in section 3.1.

Before starting the experiments, the building is analysed and prepared for the experiments. The measurement setup for measuring the PIs of Thermal Comfort, Indoor Air Quality and Visual Comfort, discussed in section 2, during the experiments is presented in section 3.2.

Reference operation is measured to identify aberrations in the building operation, the results of reference operation measurements are presented in section 3.3.

The model setup for simulations of experiments is presented, a VABI Elements model of the case study building is described in section 3.4.

Ending the chapter confirming the HVAC fans, Chiller, and lighting as the main power consumers of an office building in the discussion and conclusions section 3.5.

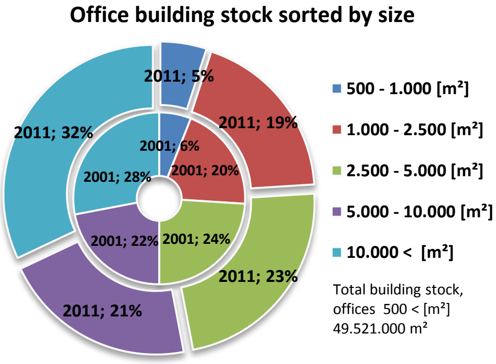


Figure 10: The Netherlands office building stock by size modified from: [Bak, 2013].

3.1 Case study building

Building and system properties of the case study building are provided in this section.

The connection to the grid is important for grid management and building energy management. With this the installed systems and appliances are of importance since the system capacities determine the possible impact on the consumption profile.

As most office buildings in the Netherlands the case study building is connected to the Mid Voltage grid by a substation as presented by section 3.1.2.

3.1.1 Building and system properties

The Kropman Office in Breda is situated in the west of the city Breda a town in the southern part of the Netherlands. The building is a three story high building. The main building and system characteristics are presented in Table 2and Table 3.

Figure 11: Test case office building Kropman Breda.

Table 2: Building characteristics

Floors:	Total floor space	Workplaces:	Windows	Office hours
3 floors mainly shallow plan	~ 1450 m² floor space	59 office desks	Most windows can be opened and are equipped with hand operated solar shading devices	7:00 and 18:00 from Monday to Friday

Table 3: Building system properties

Heating:	Cooling:	Ventilation:	Humidifier:
Central heating system, boiler	Central cooling system, compression chiller	Mechanical central Air Handling Unit, no recirculation, heat recovery wheel.	Electrical humidifier

Floor plans, technical schemes, and more detailed information about the building and systems can be found in the Appendix A.

3.1.2 Grid connection and installed capacity

The Kropman Breda office building is connected to a dedicated mid-voltage transformer station. For this study extra electrical meters have been installed indicated with I and II in Figure 12.

Figure 12 below illustrates major electricity load groups at Kropman Breda Building.

The installed electrical power capacities for all connected of both main groups is also presented in this figure. The installed electrical power capacity for lighting is about 11% of the total. While the other power connection covers about 89% of the installed capacity.

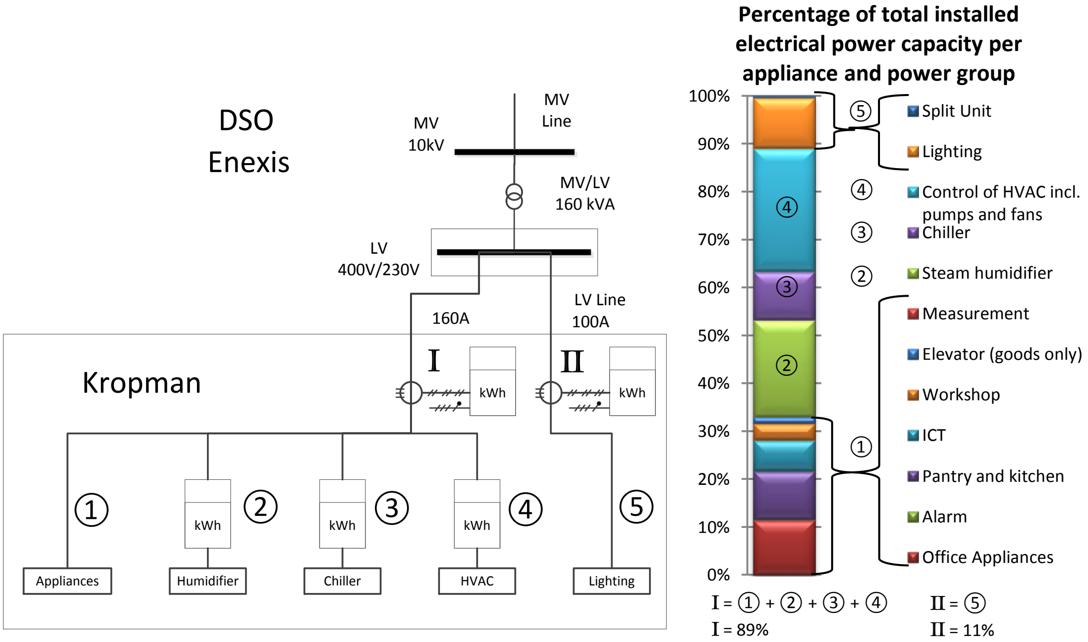


Figure 12: Simplified representation of the electrical connections from Mid Voltage grid to building and percentage of total installed electrical power capacity per appliance and power group.

The HVAC control unit, controls the building systems by sending the control signals, supplies the electrical power to the fans and pumps, and facilitates the communication signals to the BAS and all connected components.

3.2 Preparation for experimental setup

Before starting the experiments with the HVAC, chiller, and lighting system, measurements of the Performance Indicators (PI) for Thermal Comfort, Indoor Air Quality, and Visual Comfort, are needed. Measurement equipment in the building are prepared in advance. The measurement setup is described in this section.

First the comfort related measurements are presented followed by the energy related measurements.

The first floor is chosen as of most interest for more detailed measurements because the layout of the floors on different levels are not similar and since all the supply system groups are situated in the first floor (Appendix E and Figure 17), and the first floor is the most regular occupied floor.

3.2.1 Comfort related measurements

In most rooms of the first floor and outside temperature and relative humidity are measured for analysing abbreviations of the thermal indoor environment. Positions of the measurement equipment can be found in the floor plan presented in Appendix E.

In two rooms (Highlighted in blue Figure 17) a more specific setup has been placed to measure the parameters needed to estimate the PMV and PPD (Figure 14). These parameters can be compared to the values and ranges given in guidelines like ISO 7730. [NEN-EN ISO 7730, 2005]These parameters are air temperature, mean radiant temperature, and relative humidity; the mean radiant temperature is thereby generally calculated out of the globe-temperature measured with a black globe [ISO 7726, 1998].

The measurements of the air temperature and mean radiant temperatures are also used to estimate the comfort temperature as used in the ATL-method.

CO_2-sensors are used in both rooms for evaluation of the IAQ based on the ventilation. Concentrations are also compared to building code.

Illuminance has been measured horizontally at the workplace and vertical at the lower part of the window for evaluation of the natural light entering the window and intensity on the workplace.

Figure 13: Temperature and humidity measurement equipment.

Figure 14: Black globe.

Figure 15: Illuminance detectors, left at the desk right in front of the window.

The measurement equipment is placed near the workspaces of people, in order to get an impression of the conditions experienced by the office occupants.

Local discomfort measurements have not been done since this is considered too detailed for the research ends.
Room A has the external wall orientated on the south and is setup as a one person work room.

Room B has an external wall orientated on the north and is setup with multiple workplaces.

A specification of the sensors can be found in Appendix F.


Figure 16: Outside temperature and humidity measurement equipment.

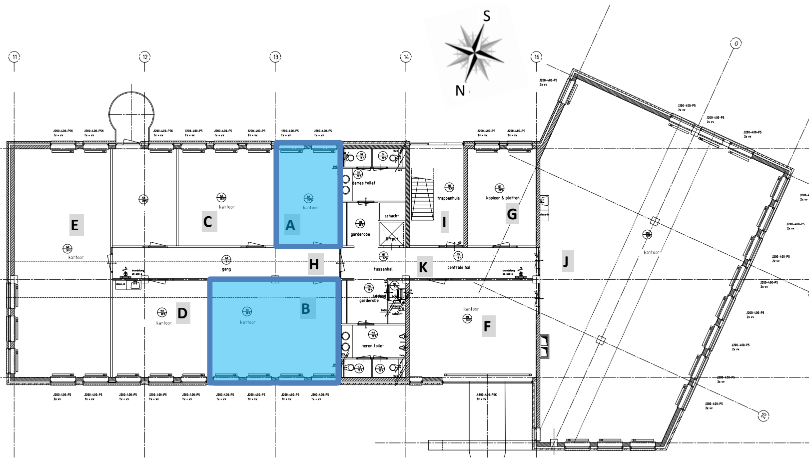


Figure 17: Floor plan first floor test case office building Kropman Breda

3.2.2 Estimation of electrical and internal loads

In the building the two main connections (presented in Figure 12 with I and II) and main power systems connected (presented in Figure 12 with ②, ③, and ④) have to be measured. Extra energy measurement equipment has been installed for measuring the main connections.

Figure 18: Applied Voltcraft energy logger 4000, logging electrical appliance load at the workplace.

Beside the measurements of the main connections some appliances and lighting equipment have been measured separately.

For analysing the energy use of office appliances belonging to ① (Figure 12) and lighting belonging to ⑤ (Figure 12) extra measurement equipment has been installed. With these measurements a more detailed insight can be gained about the energy use.


Figure 19: PlugWise Circle.

Electrical energy consumption of the appliances directly used by the occupants will be measured with Voltcraft EL4000 energy loggers. The equipment is situated between de socket and power strip at the workers desk. Specific locations are indicated in Appendix E.

Electrical energy consumption of the artificial lighting system will be measured with PlugWise devices called 'Circle'. The Circle devices have been placed in the lighting power socket from where the lighting is connected. Specific locations are indicated in Appendix E.

The PlugWise devices use a wireless mesh-network to send and receive control signals, measurement data, and status data between the Circles and the server running the Source software.

3.3 Reference operation

Operation of case study building is measured and used to identify aberrations in the building operation and will serve also as reference for the experiments. The measurements consist of two parts an energy part and a comfort related part. First the comfort related part will be discussed after which the energy related part is presented.

During the period of this study about 40 to 50 employees worked almost daily in this building. Due to external activities and holidays this number varied.

Typical work done by the building occupants are; administrative work, CAD drawing, engineering tasks, and other desk related work. Once in a wile there are some workshop related activities but since the workshop is used as a storage these activities are rare.

A questionnaire was held in advance to find if there were any complains or discomfort related to the indoor climate. Due to the low number of participants no specific or scientific findings can be abstracted from the questionnaire. The questionnaire is only used to form a general opinion of the participating building users.

From the questionnaire most people are happy with the indoor climate. The building indoor climate is rated as good. 65 % of the people working on the first floor participated, during the period the questionnaire was held.

The questions asked and corresponding answers can be found in Appendix H.

3.3.1 Comfort part reference operation

In this paragraph the measured CO_2 concentrations, Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), and Adaptive Temperature Limits (ATL) method during working hours are presented.

Evaluation of the measured CO_2 concentrations are used for assessment of building system performance and more specific the ventilation system. While the PMV, PPD, and ATL method are calculated to assess the mean thermal sensation and acceptance of the indoor climate by the occupants related to the building system performance.

With the questionnaire no complains about the indoor climate were found. This is expected to be backed up by the assessment of PMV, PPD, and ATL methods.

CO2 concentration

CO_2 concentrations have been measured in room A and B during the month July and August.

As can be seen from Figure 20 the measured CO_2 concentrations in July and August stay almost 75% of the working hours below 600 PPM and never exceed the 750 PPM. These measurements indicate the ventilation system provides sufficient ‘fresh’ air from outside.

In August the mean and median CO_2 concentrations are higher compared to July. This can be explained by the lower occupancy numbers during July due to the summer holiday period.

The measured values stay below the 800 PPM level stated by code. [Horsten, 2013]

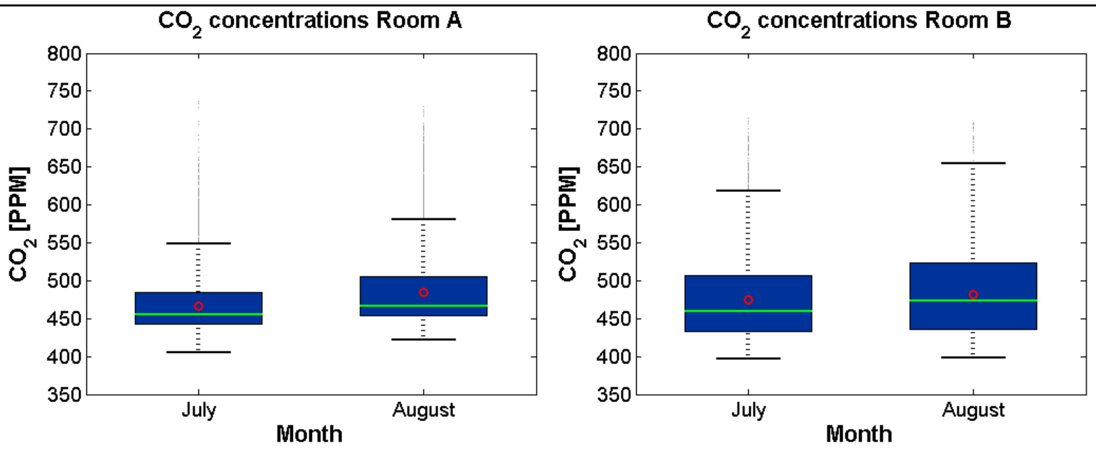


Figure 20: CO$_2$ concentrations measured each month in room A and B during daily working hours.

For these boxplots the mean is plotted with a green line while the median is plotted by a red circle. The whiskers represent the lower and upper quartile of the data. Outliers are plotted in dots.

PMV and PPD

Acceptation of the indoor comfort is evaluated by the calculated PMV and PPD values. This is done for the rooms A and B as presented in section 3.2.1.

For this research the PMV and PPD have been calculated making some assumptions since not all the parameters could be assessed from measurements.

The clo values for the occupants can only be assumed since the clothes worn by the occupants is unknown and in this case no uniforms or other standardised clothing is obligated. The clo value assumed by observation is 0.8.

Daily work of an office worker can be assumed quite constant. However walking to meetings, consulting colleagues, getting a coffee, are all actions which will increase the metabolic rate. Especially in case the person has to carry stuff or climb the stairs on his route.

This parameter also can only be assumed and is not measured or obtained on any other manner. For the calculation of the PMV and PPD values the assumed values as presented in Table 4 are used.

Table 4: Fixed parameter values for PMV calculations

Parameter	Clothing (Clo)	Air velocity	Metabolic rate	External work
Value	0.8	0.2 m/s	120 [W/m²]	0 [W/m²]

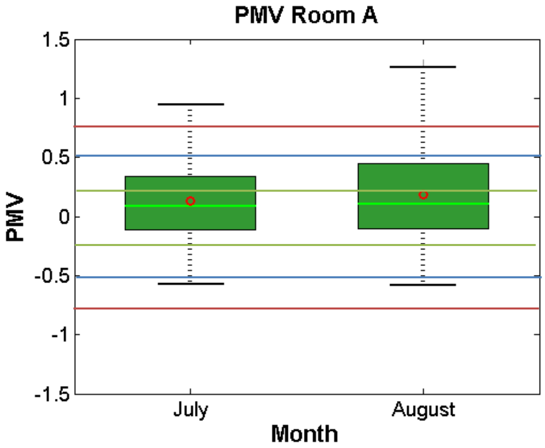


Figure 21: Calculated PMV values per month in room A during daily working hours.

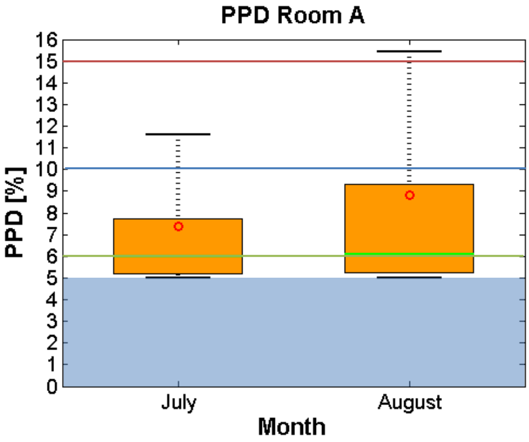


Figure 22: Calculated PPD values per month in room A during daily working hours.

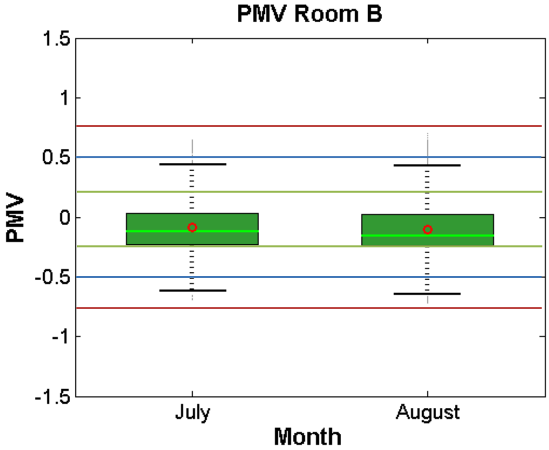


Figure 23: Calculated PMV values per month in room B during daily working hours.

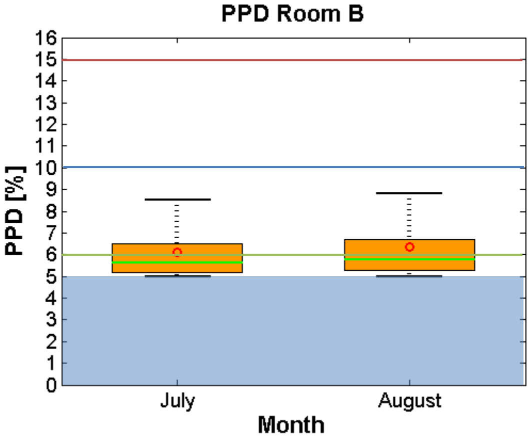


Figure 24: Calculated PPD values per month in room B during daily working hours.

NEN-EN ISO 7730 describes three classes, A, B, and C for offices as presented in section 2.2.1. The boundaries of the three classes are plotted in the figures showing the PMV and PPD values. The green lines indicate the boundaries of class A, boundaries of class B are indicated with blue lines, and the red lines indicate the boundaries of class C. [NEN-EN ISO 7730, 2005]

PMV predicts the mean thermal sensation vote on a standard scale for a large group of persons, even at PMV=0, still 5% is dissatisfied as can be seen from Figure 7 section 2.2.1. Values from 0% dissatisfaction to 5% are therefore blocked by a coloured area in the figures presenting the PPD values.

As can be seen in Figure 21 to Figure 24 the calculated PMV and PPD values for room B stay most of the working time within acceptable ranges (NEN-EN ISO 7730, Class B).

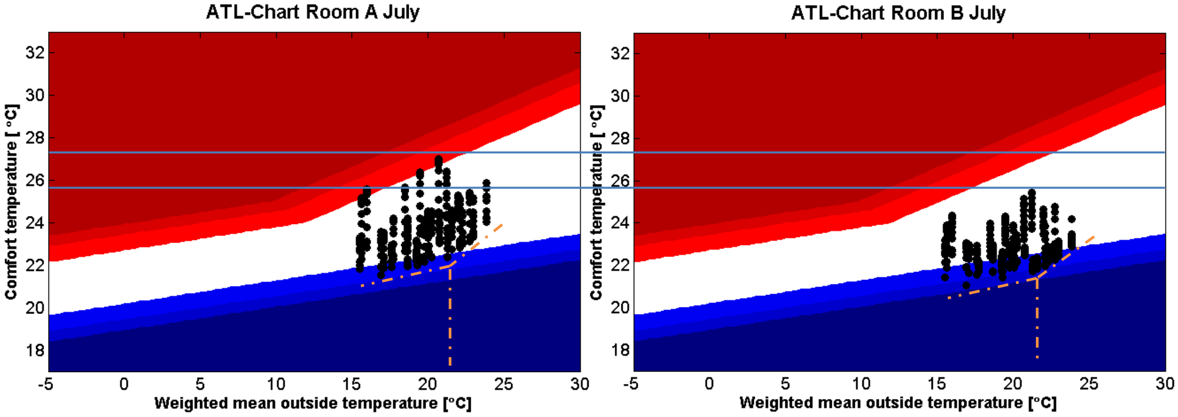
Calculated PMV and PPD values for room A compared to room B are quite different and less desirable (mainly Class B, NEN-EN ISO 7730, with values exceeding Class C). During the measurement period is found the mean radiant temperature in room A is quite higher compared to the mean radiant temperature in room B. This is mostly due to the lack of sun blind usage / adjustment during the day. The sun blind was only closed for the top 2/3th of the window area, allowing direct solar irradiation on a part of the workplace. This explains the higher calculated PMV and thus PPD values for room A.

Adaptive Temperature Limits

Adaptive Temperature Limits (ATL) method is used to get an impression of the acceptance of the indoor climate and performance of the building and systems. The ATL-Charts give a quick impression of the indoor climate but should be treated carefully not drawing any hard conclusions.

ATL-Charts for room A and room B are presented in Figure 25 and Figure 26.

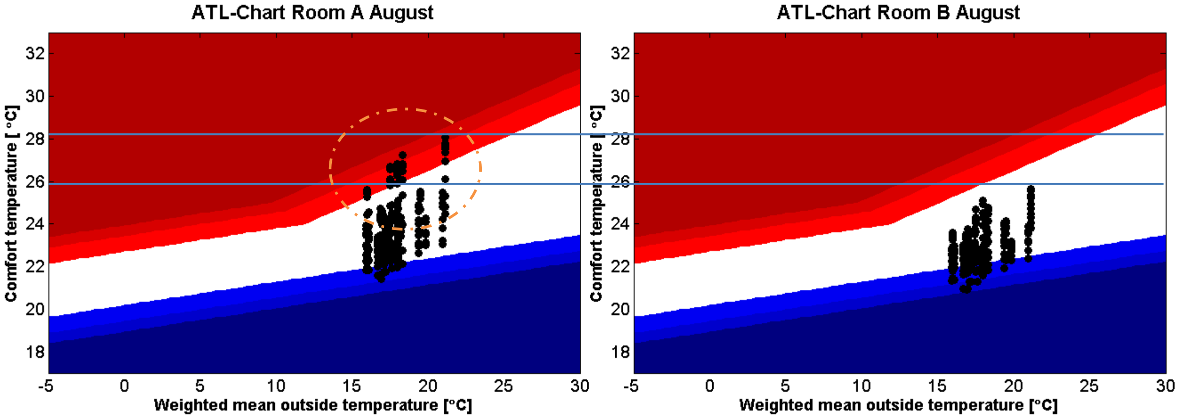
The comfort temperatures are determined with the air temperature and radiant temperatures measured in room A and B.



ATL-Chart Room A July

ATL-Chart Room B July

Figure 25: ATL-Chart over the period July of Room A on the left and Room B on the right.



ATL-Chart Room A August

ATL-Chart Room B August

Figure 26: ATL-Chart over the period August of room A on the left and room B on the right.

As can be seen in Figure 25, the comfort temperatures in the month July all are within the Class B boundaries. For the Month August, Figure 26, most of the comfort temperatures are within the class B boundaries with some outliers in class C for room A.

For both rooms we can see the comfort temperature during a day only rises, since the weighted outside temperature is estimated for each day. The comfort temperature a day starts with only rises with a rising weighted outside temperature and with a weighted outside temperature above 21 degrees Celsius or higher, the increase shows a more steep increase (orange dashed lines).

The comfort temperatures in room B are clearly lower compared to the comfort temperatures in room A. The Blue lines indicate a difference of almost 2 degrees Celsius. As earlier noticed with the difference in calculated PMV and PPD values between room A and B, where room A also has higher values compared to room B. Higher mean radiant temperatures are the reason.

Direct solar irradiation through the window can also be the reason the comfort temperatures of room A in August seem to jump at the end of the day. As indicated in the orange dashed circle (Figure 26) the highest and lowest comfort temperatures are separated a bit.

Compared to the month July the weighted outside temperatures are overall lower for August while the comfort temperatures are higher. Overall the ATL method shows the building operates with acceptable results and leave room for optimisation by better using the entire acceptable bandwidth.

As shown in the ATL-Charts the comfort temperature in room B is less critical in summer period compared to room A. With proper use of the sun blinds one can discuss there is even room for better usage of the allowable bandwidth by accepting higher comfort temperatures. As shown in the ATL-Carts of room B the comfort temperatures are about one to two degrees lower than the upper limit of Class A.

3.3.2 Conclusions comfort measurements

Comparison of the data of calculated PMV, PPD, and ATL-Charts states the building systems operate as desired to deliver an comfortable indoor climate which is also confirmed by the questionnaire.

ATL-Charts with comfort temperatures represent the acceptance of the indoor climate better compared to the PMV and PPD because the ATL method better includes the adaptation and actions of the occupants.

Looking to the findings in room B the current situation leaves potential for energy savings by allowing higher temperatures. The situation in room B is not the same as for the rest of the building. Since the system only supports central cooling fort three sections divided over the building it is not advisable to adjust the settings for cooling based on one room. It would be better to determine the comfort temperatures for multiple rooms on multiple floors to come to a better insight for energy savings based on the acceptance of comfort temperature.

The air velocity at workplaces is not measured and evaluated. Since variations of the air velocity has an impact on the PMV and PPD it is recommended to measure the air velocity in future research.

The ATL-method only uses the mean comfort temperatures per hour. Variations within the hour are not investigated. Future work could define whether the variations are significant.

3.3.3 Energy part reference operation

All the energy measurements done in this case study building started not at the same time. Due to practical limitations not all measurement equipment could be installed at the same time.

Measurements presented in this report are all done between 01-07-2013 and 31-10-2013. This implies that operations in winter period are beyond the scope of this work.

In order to evaluate the energy use of the installed systems energy measurements are done. As presented in paragraph 3.1 the main connections (lighting and appliances) are measured by kWh meters, and the biggest appliances (chiller, humidifier, and HVAC control unit) are measured separately.

For this project the following electrical power consumption measurements have been done, specific rooms are as indicated on the floor plan in Appandix E.

Table 5: Electrical power measurements.

Description	Specific room	Measurement period
Main supply power group		from 01-09-2013
Main supply lighting group		
Chiller		from 10-07-2013
Humidifier		
HVAC control unit		
Lighting equipment in 7 rooms		from 16-07-2013 to 17-09-2013
Lighting equipment in first floor hallway		
Personal Computers	A, B, E	from 01-07-2013 to 01-09-2013
Laptops	C, D, F	
Laptop docking stations	C, D, F	
Monitors	A, B, D, E, F	
Small printer	A	
Phone charger	A, B, E, F	
Water boiler	A	
Split unit	G	

Major load profiles studied in details include:

- HVAC control unit
- Chiller
- Lighting
- Remaining appliances

Details are presented in this section.

During the measurement period the humidifier did not run. This is normal for the summer period situation since the humidity of the outside air is relative high. The energy profile of the humidifier should be investigated in winter period.

HVAC control unit

Figure 27 shows two different energy profiles for the HVAC control unit, the left profile contains the Monday morning early start setting (block B), and the right shows the profile with active night ventilation (block D).

As can be seen from this figure, the maximum hourly usage by the system is 6 kWh/h and minimum is 0 kWh/h.

In the right figure the energy use by night ventilation can clearly be seen due to the energy use from 0:00 hr. till 6:00 hr. (D). The energy consumption due to night ventilation is maximum 5 kWh/h. This gives an insight in the amount of energy use by the fans compared to the other components powered by the HVAC control unit.

The night ventilation is a clear example of a Time Of Use energy management scenario. It enables the building systems to cool the building by ventilating colder outside air instead of using the buildings chiller.

The left figure shows an early start (B), as the clock program lets the building systems start up earlier on Monday morning at 5:00 hr. till 7:00 hr. to precondition the building after the weekend.

This scenario can also be called a Time Of Use energy management scenario.

Both the early start and night ventilation scenarios try to bring the indoor conditions to an optimal start situation, bringing the indoor temperature as close to the desired value, before the occupants enter the building. The workload done by both scenarios would otherwise have to be done with building occupancy and corresponding internal heat loads, higher external heat gains, and higher outside temperatures. All combined more cooling load probably to be countered by the building chiller.

As seen in the ATL-Charts, section 3.3.1, the comfort temperature a day starts with rises as the weighted outside temperature rises. The building systems have the goal to bring the starting comfort temperature as close as possible to the lower comfort temperature boundary. With weighted outside temperatures higher than 21 degrees Celsius the building systems seen to be less able to achieve this goal.

Figure 27 shows during night the HVAC control unit uses less than 1 kWh per hour (block A). Since the measurement equipment is not able to measure with a higher accuracy the exact behaviour cannot be detected.

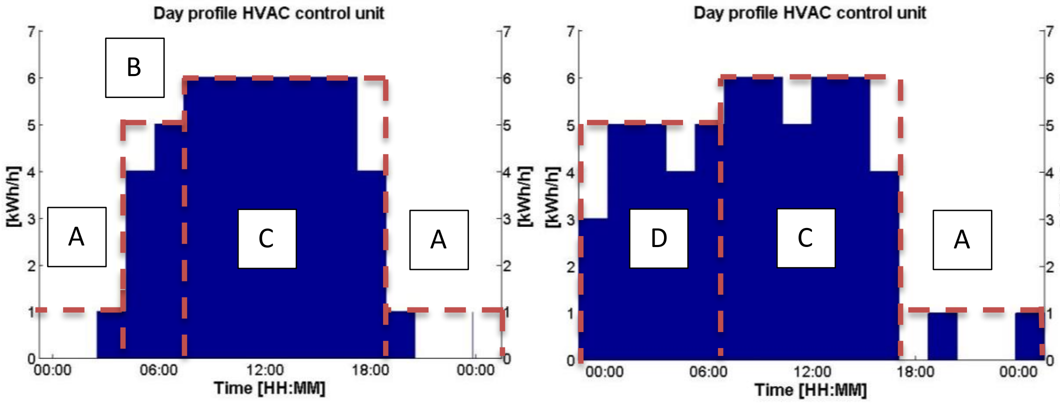


Figure 27: Energy use day profiles of the HVAC control unit, left containing the early start (Monday morning) program (B), the normal operation during day (C), and inactive night operation (A), right containing active night ventilation (D), the normal operation during day (C), and inactive night operation (A).

Figure 28 presents the energy profiles as shown in Figure 27 plotted for each day stacked by date in a 3D plot. The energy use is given a colour to accent the differences where red presents the maximum use of 6kWh/h and dark blue 0 kWh/h.

Here the energy profile with or without night ventilation can be seen more clear. Also the transition of one scenario into the other can be seen clearly since it is a direct change. This shows the two scenarios differ quite extreme. This implies the energy load during the night differs with at least 4 kWh/h comparing both scenarios.

For future energy management this means the possible service to the grid has to consider which running scenario will be active.

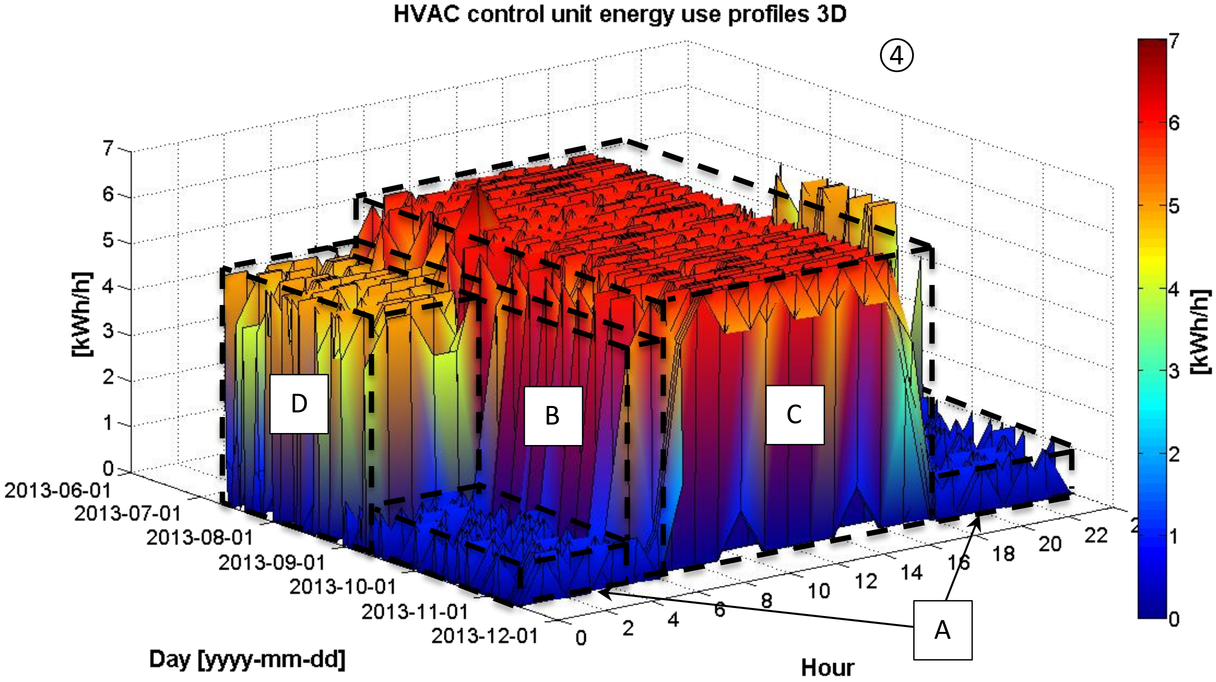


Figure 28: HVAC control unit daily energy use development in time containing inactive night operation (A), the early start (Monday morning) program (B), the normal operation during day (C), and active night ventilation (D).

Night ventilation occurs in case the outside temperature is lower than the inside air temperature while the inside air temperature is higher than the desired start value of 22 degrees Celsius, and runs from 0:00hr. till 6:00 hr. Daily energy use is 6 kWh/h from 7:00 hr. to 18:00 hr.

Table 6: HVAC Control Unit operations and energy usage per time window.

Time window	00:00 - 05:00	05:00 - 06:00	06:00 - 07:00	07:00 - 18:00	18:00 - 23:00	23:00 - 24:00
Operation	~ 1 kWh/h	~ 1 kWh/h	~ 1 kWh/h	6 kWh/h	~ 1 kWh/h	~ 1 kWh/h
Operation with night ventilation	5 kWh/h	5 kWh/h	~ 1 kWh/h	6 kWh/h	~ 1 kWh/h	5 kWh/h
Operation with early start	~ 1 kWh/h	6 kWh/h	6 kWh/h	6 kWh/h	~ 1 kWh/h	~ 1 kWh/h
Operation with early start and night ventilation	5 kWh/h	6 kWh/h	6 kWh/h	6 kWh/h	~ 1 kWh/h	5 kWh/h

Chiller

The Chiller with two stage compressors had one compressor defect during the project. This led to reduction in cooling capacity.

During the summer the chiller had a few running scenarios. As can be seen from Figure 29 where four energy profiles picture the chiller being active for full capacity the entire day as the first (A). And second, as shown in Figure 29, with reduced capacity active during the day (B). Third, with reduced capacity and partially active during the day (C and D).

From Figure 29 the maximum power used by the chiller is 14 kWh/h. In the upper right figure the energy use varies clearly during the day with an hour on full capacity from 12:00 hr. to 13.00 hr. On the upper left, as the clock program lets the building systems start the chiller starts and in two hours it runs on full capacity during the rest of the day till the clock program ends. Lower left and right picture the chiller starts later during the day and never reaches full capacity.

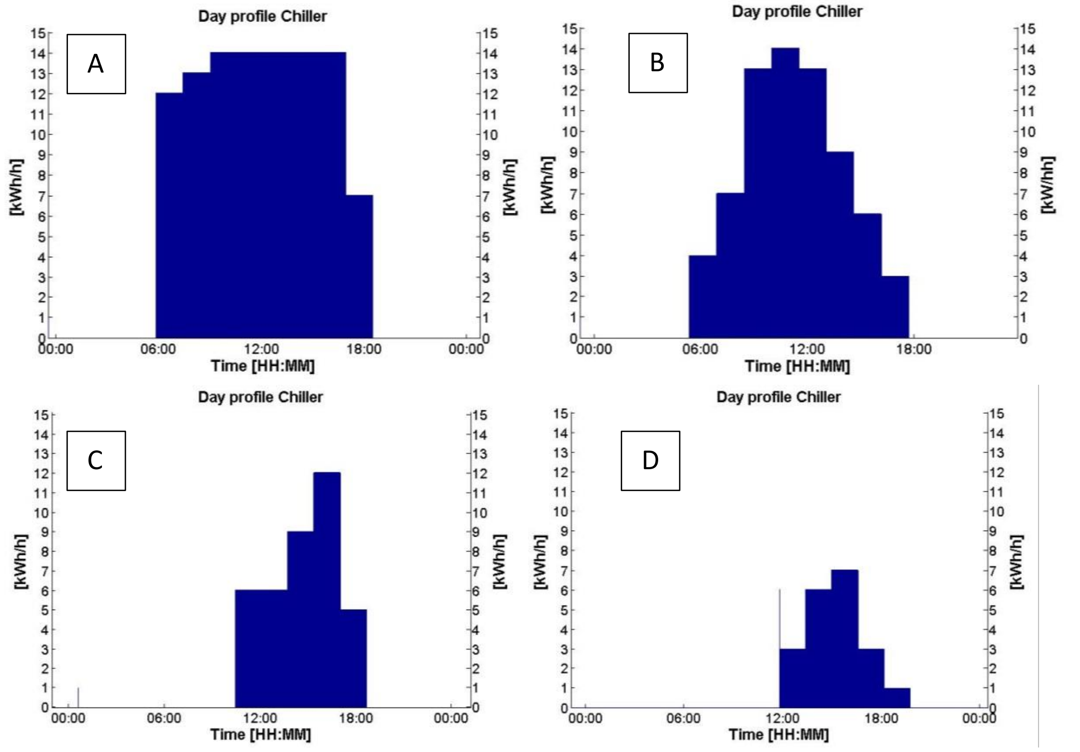


Figure 29: Energy use day profiles of the chiller, upper left (A) full day active at almost full capacity, upper right (B) full day active at varying capacity lower left (C) almost a half day active at varying capacity., lower right (D) only active in the afternoon at varying capacity.

Figure 30 presents the energy profiles as shown in Figure 29 plotted for each day stacked by date in a 3D plot. The red colour presents the maximum use of 15 kWh/h. The transition between the typical energy profiles presented in Figure 29 is quite smooth while the differences are significant.

This picture makes clear the most energy consumption by the chiller, when not running full capacity the entire day, is in the early afternoon.

With 'E' (Figure 30) the active cooling during the early start on Monday morning is shown. These two pikes occurred in days the night ventilation was unable to cool the building back to the desired temperature.

Unfortunate the energy use registration started, tenth of July, while the chiller already ran for a few weeks. Due to the late, fully operational, measurement and registration system not an entire cooling period has been captured.

Since a new chiller has been installed in December the energy consumption of the new system has to be monitored and compared to these measurements.

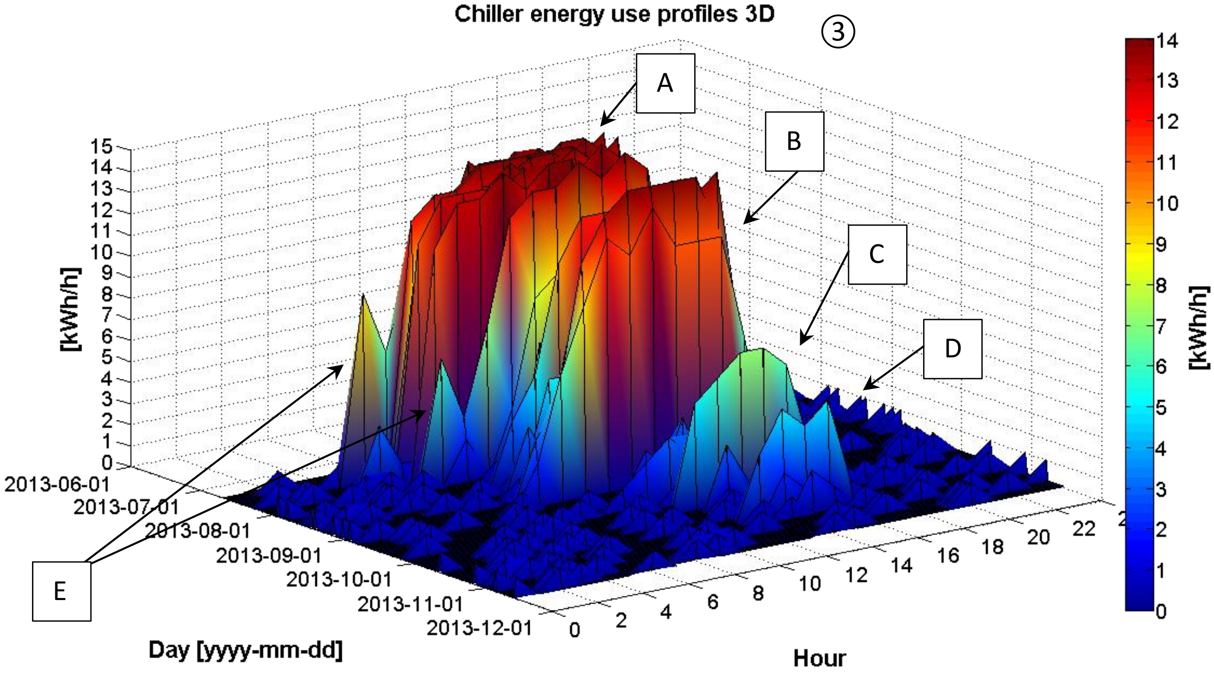


Figure 30: Development of the chiller daily energy profile in time containing (A) full day active at almost full capacity, (B) full day active at varying capacity, (C) almost a half day active at varying capacity., (D) only active in the afternoon at varying capacity, and (E) active cooling during the early start (Monday morning) program.

Lighting

Electrical energy use of the lighting is quite constant despite of the user's ability to switch during the day. Two different patterns have been found in the daily energy use by lighting. Figure 31 shows both, with the left figure representing the energy use day pattern with almost all lighting switched on (A, Figure 31). The right figure shows the energy use profile with reduced lighting switched on (B, Figure 31).

Maximum use is 13 kWh/h and minimum use is about 1 to 2 kWh/h during the night for lighting the escape routes and corridors.

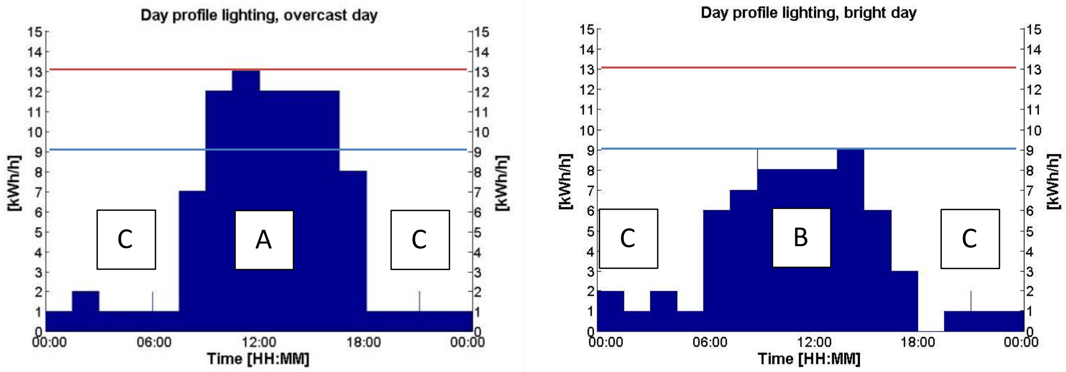


Figure 31: Energy use day profiles of the lighting, left a day with most lighting on during office hours (A) and minimum lighting on during the night (C), right only limited lighting on during office hours (B) and minimum lighting on during the night (C).

Daily energy profiles have been plotted stacked increasing by day-number (Figure 32). Most notable is the increased energy use during some nights, represented in light blue (D), corresponding to 4 kWh/h. No explenation for these findings has been found. Perhaps the building occupants forgot to switch off some of the lights.

The maximum of 13 kWh is represented in red, the minimum of 1 kWh in dark-blue.

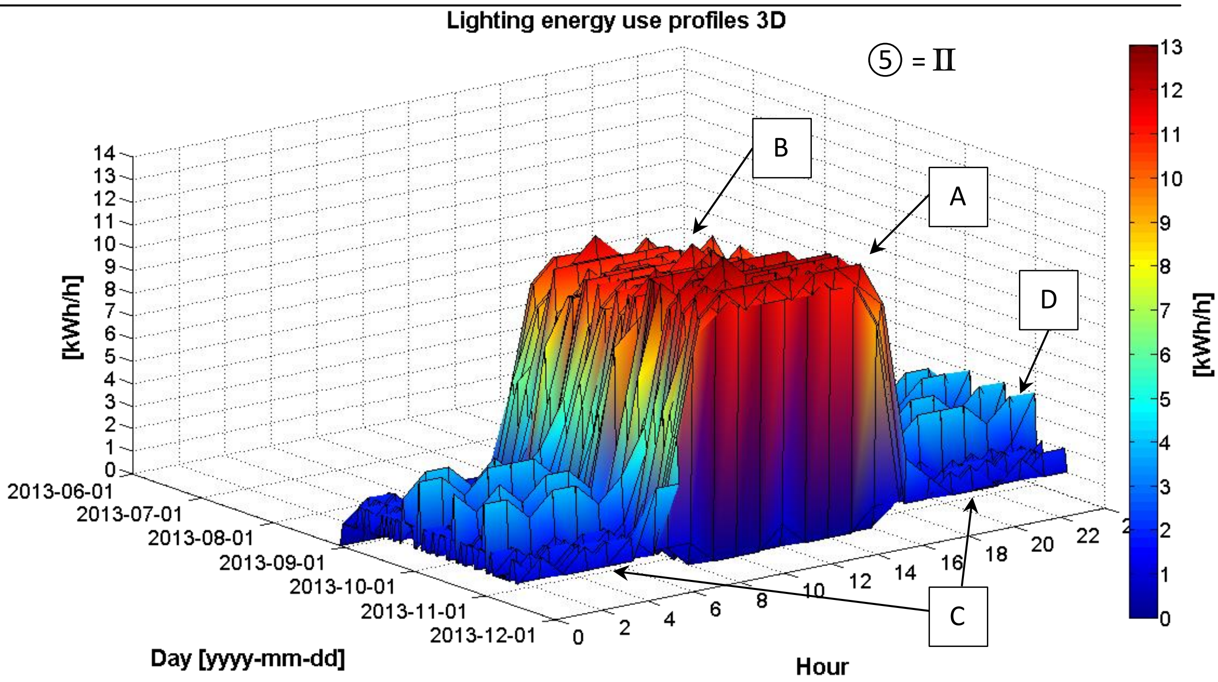


Figure 32: Lighting energy use profiles stacked by date containing (A) most lighting on, (B) limited lighting on, (C) normal night minimum lighting on, and (D) unexpected increase of lighting use during the night.

Remaining appliances

As already presented in section 3.1.2. 33% of the installed electrical power capacity consist of multiple appliances. These remaining appliances include:

- Office appliances;
- Alarm;
- Pantry and kitchen;
- ICT;
- Workshop;
- Elevator;
- Measurement equipment.

During the measurement period the energy use of following appliances can be stated as constant with a as good as steady energy 24/7 consumption pattern:

- Alarm;
- ICT;
- Measurement equipment.

The process these appliances use their energy for are uninterruptable processes and thus these appliances are unusable for energy management purposes.

To determine the energy use profiles of the office appliances the energy use of 13 workplaces has been monitored for 8 weeks. Appliances used on these workplaces are, laptops, laptop docking stations, PCs, monitors, radios, and phone chargers.

The measurement period are the calendar weeks from week 28 to week 35. Within this measurement period was the holiday period for most employees. It is found the holiday period of week 30 to 32 has a significant influence lowering the overall mean values by a minimum of 5%. The data is pictured for the total period excluding week 30 to 32 in Figure 33. Figure 33 presents the mean percent electrical energy use by the 13 workplaces for the days of an office workweek.

In this figure can be seen the Wednesday and Friday (red and purple) have a lower mean appliance use compared to the other workweek days. For the Wednesday this is mainly the case in the morning while in the afternoon the values approaching the other days. For the Friday the values during the entire day are remarkable lower.

Besides the mean values the standard deviation is determined as is found quite constant 30% during the day. A quite logical finding since an occupied workplace with the user working with the appliances scores 100% while an unoccupied workplace with appliances switched off represents 0%. In between the energy use of appliances can be in a standby modus. In the standby modus the screen of a laptop or desktop can be off or in sleeping mode while the PC still runs.

Electrical energy use of the office appliances is highly variable during the day. With an average mean appliance use of almost 35% for the Mondays, Tuesdays and Thursdays these days are about 10 to 15 % higher compared to the Wednesday and Friday.

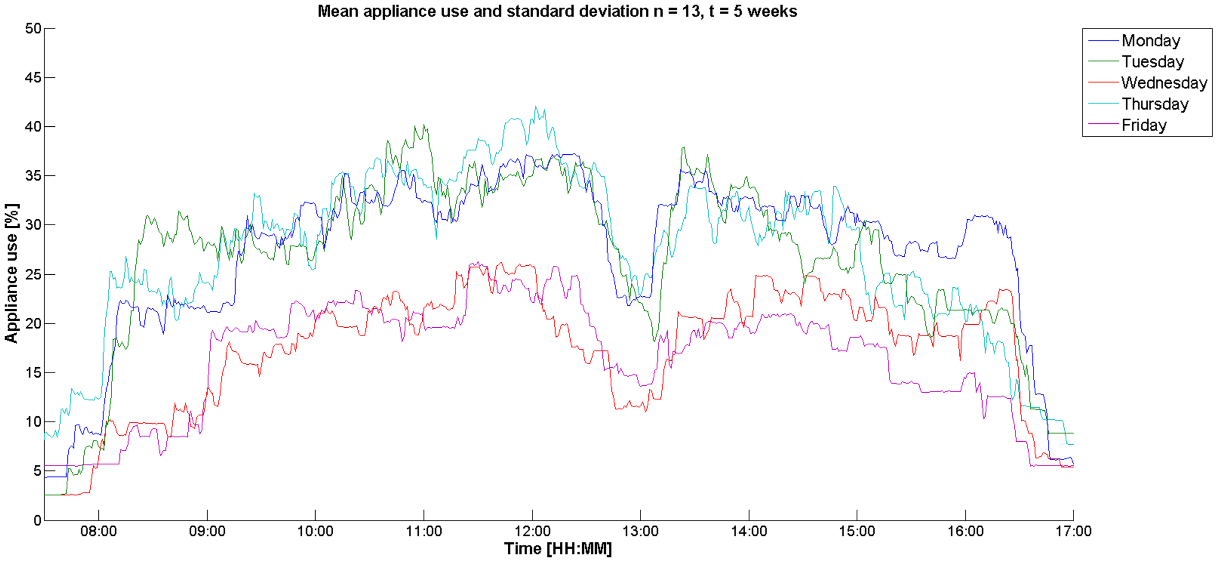


Figure 33: Mean percent appliance use profiles separated by day of the workweek measured from week 28 to week 35 excluding the holiday period of week 30 to 32.

Workplace and activity research done by the ABC Management group resulted in the findings shown in Figure 34. [Groen and Wilde, 2012]With around 30% computer work for the Monday till Thursday and an occupancy of around 60% the results seem similar to the findings of the measurements.

Also noticeable is the low appliance use on Friday. This shows also similarity with the findings of the measurements.

The lower mean office appliance use on Wednesday and Friday is mainly due to planning. This can change and does not necessary have to occur for the entire year.

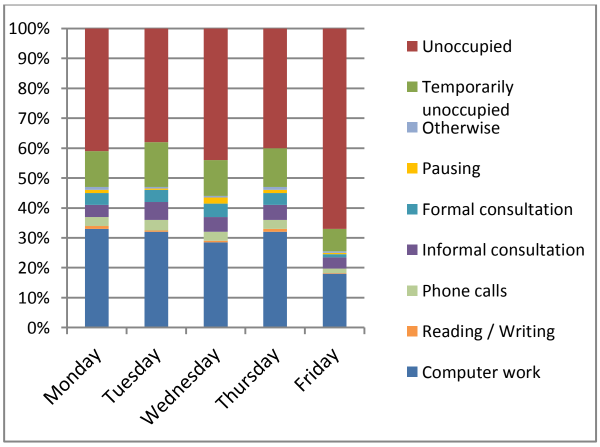


Figure 34: Occupancy of workplace and corresponding activities, modified from [Groen and Wilde, 2012].

With occupancy variations and occupant activity variations the energy use of the workplace appliances show a stochastic behaviour where the course is in the users behaviour.

The occupancy and energy use of corresponding office appliances by the users are also an internal heat load. The stochastic behaviour of the energy use indicates the internal heat load is also as variable in time.

A comparison of energy use by the user appliances on the workplace, the energy use by lighting in the room, and measured CO2 concentrations has been done. The most significant findings are presented in Figure 35.

Blue arrows indicate periods the CO_2 level drops due to no users occupancy in the room. In the same period the energy consumption on the workplace drops due to the monitor of the PC going on standby. The energy reduction of the monitor going on standby is shown by the green vertical arrow. When PCs would shut down or go into sleeping mode and lighting should switches off when nobody is in the room possibilities in saving electrical energy and also lowering cooling load can be achieved.

Also noticeable in the upper figure is the increase of almost the same amount of power (~20 W) as the day begins and decrease as the day ends before the PC is turned off. This is caused by the phone charger of the occupant.

Areas indicated with red arrows indicate moments with significant increase of CO_2 concentrations and energy use reduction due to the monitor going on standby.

Yellow arrows indicate a moment the room is occupied but no energy use is measured. In this period the occupant might have been doing no PC related work.

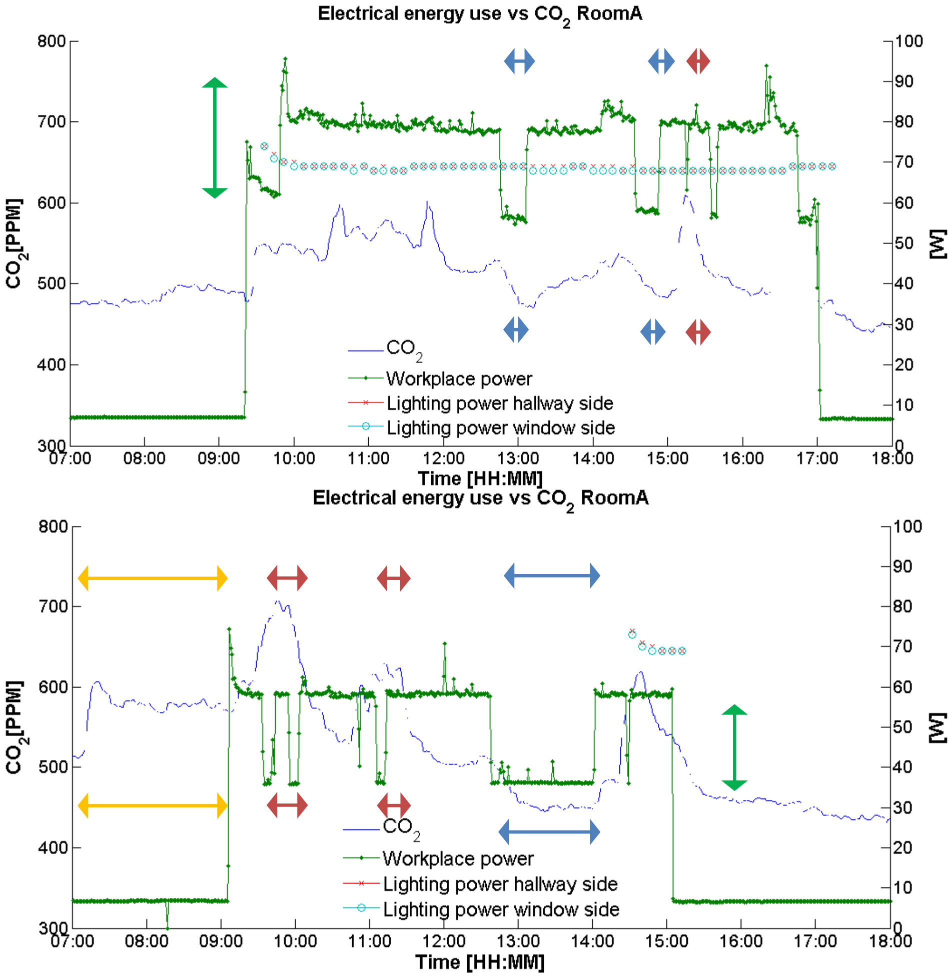


Figure 35: Energy use and CO_2 concentration room A for two random days, blue arrows indicate periods the CO_2 level drops due to no users occupancy, the energy reduction of the monitor going on standby is shown by the green vertical arrow, red arrows indicate moments with significant increase of CO_2 concentrations and lower energy use, yellow arrows indicate a moment the room is occupied but no energy use is measured.

The energy consumption of the uninterruptable appliances combined with the standby power use of all other connected is about 3 kWh/h, as can be seen in Figure 36, during the night (A).

About 6 kWh/h for appliances use with pikes to 9 kWh/h during the day (B) show the energy use during the day is variable. Equipment use in the workshop might have caused the biggest pikes (B).

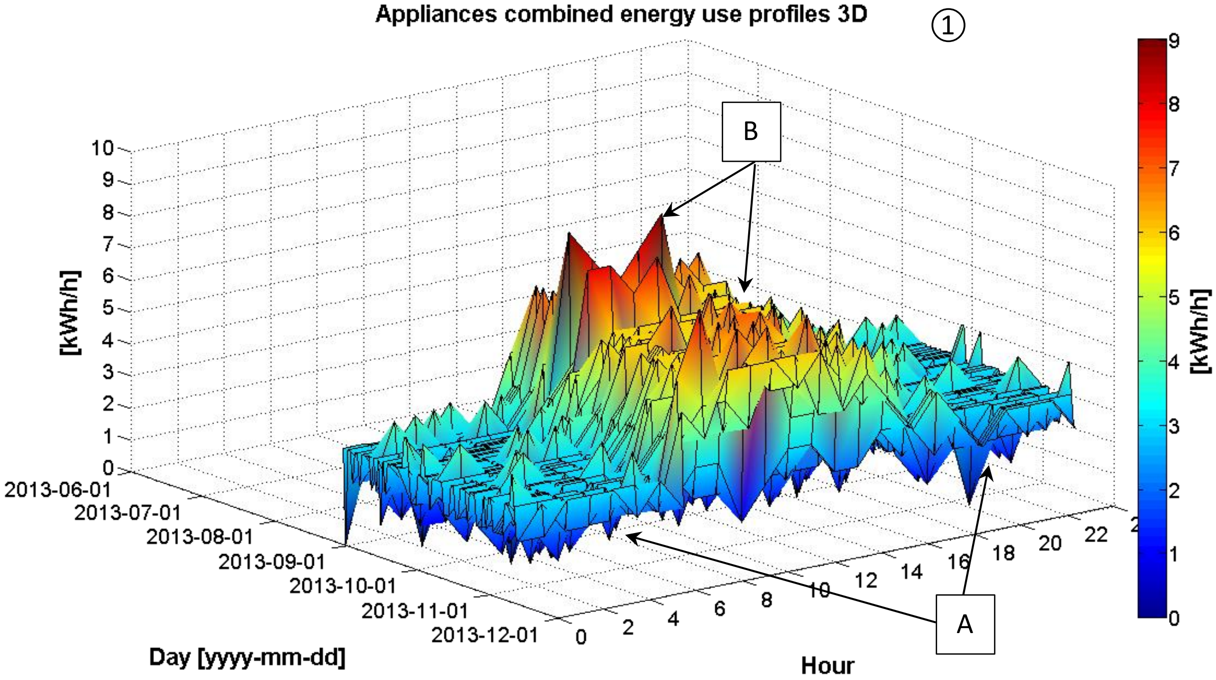


Figure 36: Development of the daily energy profile in time of the combined energy use of office appliances with constant energy use during the night (A) and stochastic energy consumption during office hours (B).

Total energy consumption

All the presented energy use profiles together form the total energy use profile as presented in Figure 37. Continuous main base load of the Kropman Breda office building is about 4 kW represented in dark-blue (A Figure 37). The maximum power use measured by the main connections $\mathrm{I} + \mathrm{II}$ during the project is 36 kWh/h, represented in red (B Figure 37).

The main energy use profile during the day looks quite stable (C) while some profiles of appliances can be clearly seen in the total profile.

With D the early start scenarios (AHU) are indicated as presented in Figure 27 and Figure 28 section 3.3.3.

The Energy use profiles of the Chiller presented before are also clearly visable (E).

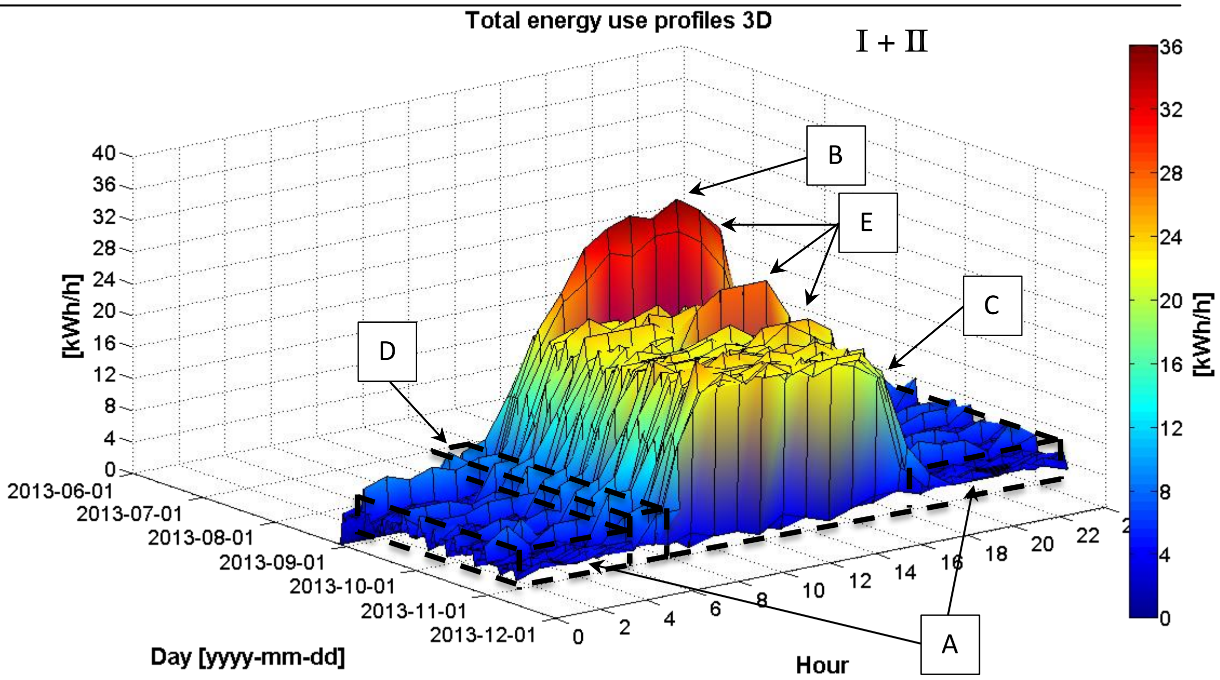


Figure 37:Total daily energy use profiles development in time containing (A) main base load during night operation, (B) maximum energy use during cooling period, (C) daily operation, (D) early start (Monday morning) operation, (E) energy use of the chiller on top of the daily operation energy use.

Despite the measurement period of the main connections (I + II) is not as long as the measurement period of the sub connections (②, ③, and ④), the variation in energy consumption over the period can be seen. Mainly the operation of the chiller stands out.

Figure 38 presents the distribution of energy consumption for the calendar weeks 36 and 42, giving a good indication in variation of the distribution of the energy consumption. Appendix J provides the tables containing the energy use figures as measured.

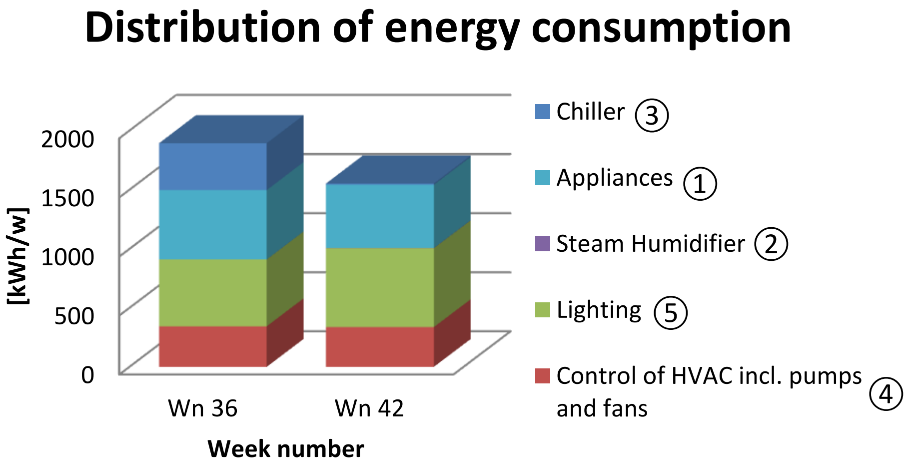


Figure 38:Total energy consumption for calendar week 36 and 42 divided by main groups.

Figure 38 shows the main energy users of the office building are; the lighting, HVAC control unit powering mainly the fans, and the chiller when active. The remaining office appliances combined form together almost an equal share in energy consumption compared to the main energy users.

Energy efficiency scenarios for the control of HVAC pumps and fans, lighting, and remaining appliances have the biggest potential since the energy use of these groups are quite constant main parts of the total consumption.

Energy consumption by chiller and humidifier are dependent on the weather conditions and with this related to the time of year. Even with the chiller active (week 36), the lighting consist of almost 25 % to 30 % of the total energy consumption. The energy use of the chiller during week 36 indicates when active use of chiller it is responsible for a significant part of the total energy use. During the summer the energy use by the chiller is even higher while during spring and autumn (as showed earlier in this section) it can be lower.

Compared to the ratio of the installed capacities presented in section 3.1.2., where lighting only consists of 11% of the total installed capacity, the energy consumption of the lighting is a main part of the total consumption (+/- 35%).

3.3.4 Conclusions energy measurements

Energy management scenarios like night ventilation can be clearly seen in the energy use profiles. The running scenarios determine which energy management adaptions have significant potential.

Main consuming major electricity load groups are lighting, HVAC control unit, and chiller when active. The lighting and HVAC control unit have rather static and stable energy consumption paters which vary little. The variation of the energy profiles of these two groups are mainly between running scenarios. The variation of the energy profiles of the chiller are seasonal due to the dependency of the weather.

The energy use of the remaining appliances however has a quite stochastic behaviour. This is mainly due to the behaviour of the occupants. These loads are besides electrical loads also internal heat loads.

Energy consumption of the installed components has a different distribution compared by the connected capacities.

With the presented findings savings by energy management scenarios have the biggest potential for lighting, HVAC fans, and in active use the chiller. The first two are continuous active through the year and claim the biggest share in the energy use.

For the lighting and remaining appliances applies, they both exist of a large number of small components. The lighting system of the Kropman office consist of 250 lighting fixtures. While the remaining appliances consist of seven sub groups each consisting specific components. These sub groups contain; the elevator, workshop, ICT, pantry and kitchen, alarm system, office appliances, and the measurements (as presented in section 3.1.2). From these seven groups the office appliances consist of the most components such as; laptops, PCs, monitors, phone chargers and others. Energy management based on occupancy has significant potential for the lighting and office appliances, since they can easily be split up per room or zone, improving the energy efficiency.

Considering the HVAC control unit which controls the building systems by sending the control signals, supplies the electrical power to the fans and pumps, and facilitates the communication signals to the BAS and all connected components. Energy efficiency scenarios have their potential in the energy use of the fans which use 5 kW of the normal operating 6 kW.

3.4 VABI Elements model

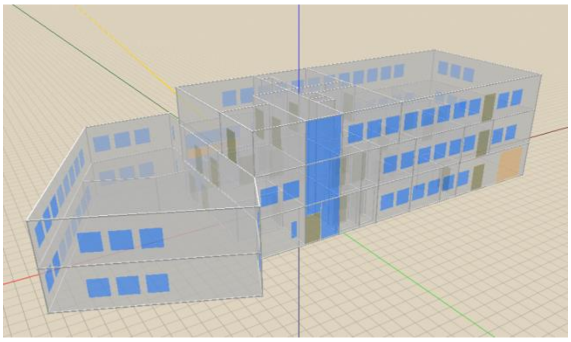


Figure 39: Case study building in VABI Elements.

For simulations of the experiments, presented in section 4, with the HVAC, chiller and lighting VABI Elements is used.

The simulations will be used to assess the influences of the energy management on the indoor comfort.

A model of the case study building has been built based on the building drawings, technical information, and current situation obtained during on site inventory.

A climate file of the KNMI measurement station Gilze-Rijen has been obtained from VABI for the measurement period. This climate file is used in the simulations. Gilze-Rijen Military airport, where the KNMI weather station is situated, lies about 17 km distance from Kropman Breda.

Comparison of model results with measurements

The model results are compared to the measured values to validate the used model.

Error! Reference source not found. shows the measured temperatures of room A and alculated temperatures by the VABI model for two weeks. The measurement values have been given a upper and lower boundary (Red) for a quick assessment of the accuracy of the modelled temperatures.

The calculated temperatures stay in mostly within the boundaries. The weekends are indicated with blue ovals. The calculated temperatures deviate more in the weekends from the measured values.

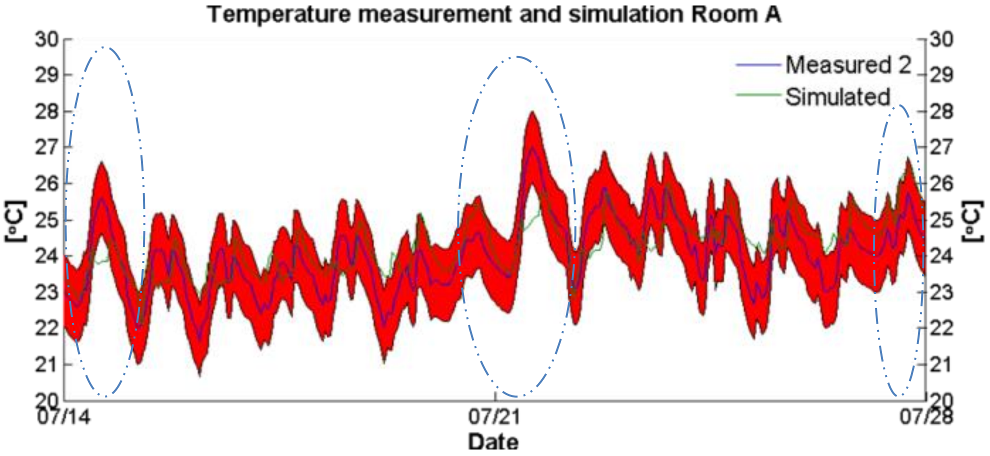


Figure 40: Comparison between the measured temperatures for room A and the simulated temperatures in VABI. Blue line is the measured temperature at the desk with in red an offset of 1 degree Celsius. The green line represents the calculated temperatures

Temperature difference between measurement and calculations are presented in Table 7. Here the maximum and mean are presented for the full period, the normal office days, and for only the normal office hours during the period.

Table 7: Statistical comparison measured and calculated temperatures.

Description	Maximum	Mean
dT Simulated and Measured [K]	2	0.63
dT Simulated and Measured workdays only [K]	1.7	0.63

dT Simulated and Measured office hours [K]	1.7	0.68

The maximum temperature difference is in higher in the weekends as stated before. The mean temperature difference is about 0.6 degrees Celsius which is considered acceptable for the purpose of the model.

Simulations with the VABI model will only be used to compare the results of the scenarios (section 4) with the original situation.

Results of current situation

The simulation cover the entire summer period. Results of the calculated comfort temperatures are shown for July and August since these are the most critical months of the summer and these months the earlier explained measurements took place.

The ATL-Chart of room A is used to assess the comfort, since room A is the south orientated room. In summer the comfort in this room is more influenced by direct solar loads compared to room B. Room B also has more occupancy differences during the day compared to room A. As shown in section 3.3.3 the internal loads can vary due to the use of appliances and occupants activity. Which will influence the calculated comfort and thus representation of the indoor comfort.

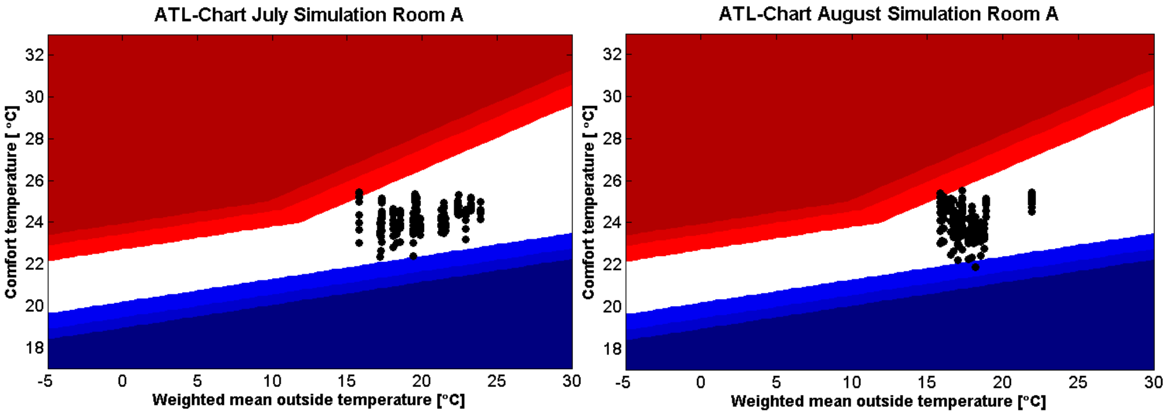


Figure 41: ATL-Chart of room A over the period July on the left and over the period August on the right, simulation current situation.

Figure 41 shows the simulated comfort temperatures by the VABI Elements model for room A. Comparing these charts with the ATL-Charts based on the measurements presented in section 3.3.1 it is found the model predicts slight higher temperatures in the morning and slightly lower temperatures in the afternoon.

Window solar screen simulation can be the reason for this. In practise the solar screens are almost continues left on 2/3 closed position while in the model they are is closed 100% by an intensity of 300 W/m² solar irradiation or higher.

Also the negatively influence by direct solar irradiation on the measurement equipment, as presented in section 3.3.1, can be the reason for lower simulated comfort temperatures in the afternoon.

Maximum occurring temperature during office hours simulated for room A is 25.5 degrees Celsius. Table 8 present the PMV exceeding hours for room A. As can be seen Class B criteria are not exceeded.

Table 8: PMV exceeding hours room A, simulation current situation.

	Class A 0.2 / -0.2	Class B 0.5 / -0.5	Class C 0.7 / -0.7
PMV exceeding hours	115	0	0

Remarks on the model

In the used model some assumptions had to be made since these could not fully be backed up.

The time of use for each room is chosen based on opening hours of the office. However the measurements of the appliance use and CO_2 concentrations (section 3.3.3) showed a more stochastic behaviour. Occupancy and occupant activity can differ.

Material properties are assumed based on the generally used building materials in the Netherlands for the period of built.

The use of solar screens is manual and thus can differ compared to the used control of solar screens in the model.

Sensitivity analysis can be done in the future to identify the impact of the assumed parameters and accuracy of the model.

3.4.1 Conclusions VABI model

A model is always an approximation of the reality. Nevertheless the used VABI model is quite accurate for the estimation of exceeding hours. Most parameters which had to filled in the model could be backed up with building drawings, technical information, on site inventory and measured values. VABI provided the climate file of this year up to 18-11-2013. The climate file contains values measured by KNMI station Gilze Rijen (350).

The calculated comfort temperatures and energy consumption of the modelled energy management scenarios will be used to compare with the original values presented in this section. The results of the experiments will be presented in section 4.

Sensitivity analysis can be done in future research to identify the impact of the assumed parameters and accuracy of the model.

VABI Elements calculates only the hourly values. In the future another model can be used to obtain more detailed simulations with a smaller time step.

3.5 Discussion and conclusions

The case study building presented in this chapter operates as desired to deliver an comfortable indoor climate. Comparison of the data of calculated PMV, PPD, and ATL-Charts confirms this.

Considering the measured indoor climate the current situation leaves room for energy savings by allowing higher temperatures. However it would be better to determine the comfort temperatures for multiple rooms on multiple floors to come to a better insight for energy savings based on the acceptance of comfort temperature.

Air velocity measurements should be included in the future for better estimation of the PMV and PPD values.

The ATL method used to evaluate the acceptance of the indoor climate and model used for simulations are based on hourly values. Changes within an hour are left out the consideration. However changes in temperature are quite slow (relative small variation over one hour) in a continuous controlled building. Energy management scenarios might cause influences which have an effect on a faster change in indoor temperature.

Already adopted energy management scenarios like night ventilation can be clearly seen in the energy use profiles. The running scenarios determine which energy management adaptions have significant potential.

Main consuming major electricity load groups are lighting, HVAC control unit, and chiller when active. The lighting and HVAC control unit have rather static and stable energy consumption paters which vary little. The variation of the energy profiles of HVAC control unit are mainly between running scenarios. The variation of the energy profiles of the chiller are seasonal due to the dependency of the weather.

The energy use of the remaining appliances has a quite stochastic behaviour. This is mainly due to the behaviour of the occupants.

Energy management based on occupancy has significant potential for the lighting and office appliances, since they can easily be split up per room or zone, improving the energy efficiency.

Considering the HVAC control unit which controls the building systems by sending the control signals, supplies the electrical power to the fans and pumps, and facilitates the communication signals to the BAS and all connected components. Energy efficiency scenarios have their potential in the energy use of the fans which use 5 kW of the normal operating 6 kW of all HVAC control unit connected.

The used VABI model is quite accurate for the estimation of exceeding hours.

The calculated comfort temperatures and energy consumption of the modelled energy management scenarios will be used to compare with the original values presented in this section. The results of the experiments will be presented in section 4.

Sensitivity analysis can be done in future research to identify the impact of the assumed parameters and accuracy of the model.

4 Chapter 4 Analyse of results

This chapter provides the results of the experiments and simulations of the energy management scenarios.

In this study the main energy consumers of the office building are detainment to be the HVAC fans, lighting, and chiller as described in section 3. With these main energy consumers energy management scenarios are tested to evaluate the possibilities for smart office energy management in the Smart Grid.

4.1 Energy management scenarios

The three energy management scenarios are investigated first separately and second all combined. The scenarios consist of; air-flow reduction with the HVAC fans, lighting reduction, and chiller interruption.

The first experiment is reducing the air-flow of the constant volume air handling unit system. The initial and reduced air-flow is measured together with the corresponding CO_2 concentrations and fans energy use. With the goal to identify when and to what extend it is acceptable to reduce the air-flow.

The second experiment is reducing the artificial lighting based on use of natural light. An experiment to identify the possibility of reduction of artificial lighting is based on the illumination of natural light. Light intensity entering the window and on the workers desk is measured for a south and north orientated room. With the goal to identify whether it is acceptable to reduce artificial lighting use based on workplace light intensity.

The third experiment is shifting chiller operation. The comfort temperature in the rooms, outside temperature, global radiation, and system temperatures have been measured. The initial and shifted operation have been simulated together with the corresponding comfort temperatures and energy use. The goal is to identify when and to what extend it is acceptable to shift the chiller operation.

And finally the last energy management scenario is a combination of all the above. This scenario is simulated finding the corresponding comfort temperatures and energy use. The goal is to identify the influence of the scenarios on each other and if the combination is better acceptable.

4.2 Air-flow reduction

The ventilation system in the office is designed for two functions, first, refreshing the air in the building and second, to transport the desired cooling capacity into the building.

The Air-flow capacity in a building is designed for transportation of full cooling capacity of an office while in practice full capacity is seldom needed.

For the heat transport per unit of time the next equation is generally true:

$$\Phi = q_v \cdot \rho \cdot c_p \cdot \left(T_{out} - T_{in}\right)$$

$$q_v = flow \left[m^3 / s\right]$$

$$\rho = density \left[kg / m^3\right]$$

$$c_p = specific\ heat \left[J / \left(kg \cdot K\right)\right]$$

$$T_{in} = temperature\ transport\ medium\ in \left[K\right]$$

$$T_{out} = temperature\ transport\ medium\ out \left[K\right]$$

Reducing the air-flow of the constant volume air handling unit system is thus limited by the air refreshment and desire for cooling. Since a flow reduction directly means a reduction in heat transport per unit of time.

The proportional change in rotation speed of the fans is equal to the proportional change in ventilation rate. Reduction of the fans speed by 25% means also a 25% reduction in ventilation capacity. While reduction of the fan speed proportion behaves to the third power compared to the proportion in energy consumption.

$$n_1 : n_2 = q_{v1} : q_{v2}$$

$$\left(n_1 : n_2\right)^3 = P_1 : P_2$$

$$n = fan\ speed\ [rps]$$

$$P = power\ [W]$$

4.2.1 Experiments

As presented in section 3 the AHU fans are powered by the HVAC control unit. The energy consumption when active is 5 kWh/h as shown by the difference in day operation and night ventilation.

Air supply of the design and redesign (2006) values have been compared. The ventilation systems has been adapted in 2009, which no records have been found of. Measurements have been done and are compared to known values. The measured air velocities are quite similar to the design and redesign values.

The extend of the reduction is based on the minimum required air refreshment in the most occupied room. Reduction of air refreshment up to 25% results in almost 10 [l/s pp] air refreshment in the highest occupied room. This corresponds to 100% relative performance given in section 2. The air velocities also have been measured when running on the reduced capacity. Appendix I provides the measured values for each room in a table.

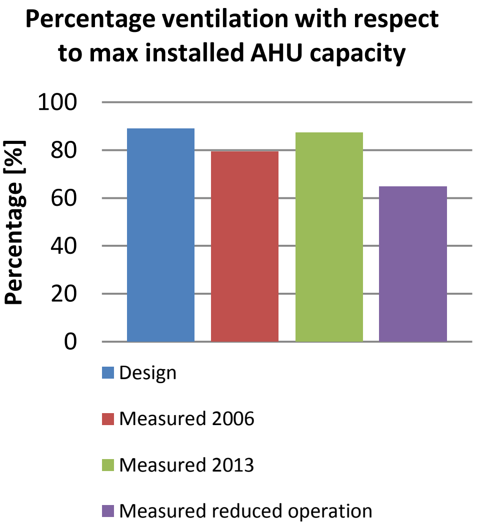


Figure 42: Percentage measured ventilation capacity with respect to installed capacity.

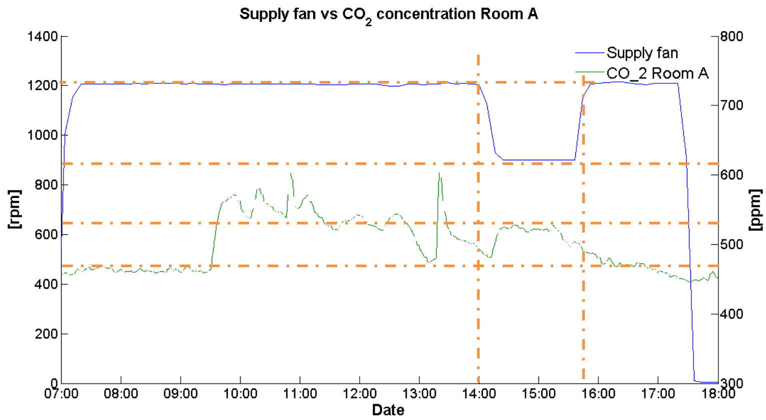


Figure 43: Supply fan speed in rpm and CO_2 concentrations in ppm for room A, a reduction of fan speed and ventilation rate causes the CO_2 concentration to rice by 200 ppm.

Influence of the ventilation capacity reduction on indoor temperature has not been found during the experiments.

The building systems maintain to control the desired lower inlet air temperatures.

The measurements with reduction of ventilation capacity occurred in September and October. Since the ventilation capacity is designed on the cooling load a simulation is used to indicate the influence of the reduction in the months July and August. These months have higher cooling demand.

A direct influence on the CO_2 concentrations has been measured and is presented in Figure 43. An increase of almost 200 ppm is almost directly noticeable for room A (1 person office).

Energy use reduction measured is shown in Figure 44. On the left te reduction in fan speed and on the right te corresponding energy use per hour. A reduction of 2 kWh/h is noticeable on a total energy use of 5 to 6 kWh/h.

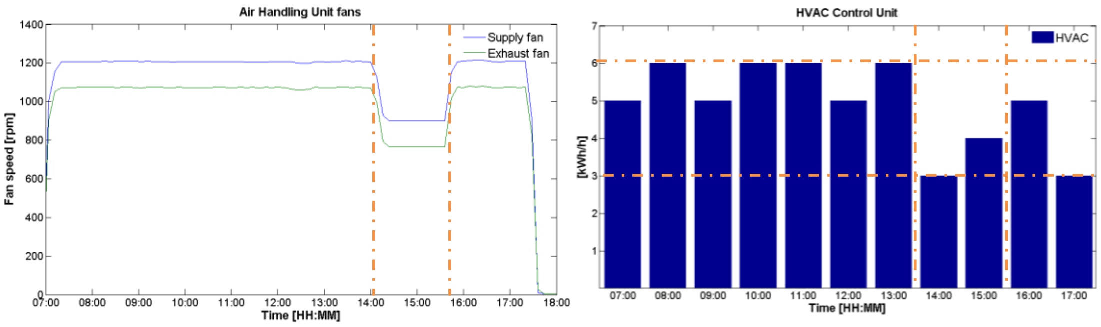


Figure 44: Supply and exhaust fan speed in rpm (left) and HVAC control unit energy consumption kWh/h (right), of fan speed and ventilation rate causes the hourly energy consumption to decrease by 2kWh/h.

For estimation of the energy use reduction over a longer period simulations have been used.

4.2.2 Simulations

A reduction of ventilation system by 25% is simulated using the VABI model described in section 3.4. The simulation cover the entire summer period. Results of the calculated comfort temperatures are shown for July and August since these are the most critical months of the summer and these months the in section 3.3 explained measurements took place. The calculated comfort temperatures of room A are presented in an ATL-Chart to compare with the original situation presented in section 3.4.

Figure 45 shows the simulated comfort temperatures by the VABI Elements model for room A.

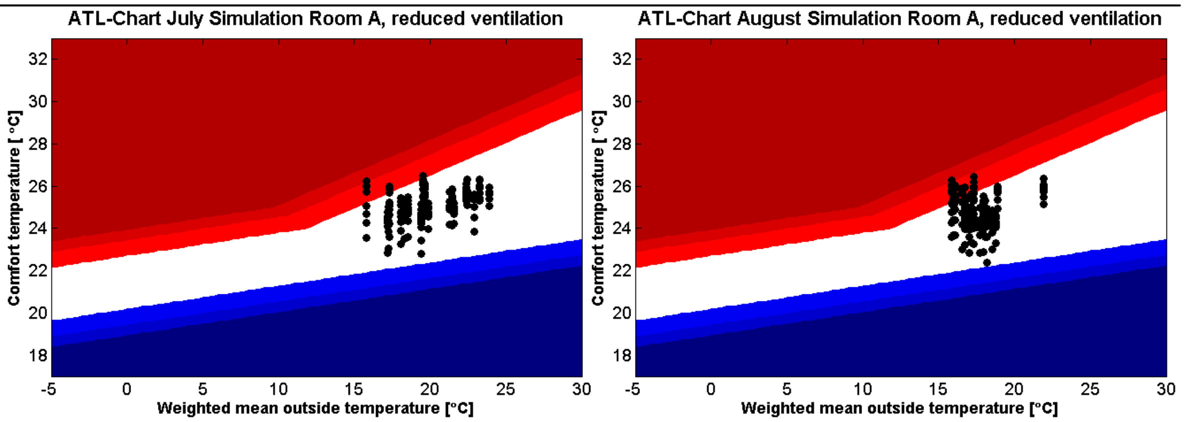


Figure 45: ATL-Chart of room A over the period July on the left and over the period August right, simulation reduced ventilation, both show the comfort temperatures stay mostly within the comfort class B.

Comparing these charts with the ATL-Charts of the original situation presented in section 3.4 it is found the model predicts slight higher temperatures in the afternoon. Still the comfort temperatures stay most of the time within class B boundaries. Only a few exceeding's of class B occur while class C is not exceeded.

Maximum occurring temperature during office hours simulated for room A is 26.5 degrees Celsius. This is slight higher compared to the original situation. Table 9 present the PMV exceeding hours for room A with reduced ventilation capacity. Class B criteria are exceeded while no exceeding's of class C occur.

Table 9: PMV exceeding hours room A, simulation reduced ventilation.

	Class A 0.2 / -0.2	Class B 0.5 / -0.5	Class C 0.7 / -0.7
PMV exceeding hours	350	60	0

The VABI model does not calculate the primary energy use for the air handling unit fans. Energy needed for heating and cooling of the ventilation air are calculated by the model. Due to a reduction of ventilation capacity the model predicts an energy use reduction of 22% for cooling.

The simulations have not been used for the winter period. This could be done in future work to find the reduction in energy use for heating and humidification.

4.2.3 Conclusions air flow reduction

Reducing the air-flow by 25% results in an electrical energy use reduction of the fans by 2 kWh/h. Simulations show an decrease in cooling energy use by 22% while maintaining the comfort most of the time within class B. Except for the days full cooling capacity is needed, during these days the comfort class C is achieved.

Reducing the air-flow with more than 25% is not investigated since the most occupied room is kept as a boundary by supplying at least 10 l/s fresh air per person.

Lower ventilation rates also imply lower air speeds from the air supply in the room. This can lead to the perception of a less desirable indoor climate since air speed is one of the parameters estimating the PMV.

Also lower air speeds of the air supply in the room can cause a different mixing pattern which can cause discomfort in cooling season. In cooling season the air supply can be 16 degrees Celsius. Occurrence and the magnitude of this can be a point of further research.

This study focuses on the summer period while this scenario implies possibilities for winter operation which could be done in future work. It is expected to find reduction in energy use for heating and humidification by reducing the ventilation capacity.

4.3 Lighting use reduction

The artificial lighting system in the office is designed to provide sufficient light intensity on and around the work area of the office worker.

With natural light entering the room through the windows the desired lighting levels could already be reached. Reducing the artificial lighting use in such a situation also leads to reduction of internal heat load. While together with the natural light entering the room the external heat gain in form of solar radiation enters the room.

Light intensity entering the window and on the workers desk is measured for a south and north orientated room. The goal is to identify when it is possible to reduce artificial lighting use based on workplace light intensity provided by natural lighting.

4.3.1 Experiments

During the period from 22 July till the 10th of August the lighting at the window side in room A and room B is kept out. During this period the light intensity entering the window and on the desk is measured to verify the potential for natural lighting.

The lighting consist of two TL lighting groups, having each two TL lighting bars. One lighting group is located at the hallway side of the office room and the other is situated at the window side of the office room above the workplace. Positions of the lighting equipment can be found in the floor plan presented in Appendix E.

The illuminance levels measured on the desk in room A and room B are presented in Figure 46.

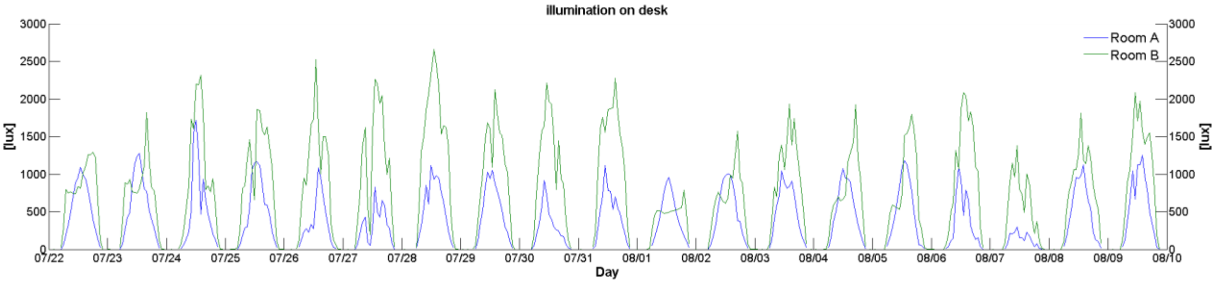


Figure 46: Illuminance levels measured on the desk for room A and room B from 22-07 till 10-08.

In room A 60% of the time a level of 500 Lux or higher on the desk is obtained during daily working period from 7:00 hour till 18:00 hour. Corresponding natural lighting levels measured vertical in front of the window entering the room are 7792 Lux or higher.

These lighting levels occur with an horizontal solar irradiation of 248 W/m² or higher. Based on the KNMI data of 2013 this occurs during 36% of the office hours in 2013.

A level of 300 Lux or higher on the desk is measured 75% of the time during daily working period from 7:00 hour till 18:00 hour. Corresponding natural lighting levels measured vertical in front of the window entering the room are 4980 Lux or higher. Which occur with an horizontal solar irradiation of 150 W/m² or higher. Based on the KNMI data of 2013 this occurs during 50% of the office hours in 2013.

As can be already seen in Figure 46 illumination levels measured on the desk in room B are significant higher. This is mainly due to the use of solar blinds in room A. In room A the solar screens were closed for 2/3 of the window area. In room B no solar blinds are in front of the windows.

This resulted in a level of 500 Lux or higher on the desk for 91% of the time during daily working period from 7:00 hour till 18:00 hour. The natural lighting levels measured vertical in front of the window entering the room are 2227 Lux or higher. With an horizontal solar irradiation of 67 W/m² or higher

With 98% of the time a level of 300 Lux or higher on the desk during daily working period and corresponding lighting levels measured vertical in front of the window of 1632 Lux or higher. These occur with an horizontal solar irradiation of 47 W/m² or higher.

Distribution of luminance levels in the room are not measured and uniformity on the working place cannot be assessed. Future work should take the distribution of the light intensities into consideration.

Also the user acceptance is only based on the lighting levels from code. Future work should include a better representation of the user acceptance.

4.2.2 Simulations

Reducing the artificial lighting use is simulated for the summer period using the VABI model. Figure 47 presents the calculated comfort temperatures of room A in an ATL-Chart. Comparison with the original situation presented in section 3.4 lower temperatures are found overall.

With lower internal heat gain due to the reduced use of artificial lighting lower comfort temperatures can be achieved. Resulting in no exceeding's of the upper boundary of class A. The lower boundary of class A however is exceeded for some days.

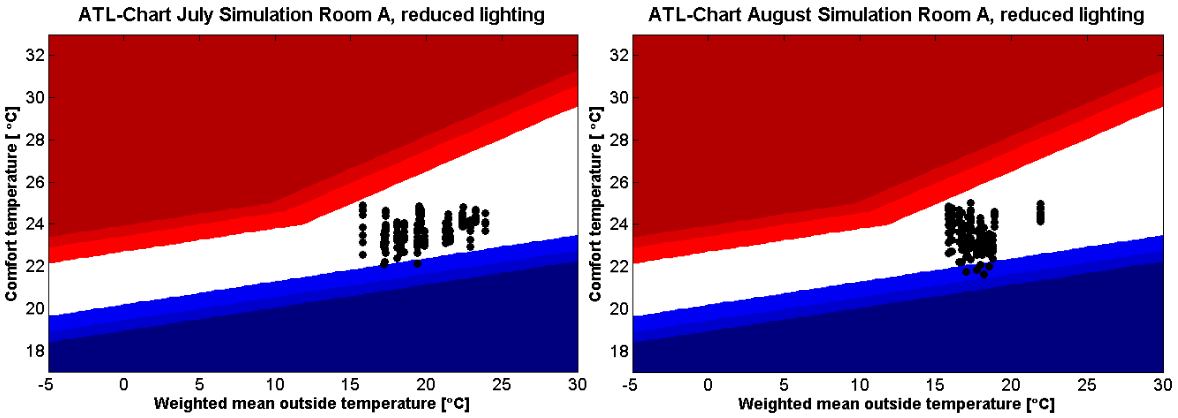


Figure 47: ATL-Chart of room A over the period July on the left and over the period August right, simulation reduced lighting, both show the comfort temperatures stay mainly within the comfort class A.

The reduction of artificial lighting use also result in lower exceeding of PMV comfort classes. Table 10 shows class B is not exceeded while class A has just a few exceeding hours.

Table 10: PMV exceeding hours room A, simulation reduced lighting.

	Class A 0.2 / -0.2	Class B 0.5 / -0.5	Class C 0.7 / -0.7
PMV exceeding hours	26	0	0

The energy use of the lighting is not calculated by VABI, only the energy use for cooling and heating. The electrical energy reduction is calculated by hand based on the installed components power. An electrical energy use reduction of 16% can be achieved considering only the small office rooms.

In case the open office rooms of the first floor and the second floor are also considered for artificial lighting reduction the electrical energy use reduction can even be 30%.

Acceptance and illuminance levels in the open office rooms should be assessed in future work.

With the reduction of artificial lighting use the simulation shows there is no cooling demand reduction. Only a better indoor climate is achieved.

4.3.3 Conclusions of artificial lighting use reduction

Artificial lighting use reduction results in an electrical energy use reduction of 16%. In case the open office rooms of the first floor and the second floor are used for artificial lighting use reduction the energy use reduction can increase to 30%.

This reduction can be used in about 36% of the office hours a year based on the year 2013.

With the reduction of artificial lighting use the simulation shows there is no cooling demand reduction. Only a better indoor climate is achieved.

Distribution of luminance levels in the rooms are not measured and uniformity on the working place cannot be assessed with current setup. Future work should take the distribution of the light intensities into consideration.

User acceptance is only based on the lighting levels from code. Future work should include a better representation of the user acceptance.

4.4 Shifting chiller operation

The chiller is designed for high summer for which the full capacity will be needed, for periods were not the full capacity is required, it might be possible to shift the operation of the chiller. The goal is to identify when and to what extend it is acceptable to shift the chiller operation considering the effects on the thermal comfort in the building.

4.4.1 Experiments

With an 14 kW electric power the system produces relative high peaks when switching on. The duration of these peaks determine the energy consumption. The peak loads produced by the chillers make this system responsible for about 20% of the energy use over a time period of a week as presented in section 3. The chillers energy use behaviour is dependent on the weather.

In order to find if it is possible to shift the operation and when this is possible first the active operation is sorted by clock hour. Second, active operation of the chiller is categorised by the number of running hours per hourly energy use. Together with the minutes of inactivity per hourly energy use.

During the measurement period from 10th of July till 31 October, 374 hours of active cooling are measured. Figure 48 presents the operative hours sorted by the clock hour based on the measurements and limited by the measurement period. As can be seen the chiller is most active in the afternoon.

Considering the months April, May, and June which also have the potential of active chiller operation the activity of the chiller will still be most in the afternoon.

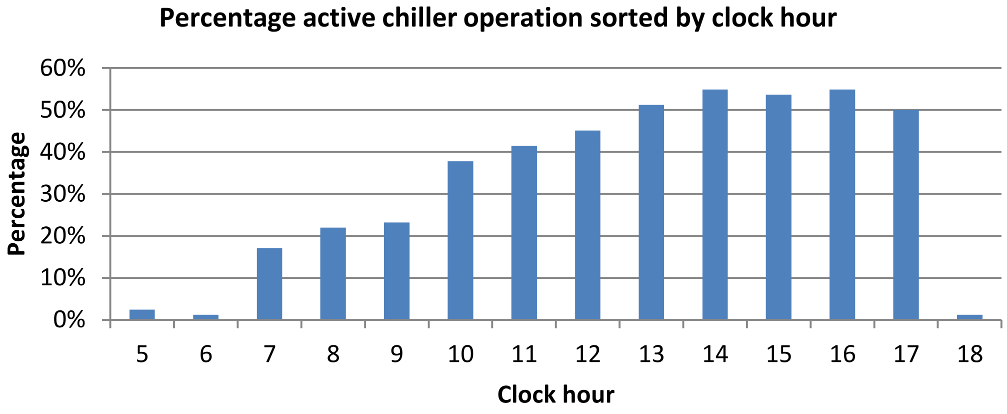


Figure 48: Percentage active chiller operation on specific clock hour during the measurement period (10-07 till 31-10).

With the knowledge the chiller operates mostly in the afternoon the duration of the operation and corresponding hourly energy use are sorted. Figure 49 presents the number of active operation sorted by the hourly energy use.

In this figure the blue bars indicate the number of running hours for each hourly energy consumption. While the red line indicates the minutes the chiller is inactive during one corresponding hour.

For example, with and energy use of 9 kWh/h, the chiller is not active for about twenty minutes during the hour. This provides the opportunity to shift the chillers active operation.

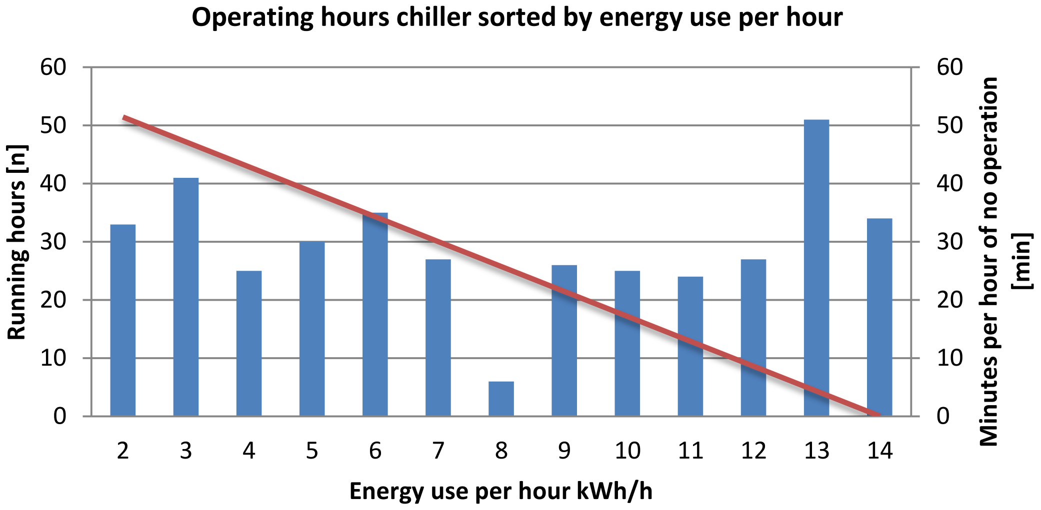


Figure 49: Operating hours chiller sorted by output per hour with in red the minutes per hour of no operation (10-07 till 31-10).

Sorting the chillers active operation by capacity groups and corresponding running hours, it is found that 36% of active operation is on 11 kWh/h to full capacity. Which gives almost no room for shifting the chiller operation without influencing or even compromising the indoor thermal climate.

Looking at the inlet and outlet temperature of the chiller, four typical running scenarios can be found. Figure 50 shows the inlet and outlet temperature of the four typical running scenarios of the chiller.

Running continuously on full capacity is indicated with the letter ‘A’. The inlet and outlet temperature have the entire active period a maximum temperature difference.

For the running scenario indicated with ‘B’, the chiller first operates in cyclic behaviour which changes in continuous full capacity in the early afternoon, ending the day in cyclic behaviour. The cycles can be clearly seen in the fluctuations of inlet and outlet temperature.

The running scenario indicated with ‘C’ shows a full day of cyclic (on off) behaviour. In the morning the cyclic behaviour shows longer off periods compared to the afternoon. In the afternoon the cyclic behaviour shows quite fast on off changes.

The last typical running scenario is indicated with ‘D’ and shows only cyclic behaviour in the afternoon.

From these typical running scenarios scenario A leaves no room for shifting chiller operation without influencing or even compromising the indoor thermal climate. While for scenario B the time to shift the chillers operation is most limited compared to C and D.

With almost 36% of operation in noncyclic behaviour this leaves room for shifting chiller operation in the remaining 64%. The influence of chiller operation interruption on the indoor climate is simulated with the VABI model.

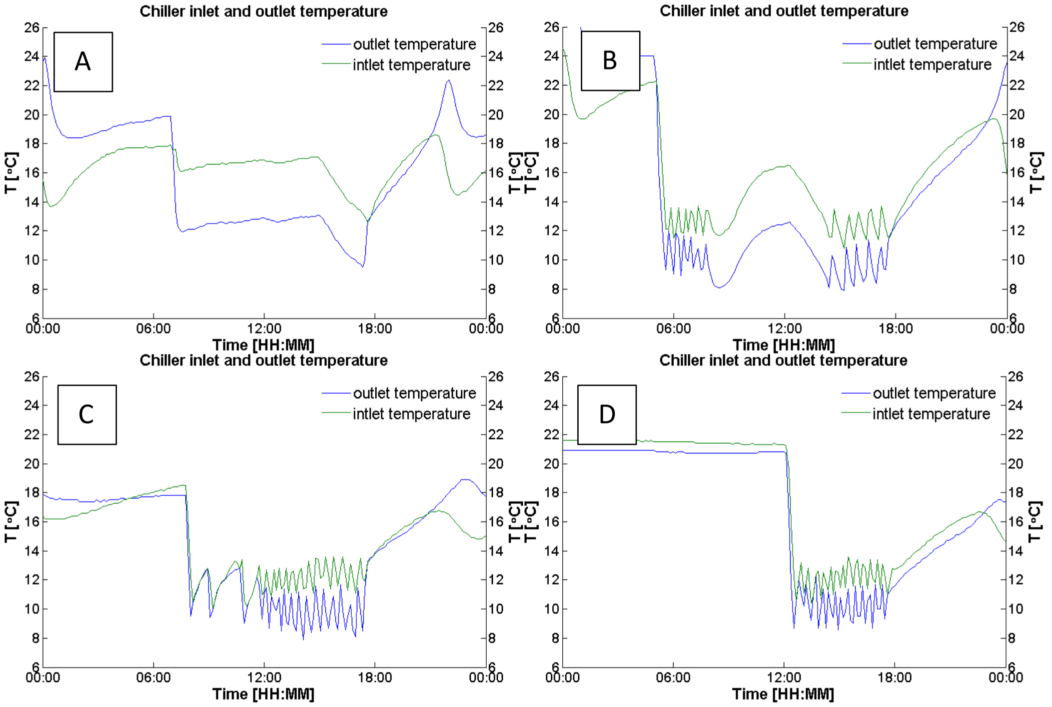


Figure 50: Chiller input and outlet temperature day profiles, upper left (A) full day active at almost full capacity, upper right (B) full day active at varying capacity with on off sequences in the morning and late afternoon, lower left (C) full day on off sequences with varying capacity in the morning and in the afternoon, lower right (D) only active in the afternoon with on off sequences.

Chiller behaviour is in on- off-cycles 64% of the operating time. These cycles operate within the system boundary’s. One of the system boundaries is the lowest acceptable output temperature of the chiller which is 6 degrees Celsius. The cycle time the chiller stays on is depending on this lowest temperature while the off period of the cycle is at least 5 minutes.

This is a pre-set value to make sure the chiller is not switching on and off to fast. The cooling system is equipped with a buffer which is designed to smoothen the systems control. The thermal capacity (buffer) of the system and cooling demand determine the time the chiller stays off in case the off time is longer than 5 minutes.

As stated before the chillers operation is dependant of the weather. Therefore the hourly energy use is compared with the temperature and solar irradiation measured. Figure 51 shows the relation between the hourly energy use and outside temperature in red. The hourly energy use and solar irradiation is shown in blue.

The red area indicated with 'A' shows the linear relation between the outside temperature and the hourly energy use. 'B' indicated the chiller runs on full capacity with outside temperatures of 28 degrees Celsius and higher.

For the relation between the solar irradiation and hourly cooling demand is found it is less dominant compared to the outside temperature. As can be seen by the wide spread of the blue are indicated with 'C'. From the blue are indicated with 'D' the chiller runs on full capacity when solar irradiation is higher than 700 W/m².

For energy management of chiller operation the outside temperature has a dominant role and is a good indicator for the prediction of chiller behaviour. Appendix L shows the ranges and mean values sorted per hourly energy consumption of the chiller.

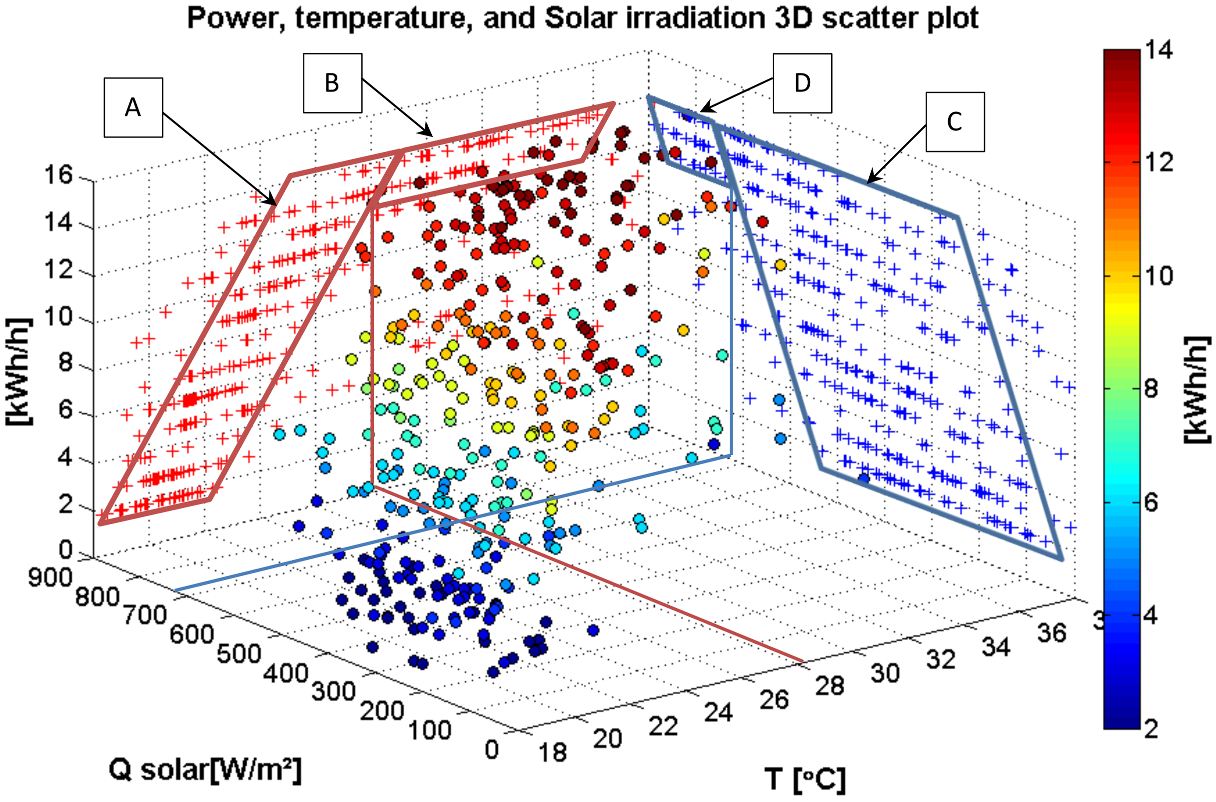


Figure 51: Chiller energy use per hour related to temperature and solar irradiation, red presents the relation between hourly energy use and outside temperature, surface A shows the linear relation between the outside temperature and hourly energy use of the chiller, surface B shows the chiller runs on full capacity with outside temperatures above 28 degrees Celsius, blue presents the relation between hourly energy use and solar irradiation, surface C shows the solar irradiation has less of an effect on the hourly energy use of the chiller compared to temperature since the surface is more spread-out, surface D sows the chiller runs on full capacity with solar irradiation above 700 W/m².

4.4.2 Simulations

Chiller operation interruption is simulated for the summer period using the VABI model. From Figure 48 the chiller is most active in the afternoon. Since the hour 14:00 is likely the worst hour to interrupt chillers operation, this is chosen to simulate. In the hours afterwards the indoor climate could still be negatively influenced by the interruption. And the chiller will try to make up the loss by active operation.

The calculated comfort temperatures of room A are presented in an ATL-Charts presented in Figure 52. As can be seen the comfort temperatures exceed the acceptable comfort classes (orange circles). In most cases the hours afterwards the temperature can be sufficient be lowered to regain an acceptable indoor climate. This can only be achieved with the chiller operating on full capacity which means the system has to make up for the period of inactivity.

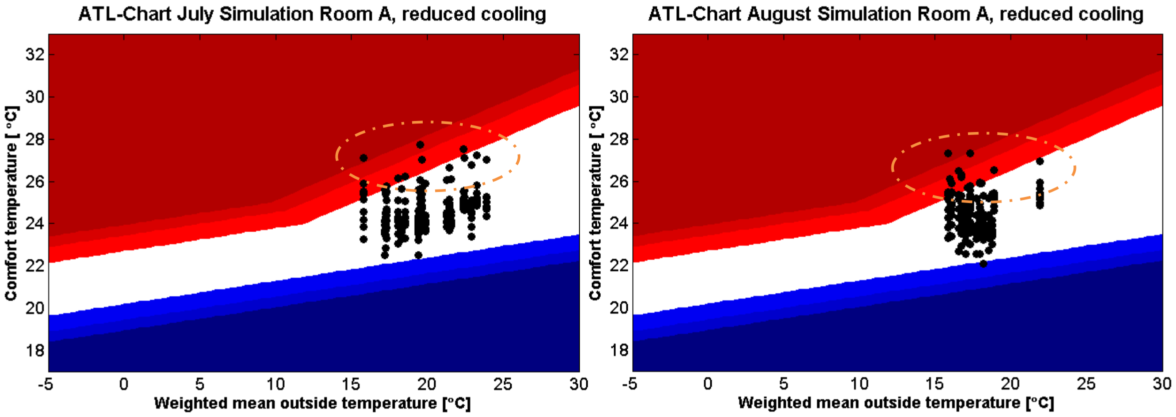


Figure 52: ATL-Chart of room A over the period July on the left and over the period August right, simulation shifted chiller operation, both show the comfort temperatures exceed the comfort class C which is unacceptable.

Total energy consumption is slight lower compared with the original situation. A reduction of 12 % energy use due to the inactive operation of the chiller. This reduction comes with the cost of unacceptable comfort changes and an indoor temperature of 28 degrees Celsius.

Higher indoor temperatures are the result but in most cases during the hours afterwards the temperature can be sufficient reduced to normal operating conditions (comfort class B). The hours chillers operation is interrupted cause unacceptable indoor temperatures which also lead to exceeding the PMV class C.

Table 11: PMV exceeding hours room A, simulation shifted chiller operation.

	Class A 0.2 / -0.2	Class B 0.5 / -0.5	Class C 0.7 / -0.7
PMV exceeding hours	241	34	16

4.4.3 Conclusions of shifting chiller operation

Shifting chiller operation in case it runs on full capacity results in an unacceptable indoor climate. With the chiller operating 64% of the time in cyclic behaviour this leaves room for shifting operation while maintaining a somewhat acceptable indoor climate. Shifting the operation could result in an indoor climate of class C which is the trade-off.

The afternoon has proven to be more critical compared to the morning for shifting chiller operation.

Cyclic behaviour of the chiller is within the system boundary's. Which are the lowest acceptable output temperature of the chiller of 6 degrees Celsius. The cycle time the chiller stays on is depending on this lowest temperature while the off period of the cycle is at least 5 minutes. The thermal capacity (buffer) of the system and cooling demand determine the time the chiller stays off in case the off time is longer than 5 minutes.

For energy management of chiller operation the outside temperature has a dominant role and is a good indicator for the prediction of chiller behaviour.

The used model calculates only hourly values. In future research a more detailed model should be used to investigate the chillers behaviour shifting chillers operation.

Shifting the operation with smaller time steps can increase the feasibility of maintaining an acceptable indoor climate.

Pre-cooling and increasing the system capacity also increase the feasibility of maintaining an acceptable indoor climate while shifting chiller operation. The magnitude of buffer increase and precooling should be investigated.

4.5 Mix of energy management scenarios

A combination of presented energy management scenarios is simulated to find whether they have a significant impact on each other.

4.5.1 Simulation

Chiller operation interruption, lighting reduction, and ventilation capacity reduction are simulated together.

The artificial lighting use reduction was the only scenario with a positive effect on the thermal indoor climate. While ventilation reduction and chiller operation interruption negatively influence the thermal indoor climate.

Figure 53 shows the ATL-charts of the scenarios combined. These charts present the model predicts higher comfort temperatures in the afternoon. Still the comfort temperatures stay most of the time within class B boundaries. Only a few exceeding's of class B occur while class C is not exceeded.

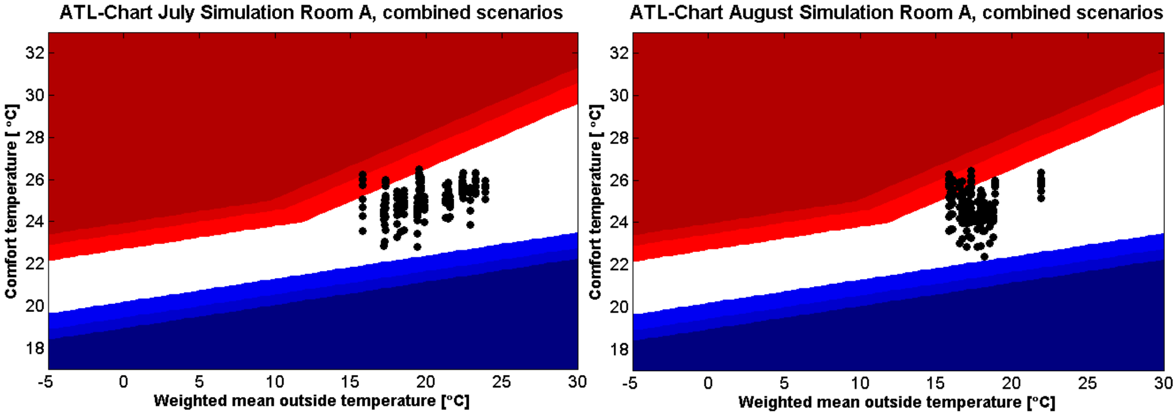


Figure 53: ATL-Chart of room A over the period July on the left and over the period August right, simulation combined scenarios, both show the comfort temperatures stay within the comfort class C.

A maximum occurring temperature during office hours of 28 degrees Celsius is simulated. The influence of interrupting chiller operation is causing this high temperature. Due to the reduced ventilation capacity the temperature rise, and decrease afterwards are minor.

The PMV values calculated are higher compared to the ATL classes. Comfort class C is exceeded for the PMV values while the ATL-charts show the class C is not exceeded.

The hours chillers operation is interrupted cause these exceeding's of the PMV class C.

Table 12: PMV exceeding hours room A, simulation combined scenarios.

	Class A 0.2 / -0.2	Class B 0.5 / -0.5	Class C 0.7 / -0.7
PMV exceeding hours	305	57	17

4.5.2 Comparison with separate scenarios

Comparing the combined scenarios with the separate scenarios it is found that the influence of the chiller operation interruption result in the same undesired exceeding of comfort classes. While the temperatures of the exceeding hour differ less with the hours after the event due to the reduced ventilation capacity.

The exceeding of PMV class B occurs more for the combined scenarios compared to the chiller interruption scenario. The reduced ventilation is the reason for this.

The improvement of the lower artificial lighting use is not remarkable with the combined scenario. But it is probably the reason the exceeding of comfort classes is not higher compared to the interruption of chiller operation scenario.

4.6 Discussion and conclusions

With the experiments and simulations of the energy management scenarios answers can be given on the sub-questions stated in section 1.

Sub question:

a) The airflow in a building is has to be sufficient for air refreshment and is designed for transportation of full cooling capacity of an office, while in practice full capacity is seldom needed. How can the air-flow be adapted to required refreshment based on the actual occupancy?

Reducing the airflow to 10 l/s per person for the most occupied room results in a reduction of 25% compared to the original situation. Electrical this means a reduction of 2 kW.

For the cooling energy use this means a reduction of 22% while maintaining the comfort in most of the time in class B. The indoor thermal comfort only becomes class C in the days full cooling capacity is needed.

Providing the air flow reduction as a service to the grid is for the days with no need for full cooling capacity acceptable. In case of full cooling need the airflow reduction is only acceptable when the thermal comfort may decrease to class C.

Furthermore it is recommended to investigate the influence of lower air speeds on the comfort due to the reduction of air-flow.

Also lower air speeds of the air supply in the room can cause a different mixing pattern which can cause discomfort in cooling season. In cooling season the air supply can be 16 degrees Celsius. Occurrence and the magnitude of this can be a point of further research.

The ventilation reduction could also decrease the need for heating and humidification of the supply air.

Sub question:

b) Currently the artificial lighting is a constant consumer of power, the full capacity is used almost the whole year. Is it possible to reduce artificial lighting based on the use of available natural light, and what will be the effects on illuminance / luminous intensity in the office?

Artificial lighting use reduction results in an electrical energy use reduction of 16%. In case the open office rooms of the first floor and the second floor are used for artificial lighting use reduction the energy use reduction can increase to 30%.

This reduction can be used in about 36% of the office hours a year based on the year 2013 and the natural lighting entering the room.

With the reduction of artificial lighting use the simulation shows there is no cooling demand reduction, while the indoor thermal climate improves.

The artificial lighting electricity use can be reduced by 16% for 36% of the year.

Future work should include measurements of the distribution of luminance levels in the rooms and uniformity on the working place combined with the user acceptance.

Also the open offices should be investigated for artificial lighting use. This could raise the electrical energy reduction for lighting to 30%.

Sub question:

c) The chiller is a large consumer, in high summer the full capacity will be needed, for periods were not the full capacity is required, is it possible to shift the operation of the chiller, and what are then the effects on thermal comfort in the building?

With the chiller operating 64% of the time in cyclic behaviour this leaves room for shifting operation while maintaining a somewhat acceptable indoor climate. Shifting the operation could result in an indoor climate of class C which is the trade-off. After the event the chiller will try to make up for the event which results in active operation.

The afternoon has proven to be more critical compared to the morning for shifting chiller operation.

For energy management of chiller operation the outside temperature has a dominant role and is a good indicator for the prediction of chiller behaviour.

Future work should include a more detailed model for investigation of chiller behaviour. The model should have time steps smaller than an hour and suitable for different shifting scenarios.

Shifting the operation with smaller time steps can increase the feasibility of maintaining an acceptable indoor climate. Pre-cooling and increasing the system capacity also increase the feasibility of maintaining an acceptable indoor climate while shifting chiller operation. The magnitude of buffer increase and precooling should be investigated.

Beside answering the sub-questions it is found the combinations of energy management scenarios effect each other which should be kept in mind when facilitating energy management in service of the Smart Grid.

5 Conclusion

This chapter provides the conclusions, discussions of this work together with recommendations for future work.

5.1 Introduction

The Smart Grid (SG) is required to be the solution to the latest developments on the electrical energy grid managing electrical energy production, distribution, buffering, and consumption matching supply and demand making use of the available system flexibilities [Slootweg et al., 2011].

The biggest change as a result of transformation to SG will be the requirement of active participation of end users in grid management [Hommelberg et al., 2010; Slootweg et al., 2011]. Turning the distribution grid from a passive system into a more active system. This implies active participation of buildings in the grid.

For an optimal SG from a system of systems point of view, the BEMS has to be coupled with the management platform of the grid [Dave et al., 2011]. The control of loads in the building, may also be a resource to the grid using the flexibilities in service of the grid in Demand Side Management (DSM) scenarios as so called Demand Response (DR) or Load Control (LC). [Callaway and Hiskens, 2011]

5.2 Objective and conclusions

This study evaluated the possibilities for adapting the consumption patterns of Dutch office building to participate in the Smart Grid, with respect for thermal comfort and IAQ related to the productivity of occupants in these buildings. Focusing on the main consumers of power of a contemporary office building. These are the chiller, HVAC air handling unit, and artificial lighting system.

Increasing Energy Efficiency is the first goal for supporting the Smart grid. In this study is discussed to what degree the pattern of consumption can be influenced, and whether it is useful with a certain amount of constrains for Demand Response.

Shifting chiller operation
Adapting the chiller operation as a service to the grid, by shifting the time of active operation with a power of 14 kW, is feasible in 64% of the total operation time. After the shifting event increased active chiller operation will be needed and has to be taken into account for Demand Response. (section 4.4)

Air-flow reduction
Air-flow reduction can be used as a service to the grid or energy efficiency measure, with a power of 2 kW. Beside the direct energy use reduction of the air handling unit fans the cooling demand reduces with 22%. Reduction of the air-flow can be used almost during the entire year except for the days full cooling demand is desired. The behaviour of air-flow reduction in the winter period however has to be investigated in future research. (section 4.2)

Artificial lighting use reduction
Artificial lighting use reduction shows potential for energy efficiency measure with a power of 2 to 4 kW for 36% of the office hours a year, however further research is needed. (section 4.3)

5.3 Answers on the research questions

The main research question of this study is:

- To which extent can the consumption patterns of current office buildings be adapted, with smart energy management, to support the Smart Grid, and what are the consequences for the operation of the building regarding thermal comfort and IAQ?

With the results of the experiments described in section 4 the question regarding the flexibility in power consumption and the influence on the thermal comfort and IAQ can be for the main part be answered.

Beside answering the sub-questions it is found the combinations of energy management scenarios effect each other which should be kept in mind when facilitating energy management in service of the Smart Grid.

Shifting chiller operation
With the chiller operating 64% of the time in cyclic behaviour this leaves room for shifting operation while maintaining a somewhat acceptable indoor climate of class C which is the trade-off. After the event the chiller will try to make up for the event which results in active operation to regain the comfort class B.

For energy management of chiller operation the outside temperature has a dominant role and is a good indicator for the prediction of chiller behaviour. Outside temperatures above 28 degrees Celsius will cause the chiller to run continuous on full capacity and shifting operation in this case will cause an unacceptable indoor comfort. (section 4.4)

Air-flow reduction
Reducing the airflow to 10 l/s per person for the most occupied room results in a reduction of 25% in airflow compared to the original situation. The CO_2 concentrations measured increase but stay within acceptable limits. Thermal comfort is maintained in class B most of the time. Except for the days full cooling capacity is needed the comfort decreases to class C.

In case of full cooling need the airflow reduction is only acceptable when the thermal comfort may decrease to comfort class C. (section 4.2)

Artificial lighting use reduction
Reduction of the artificial lighting shows potential to be used in about 36% of the office hours a year based on the natural lighting entering the room maintaining a 500 Lux or higher on the desk.

With the reduction of artificial lighting use the simulation show the indoor thermal climate improves. (section 4.3)

5.4 Discussion

This paragraph looks towards a discussion of the proposed energy management scenarios in service of the Smart Grid. The results of the case studies were already discussed at the end of sections 3 and 4. This study and results are limited by the measurement period during the summer period. A similar study should be assessed on different office buildings to find whether results are similar.

Energy management

Already adopted energy management scenarios like night ventilation can be clearly seen in the energy use profiles. The running scenarios determine which energy management adaptions have significant potential.

The energy use of the remaining appliances has a quite stochastic behaviour. This is mainly due to the behaviour of the occupants. Energy management based on occupancy and user location has significant potential for the lighting and office appliances, since they can easily be split up per room or zone, improving the energy efficiency.

Shifting chiller operation

The chiller measured in this study had only one compressor. Different chillers can have other behaviour which could result in different flexibility as a service to the grid.

The cooling system is not equipped with a significant buffer capacity. Cooling systems with larger system and buffer capacity have the potential for more flexibility.

For buildings with higher constant occupation the flexibility can be less. In this study it is found the occupation and appliance use differ during the day and week.

Air-flow reduction

Improving the airflow based on the occupancy and required air refreshment can even improve the energy use reduction of the air handling unit fans. Together with this the energy required for cooling or heating of the ventilation air in case full cooling capacity is not required.

Air refreshment systems with variable flow on room level have the potential for better results and service for the grid.

Artificial lighting use reduction

Improving the energy efficiency of the lighting system will decrease the service which can be delivered to the grid. However a better energy efficient lighting system requires less energy which should be the first goal.

Lighting systems based on occupancy and daylight control already improve the use of natural light and reduce the unnecessary use of artificial light. Offices like the case study building could easily be equipped with such a system.

Automated solar blinds combined with the occupancy based and daylight control lighting systems can even more improve the energy efficiency for lighting systems together with the reduction for cooling demand.

Used model and comfort indicators

The ATL method used to evaluate the acceptance of the indoor climate and model used for simulations are based on hourly values. Changes within an hour are left out the consideration. However changes in temperature are quite slow (relative small variation over one hour) in a continuous controlled building. Energy management scenarios might cause influences which have an effect on a faster change in indoor temperature.

Productivity is hard to quantify for the indoor comfort. Thermal comfort, IAQ, and visual comfort are all influencing the indoor comfort and it is known in case one of the comfort is insufficient the productivity is jeopardised. The magnitude and influence of these indicators on each other and the productivity of office workers requires more research.

5.5 Recommendations

Further research on the presented topics should consider the following recommendations.

Shifting chiller operation
Future work should include a more detailed model for investigation of chiller behaviour. The model should have time steps smaller than an hour and suitable for different shifting scenarios.

Shifting the operation with smaller time steps can increase the feasibility of maintaining an acceptable indoor climate. Pre-cooling and increasing the system capacity also increase the feasibility of maintaining an acceptable indoor climate while shifting chiller operation. The magnitude of buffer increase and precooling should be investigated.

System optimisation can also be investigated to improve the energy efficiency and lifespan op equipment while providing service to the grid.

Air-flow reduction
For estimation of the indoor comfort air velocity measurements should be included in the future for better estimation of the PMV and PPD values.

Furthermore it is recommended to investigate the influence of lower air speeds on the comfort due to the reduction of air-flow.

Also lower air speeds of the air supply in the room can cause a different mixing pattern which can cause discomfort in cooling season. In cooling season the air supply can be 16 degrees Celsius. Occurrence and the magnitude of this can be a point of further research.

The ventilation reduction could also decrease the need for heating and humidification of the supply air.

Energy measurements can be done in future with increased accuracy. The used measurement equipment has a resolution of 1 kW with the system running on 6 kW full capacity.

Artificial lighting use reduction
Future work should include measurements of the distribution of luminance levels in the rooms and uniformity on the working place combined with the user acceptance.

Also the open offices should be investigated for artificial lighting use. This could raise the electrical energy reduction for lighting to 30%.

5.6 Practical recommendations for future experiments

In this paragraph some practical recommendations based on the experiences and findings in the field. These practical recommendations can improve future experimental research.

The software necessary for the used monitoring and controlling tools runs on a PC / server, several accounts (Kropman network dedicated) have rights to this platform. The rights can differ from each other meaning not all of the people using their own account can make adjustments. The software running on the background, for example; Insite View, Plugwise server, and others, also need an account. The account first needs all the rights needed for the software to run, second needs to be dedicated for the system. At the moment user accounts of employees are used for the software. The problem in this is, the user can change his password, this has to be done once in a while (required by ICT department of Kropman), causing the account credentials in the software settings also have to be adjusted. Otherwise the network blocks the software by not accepting the account settings.

A second problem noticed, software like Plugwise Server and Plugwise Source cannot run simultaneously. Source is used to set and adjust settings in the Plugwise network, download data manually, and other functionalities. While using Plugwise Source, Plugwise Server is temporary shutdown. Plugwise Server which is normally running under a user account at the background and kept ‘alive’ by Watchdog causes Plugwise Source to shut down while someone is working in it. Every time Watchdog detects Plugwise Server is not running it restarts the software, the detection frequency of Watchdog is adjusted every time work had to be done in Plugwise Source. The Watchdog settings had to be restored every time the work in Plugwise Source was finished. First, because humans are not perfect this could lead to forgetting or accidently making mistakes in the settings. Second, the authorisation problem of users and their accounts, one may not have the rights to change the settings or to interrupt the software running under an account with different rights.

The best way to solve these problems I would suggest a system account for the software to run on. The account should be system dedicated and not user dedicated.

In this research measurements have been done on the energy use of appliances at the workplace. In future research I would suggest to use different equipment. The energy meters work just fine exempt the data has to be downloaded manual with a SD-card. First, making it a slow and time consuming process and second, prone to errors. In this case the energy consumption could also be measured by Plugwise devices since the network is already there.

Using the Plugwise devices brings some advantages. First, the data collection is automated and can be coupled to the software platforms in place. Second, data logging can be coupled in Insite History. Third, a better insight can be created on current energy use by appliances, instead of looking at historic data, the data at the moment can be monitored. Fourth, the mesh network of the devices will improve. In practice is found the network is weak in the other fire compartment compared to the compartment the server is in. Adding extra nodes was used to improve the network strength, still some difficulties where mentioned.

Temperature measurements done in this research are logged and saved by a separate system. In future projects these measurements could be done to analyse the indoor climate in response of building system control scenarios. For acting on or reacting on similar measurements by building control a different measurement system should be used. At least te measured data should be directly (with a slight delay for communication) available for the building system control. The setup was sufficient for now, we used it to get a feeling about the characteristics and their behaviour.

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Appendices

Appendix A:

A.1 The Case Study-Kropman Breda Office Building

A general data collection should provide the needed insight and generate an expectation of the on-site measurements. Based on this risks and expected deviations can be mapped. The building used for this research is the office building of Kropman Breda.

The Kropman Office in Breda has been built in 1992 and revised in 2009. It is situated in the west of the city Breda a town in the southern part of the Netherlands. The building is a three story high building. Figure 54 shows the building as seen in GoogleMaps. In this figure the orientation, and surroundings of the Kropman terrain is pictured.

Figure 54: Kropman Breda Office [Edited from GoogleMaps].

A.1.1 Building Physics

Since the building has been built in 1992 some of the information about the building physics is not available anymore. Most of the building materials used to build the office are unknown since the design data is missing.

The only information about the construction of the office has been found in drawings and floor plans.

Furthermore an inspection on site has led to the findings presented in this paragraph.

The ground floor of the building consists of the following rooms; entrance, cafeteria, meeting room, storage / workshop, toilets, electricity power board room, small offices, and large office room.

On the first floor the following rooms are situated; Electrical engineering room, three large manager offices, one small secretary office room, a storage room, toilets, patch server and plotter room, and two large engineering office rooms.

Situated on the second floor are the following rooms; technical room for heating systems, technical room for air handling unit and control systems, mechanical engineering room, and two small manager offices.

The manager offices are also used as meeting rooms.

All the windows of the office are double glazed windows with wooden frames. Almost all the windows on the east, south, and west side have inside and outside shading devices which are all hand controlled. Some windows situated on the north side also have hand controlled inside and outside shading devices.

Almost all the windows have the ability to be opened and tilted.

The staircases situated in the middle of the building have a glass façade on the south west. This façade has no shading devices making it of risk in case of overheating the staircases by solar irradiation. The doors between de corridors of the ground-, first, and second floor and the staircases are equipped with mechanical door closers. During the inspection on site is found, the door on the top floor was kept open by blocking the door. Questioning the office personal led to the finding they prefer the ease of the opened door especially when they need to collect printed material, go for a cup of coffee, or other daily working activities. Measurements have to show the influence of heat gains by solar irradiation and rooms situated close to the staircases.

The roof of office is flat. On top of the roof above the Electrical engineering room, on the first floor, the chiller is situated next to the technical room.

A.1.2 Systems

The central building systems can be divided in heating, ventilation, cooling, lighting, humidification, and appliances. The central building systems can be separated into groups according to their orientation and position in the building. These groups were determined engineering the building.

The heating groups are the North East radiator group, South West radiator group and the air handling unit group.

Ventilation supply groups are the North East group, South West group, and Electrical Engineering group.

Ventilation exhaust groups are the North East group, South West group, and Electrical Engineering group.

Cooling groups are the same as the ventilation supply groups since the cooling is transferred in the ventilation supply.

Lighting can be divided into three groups; commercial lighting, central lighting, and room lighting.

In abstract the heating, ventilation, and cooling systems are presented in Figure 55 and Figure 60. In these pictures also the positions of temperature measurements for system control are pictured.

In Appendix B the systems and measurements for systems control are presented in an matrix.

The building has a building management system, monitoring, and controlling the systems for heating cooling and ventilation. The software platform InsiteView gathers all measurement data from the sensor listed in Appendix C. With the measurements and programed building control the system controls the system components as listed in Appendix D.

In the server and plotter room at the first floor a split unit has been added to cool down the room and prevent it from overheating due to the internal heat loads of the server, patches, printers, and plotters. The thermostat of the split unit has been set to 22 degrees Celsius and the thermostat has been locket to prevent adjustments.

Beside the building systems all different kind of appliances are used by the building occupants.

These appliances are; personal computers, monitors, laptops, laptop docking stations, phone chargers, radios, water boilers, coffee machine, dish washer, small printers, and fridges.

The systems in the office work on a timer schedule and overworking timer. The timer schedule is as follows

Monday	from 5:00 till 17:30
Tuesday till Friday	from 7:00 till 17:30
Saturday and Sunday	out of order

When overworking timer is active, the systems run as long as the timer keeps active.

A.1.2.1 Heating

The heating system has a central boiler providing the desired thermal power to the distribution system. From the distribution system the groups connected to it take only the thermal power needed by controlling the intake flow.

The boiler control starts the boiler when at least one of the groups requests thermal power. Temperatures of the intake and outlet of the distribution system are used for further control. The boilers temperature set point (temperature of the water leaving the boiler) will be the highest temperature desired by the groups plus an additional 5 degrees Celsius compensating transport losses and possible control influences.

The groups connected to the heating distribution system are controlled by a three way valve mixing inlet (supply) water with return water. In case of 100% inlet water all of the return water will flow to the heat distribution system to be reheated by the boiler. Setting the valves of the valves is done with PI-controllers based on temperature measurements of the supply water, exhaust air, indoor temperature, outside temperature, and corresponding heating curves. The heating groups control will be presented in more detail below.

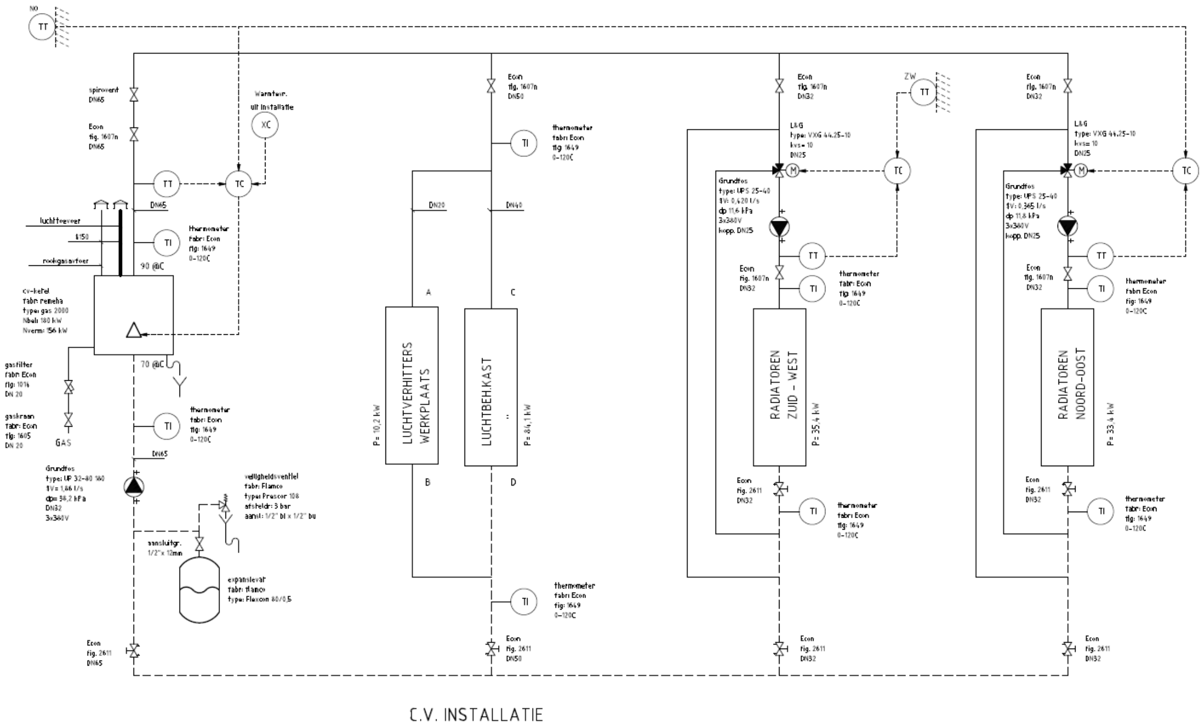


Figure 55: Abstract presentation of the heating system.

The supply water temperature of each radiator group is controlled weather dependant by the following linear heating curve presented in Figure 56.

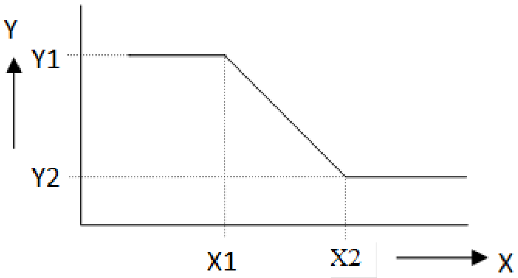


Figure 56: Linear heating curve, X = outside temperature, Y = set point supply water temperature.

X1= -10°C Y1 =90°C Ymin. = 20°C
X2= 20°C Y2 = 20°C Ymax. = 90°C

The control has an optimal start setting. This means the system has a preheating period that end at the starting time of the time schedule. This period is only active in case the outside temperature is below 17 degrees Celsius. During this period the system desires to reach an indoor temperature of 21 degrees Celsius. In case the optimal start is applied the supply temperature set point of the boiler is raised with 15 degrees Celsius. The optimal start setting will be blocked when night ventilation program has been used for cooling.

Minimum indoor temperature set point during the hours outside of the timer schedule is 18 degrees Celsius with a time constrain. This means the heating system will become active after the indoor temperature drops below 18 degrees Celsius for a certain amount of time while the building is not in use.

The control valves of the radiator groups in the cafeteria and meeting room on the first floor are coupled on the North East radiator group. These groups are controlled by a PI controller, desired indoor temperature set point and measurements of the indoor temperature. The set points of these rooms is 21 degrees Celsius. The PI controllers are controlled based on the temperature difference between desired and measured room temperature.

The air handling group for heating controls the heat demand based on the measured and desired supply air temperature. The desired supply air temperature will be determined by the maximum accepted supply temperature of the cooling groups. The air supply temperature will be controlled by control of first the heat recovery wheel and second the heater.

The temperature set points are based on temperature difference dT, presented in Table 13. dT heater is the difference between the measured temperature minus the desired temperature. dT heat recovery wheel is the difference between the outside temperature minus the average indoor temperature. The average indoor temperature is calculated with the measured room temperatures and corresponding weight factors.

Table 13: Temperature difference set points heater and heat recovering wheel air handling unit.

	On	Off
dT heater	-0,5°C	0°C
Time delay heat demand heater	00:00 mm:ss	00:00 mm:ss
dT heat recovery wheel as heater	-0,5°C	0,0°C
Time delay heat demand heat recovery wheel	03:00 mm:ss	00:00 mm:ss

In case the heat recovery wheel cannot be used as a cooler of heater due to the set points it will remain neutral.

The supply water temperature of the air handling unit heater is controlled weather dependant when the frost limit is active. This is done by the following linear heating curve, presented in Figure 57.

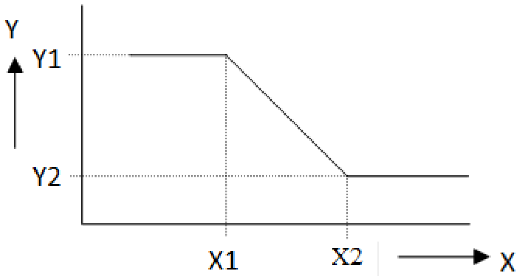


Figure 57: Linear heating curve, X = outside temperature, Y = set point supply water temperature.

X1=	-10°C	Y1 = 40°C	Ymin.	= 10°C
X2=	10°C	Y2 = 10°C	Ymax.	= 40°C

These settings are always used even when the air handling unit is not active. Beside these control settings the heater group has an extra control mechanism to prevent the system from freezing.

This control is called anti-frost control and becomes active when the air temperature after the heater unit becomes 5 degrees Celsius or lower. During the anti-frost control the following steps will take place:

- Fist, the supply and exhaust fans stop;
- Second, the air inlet and outlet valves of the air handling unit close;
- Third, the heating group control valve opens up to 100%, requesting maximum heat demand.

In the workshop the heater in the ventilation system is directly coupled to the distribution system. The ventilator and heater are controlled on the room temperature and desired temperature set point which is 20 degrees Celsius. The desired supply water temperature is set to 55 degrees Celsius in case the ventilator and heater in the workplace is active.

The control of the heater groups are disabled when the summer scenario is active. The summer scenario becomes active when the outside temperature is above 17 degrees Celsius for longer than 60 minutes. The scenario ends when the outside temperature is below 18 degrees Celsius for longer than 20 minutes.

A.1.2.2 Cooling

The cooling system has a central cooling machine providing the desired thermal power to the distribution system equipped with a relative small buffer. From the distribution system the cooling groups connected to it take only the thermal power needed.

The control starts the cooling machine when; at least one hour the outside temperature is above 18 degrees Celsius, and at least one of the groups needs thermal cooling power. The temperatures from and to the distribution system are used for further control.

When the outside temperature becomes higher than 26 degrees Celsius for at least 30 minutes, the second stage of the cooling machine will be activated. The second stage of the cooling machine will be deactivated after the outside temperature becomes less than 24 degrees Celsius for 30 minutes. The cooling machine will stop working when the outside temperature becomes lower than 16 degrees Celsius or when there is no demand from the cooling groups.

The groups connected to the cooling distribution system are controlled by a three way valve mixing inlet (supply) water with return water. The three way valves are controlled on the measured and desired air temperature. Setting the valve is done with a PI-controller based on temperature measurements of the exhaust air and the desired air temperature. The supply air temperature of the cooler group is controlled weather dependant by the following linear cooling curve, presented in Figure 58.

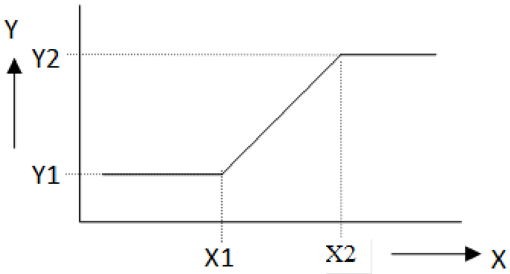


Figure 58: Linear cooling curve weather dependant, X = outside temperature, Y = set point exhaust air temperature

X1= 26°C Y1 = 22°C Ymin. = 22°C
X2= 32°C Y2 = 24°C Ymax. = 24°C

The supply air will be controlled according to the temperature difference presented in Table 14. dT is in this case the temperature difference between the measured supply air temperature minus the desired supply air temperature.

Table 14: Temperature difference set points cooler groups.

	On	Off
dT cooler group	0,2°C	-0,2°C
Time delay cool demand cooler group	00:00 mm:ss	00:00 mm:ss

The minimum supply air temperature is limited by the linear curve presented in Figure 59.

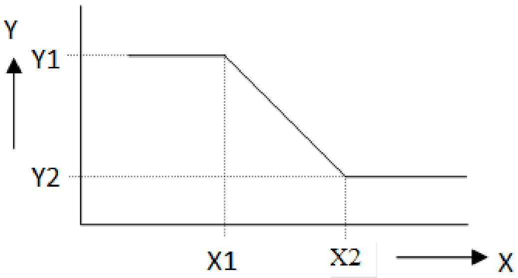


Figure 59: Linear curve minimum supply air temperature limit, X = outside temperature, Y = set point minimum temperature air supply.

X1=	18°C	Y1 = 20°C	Ymin.	= 16°C
X2=	22°C	Y2 = 16°C	Ymax.	= 20°C

Below an abstract representation of the ventilation and cooling system is pictured. The temperature measurements are also presented in this figure.

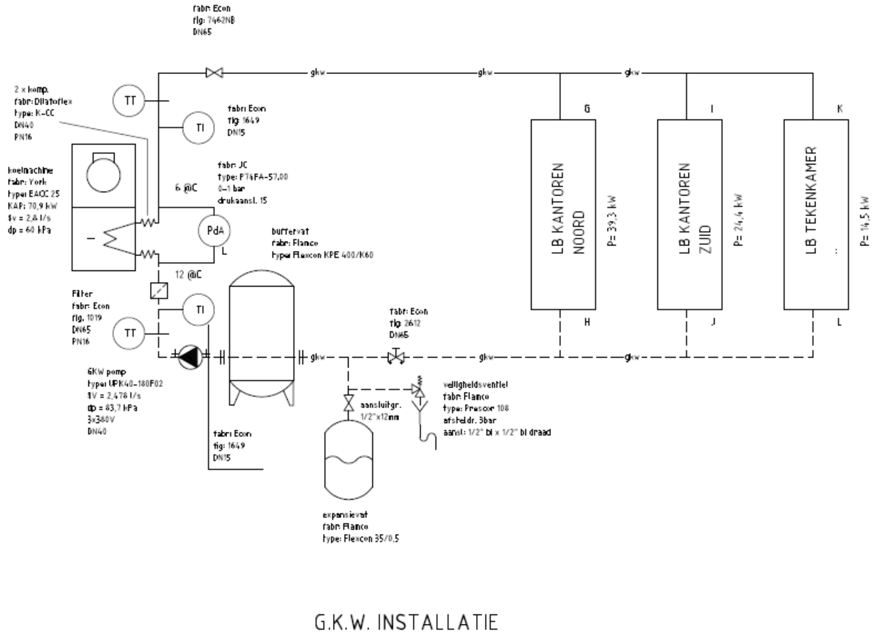


Figure 60: Abstract presentation of the ventilation and cooling system.

Similar to the control of the heat recovery wheel in heating mode the heat recovery wheel in cooling mode will be started first to provide cooling before the cooling groups are activated. In Table 15 the set points are presented with dT heat recovery wheel as the difference between the outside temperature minus the average indoor temperature. The average indoor temperature is calculated with the measured room temperatures and corresponding weight factors.

Table 15: Temperature difference set points heat recovering wheel air handling unit.

	On	Off
dT heat recovery wheel as cooler	1,0°C	0,0°C
Time delay cool demand heat recovery wheel	03:00 mm:ss	00:00 mm:ss

In case the heat recovery wheel cannot be used as a cooler of heater due to the set points it will remain neutral.

A.1.2.3 Air handling unit

The air handling unit also works with the time schedule presented before. In the time the systems are active the pressure in supply air duct is tried to maintained constant by the air supply fan. The frequency regulator, controlling the electric engine of the supply air fan, is controlled by a PID controller. The PID controller determines the output based on the desired pressure (250Pa) and the measured pressure in the air supply duct.

The air exhaust fan is also controlled by a frequency regulator, the PID controller determines the output based on the amount of the supply air controller with an offset of minus 5%.

Pressure difference is measured over the supply air filter and exhaust air filter. These measurements are used to protect the system in case of snare (good / correct term?) break and to detect polluted filters. The snare break alarm will only be triggered in case the supply fan is running and the pressure difference stays below 10 Pa for about one minute. In case of snare brake the air handling unit will be shut down and a manual reset is needed before the system can run again.

A polluted filter will be detected in case the pressure difference over the filter is 120 Pa or higher for at least five minutes. The system will alarm and needs a manual reset to shut off the alarm.

In case the systems starts up first the supply fan starts spinning, and the intake valve will open automatically. At the moment the supply fan runs the exhaust fan will be activated. At the moment the exhaust fan starts spinning the exhaust valve opens automatically.

The air handling unit can run from 23:00 to 06:00 in night ventilation. Night ventilation is created to allow the air handling unit to supply cooler air to the building. In this case the indoor temperature is 22 degrees Celsius or higher and the outside temperature is at least 2 degrees Celsius lower. The night ventilation will stop in case the outside temperature is below 10 degrees Celsius, the inside temperature has become lower than 20 degrees Celsius or the end time is reached.

Extra air supply in the canteen is only activated in case the overwork timer in the canteen is activated. In this case the air supply valves to the canteen will open.

Toilets, washrooms, corridors ,and staircase will be ventilated separately. In these rooms a roof ventilator will facilitate, separate from the air handling unit, exhaust ventilation. The ventilator will run dependant from the time schedule and continues for an extra 120 minutes after the schedule ends.

Outside temperature below 5 degrees Celsius will cause the air handling unit to start with a time delay of 10 minutes. The heater in the air handling unit will start normally while the rest of the air handling unit waits for 10 minutes to start up. This ensures the system heats up before the cold outside air comes into the system. Starting up with no time delay has the risk of possible activating the frost detection. The frost detection will force the ventilators to stop and the intake and exhaust value to close so the heater in the air handling unit get the chance to heat the system to a frost free temperature.

A.1.2.4 Humidifier

The humidifier is placed in the air handling unit. The humidifier is controlled on the desired humidity in the supply air, which is 8 g/kg, and measured humidity in the supply air. The difference set points and corresponding time delay of the humidifier control is given in Table 16.

Table 16: Humidity difference set points humidifier.

	On	Off
dH humidity	- 5 %	0 %
Time delay humidifier	05:00 mm:ss	00:00 mm:ss

A.1.2.5 Lighting

The building has a central lighting switch to switch off and on all the lighting when the first employee enters or the last leaves the building. Some of the lights belong the central lighting group, this group is also on during the night. The lighting lights the escape routes like corridors and the staircases.

In most rooms the lighting can be switched manual. The lighting in most rooms is split into two groups, one on the window side and one on the corridor side.

Table 17: Inventories of installed lighting,

Ground floor					**First floor**				
Room	20 W	2*36 W	58 W	3*15 W	Room	20 W	2*36 W	58 W	3*15 W
Small office 1	0	0	0	4	Open plan office 1	0	32	0	0
Small office 2	0	0	0	4	Large office 1	0	4	0	0
Small office 3	0	4	0	0	Large office 2	0	4	0	0
large office 1	0	10	0	0	Large office 3	0	7	0	0
Workshop office	0	0	0	3	large office 4	0	4	0	0
Workshop storage	0	0	7	0	large office 5	0	10	0	0
Meeting room	0	0	0	4	Small office 1	0	2	0	0
Entrance	23	0	0	0	Storage room	0	2	0	0
Kitchen / Cafeteria	2	0	0	16	Washroom 1	4	0	0	0
Washroom 1	4	0	0	0	Washroom 2	4	0	0	0
Washroom 2	4	0	0	0	Toilet 1	1	0	0	0
Toilet 1	1	0	0	0	Toilet 2	1	0	0	0
Toilet 2	1	0	0	0	Toilet 3	1	0	0	0
Toilet 3	1	0	0	0	Toilet 4	1	0	0	0
Toilet 4	1	0	0	0	Server / plotter room	0	2	0	0
hallway	3	0	0	0	Hallway 1	7	0	0	0
					Hallway 2	6	0	0	0

Second floor					**Stair cases**				
Room	20 W	2*36 W	58 W	3*15 W	Room	20 W	2*36 W	58 W	3*15 W
Open plan office 1	0	35	0	0	Stair cases	15	0	0	0
Large office 1	0	3	0	0					
Large office 2	0	4	0	0					
Hallway 1	2	0	0	0					
Technical room 1	0	0	2	0					
Technical room 2	0	0	5	0					

A.1.2.6 Appliances

The appliances used by the building occupants are; personal computers, monitors, laptops, laptop docking stations, phone chargers, radios, water boilers, coffee machine, dish washer, small printers, and fridges.

An inventerization has led to the devices in Table 18. These appliances have been inventoried twice during the time of the project. Noticeable is the use of phone chargers, some people intend to put the charger away when not in use or not use a charger at the office.

Table 18: Inventories of electrical appliances.

Ground floor

Room	Flat screen monitor	PC	Laptop	Laptop docking station	water boilers	fridge	small printer	Radio	Phone charger
Small office 1	2	1	1	1	0	0	1	1	1
Small office 2	1	1	0	0	0	0	0	0	1
Small office 3	2	2	0	0	0	0	0	0	1
large office 1	8	8	0	0	0	0	1	1	2
Workshop office	1	1	0	0	0	0	0	1	1

First floor

Room	Flat screen monitor	PC	Laptop	Laptop docking station	water boilers	fridge	small printer	Radio	Phone charger
Open plan office 1	12	8	1	2	1	1	0	2	6
Large office 1	1	0	1	1	0	0	0	0	0
Large office 2	1	0	1	1	0	0	0	0	1
Large office 3	1	0	1	1	0	0	0	0	1
large office 4	5	4	1	1	0	0	0	1	2
large office 5	8	5	2	2	0	0	0	1	4
Small office 1	1	1	0	0	1	1	1	1	1
Storage room	0	0	0	0	0	0	1	0	0

Second floor

Room	Flat screen monitor	PC	Laptop	Laptop docking station	water boilers	fridge	small printer	Radio	Phone charger
Open plan office 1	12	12	0	0	1	1	0	1	5
Large office 1	0	0	1	0	0	0	0	0	0
Large office 2	0	0	0	0	0	0	0	0	0

Kitchen / Cafeteria

	Electric grill	water boilers	coffee machine	dish washer	fridge	Radio
Kitchen / Cafeteria	1	1	1	1	1	1

A.1.3 Connection to the grid

On the terrain of the Kropman Breda office a mid-voltage transformer station is situated.

From this station two low-voltage cables are connected with the buildings cupboard. In the building the main connections are measured. One power connection is for the lighting and the other power connection is for the appliances. The biggest appliances, chiller, humidifier, and HVAC control unit, are measured separately. From the HVAC control unit the fans and pumps are powered.

In the main switch board room the electrical connection enters the building. The main connection is split into two groups, the lighting group and the appliances group. The distribution of installed electrical power capacities for both groups is presented in Figure 12. Notice the installed electrical power capacity for lighting is about 11% of the total.

A.1.4 Points of attention for deviating indoor climate and undesired energy use

Several spots in the building ask for extra attention regarding the influence on the indoor climate or energy use. Due to passive and or active influences the indoor climate can become worse or the energy consumption can undesirable increase.

For the server and plotter room at the first floor the split unit has the potential of being a large energy consumer. Wrong use or bad set point can make it run unnecessary continuous. The door to this room is most of the time open due to the frequent use of printers, scanners, and plotters in the room. Therefore the temperature and humidity of the room and hallway connected should be monitored.

Also connected to the hallway are the staircases situated in the middle of the building next to the server and plotter room. These staircases have a glass façade on the south west as discussed before this façade has no shading devices making it of risk in case of overheating. Measurements have to show the influence of heat gains by solar irradiation and the influence on the rooms and hallway situated close to the staircases.

Most of the rooms have solar blinds, especially the influence of the sun on the south west façade should be investigated and compared with the north east façade. The heat gains can lead to higher energy use for cooling and lower natural light can lead to more energy use for artificial lighting.

Since all the system groups are situated in the first floor, and the first floor is the most regular occupied floor, this floor is most of interest for measurements.

The floor plan of the first floor of the building is shown in Appendix E. In the floor plan, the radiator groups, the ventilation supply groups, the ventilation exhaust groups, and the location of the split unit are pictured.

Appendix B:

B.1 System and sensor matrix Kropman Breda Office

Systems in the Kropman Breda Building

Level	Heating	Cooling	Ventilation	lighting	Appliances
Environment	-	-	-	-	-
Building	Central Boiler and distributor system, preheater in air handling unit	Central chiller and distribution system,	Central air handling unit with humidifier and heat recovery wheel	Commercial lighting	(e-mail) server, patches, coffee machine, printer, plotter, dishwasher, fridge
Floor	-	-	-	-	-
Zone/Room	Radiators with thermostatic valve (2 zones; NE, SW)	Coolers in ventilation system (3 zones; N, S, E-eng. room)	Slot diffusor groups (3 zones; N, S, E-eng. Room) separate kitchen inlet on group north	Tl lighting, downlighters, manual internal blinds and manual external blinds	-
Workplace	-	-	-	-	Computers, Laptops, Monitors, Phone chargers, Wather boilers, Small Printers, Radio's

Sensors in the Kropman Breda Building

Level	Heating	Cooling	Ventilation	lighting	Appliances
Environment	Temperature	Temperature	-	-	-
Building	Temperature of the supply water and return water	Temperature of the supply water and return water	Humidity, pressure, temperature, supply and return in air handling unit	-	-
Floor	-	-	-	-	-
Zone/Room	Tempearture in the zone, temperature of radiator groups, valve positions in distribution groups.	Temperature of the Inlet and exhaust air, valve position in distribution to coolers	Temperature inlet and exhaust	-	-
Workplace	-	-	-	-	-

Appendix C:

C.1 Sensor list building systems Kropman Breda office

Sensor code	Sensor name	Measures	Level	Units	Accuracy level	Time constant	Notes
1-1TT1	Supply temperature sensor boiler	Temperature	Building	°C	0,1	History, 180 points a day (480 sec.)	
1-1TT2	Return temperature sensor boiler	Temperature	Building	°C	0,1	History, 180 points a day (480 sec.)	
1-2TT1	Room temperature sensor	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	Room F
1-2TT2	Outside NO temperature sensor	Temperature	Environment	°C	0,1	History, 180 points a day (480 sec.)	
1-2TT3	Supply temperature sensor Radiators NO	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-2TT4	Return temperature sensor Radiators NO	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-2TT5	Cafeteria temperature sensor	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-2TT6	Meeting room temperature sensor	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-3TT1	Outside SW temperature sensor	Temperature	Environment	°C	0,1	History, 180 points a day (480 sec.)	
1-3TT2	Supply temperature sensor Radiators SW	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-3TT3	Return temperature sensor Radiators SW	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-5PdT1	Pressure differential Supply filter	Pressure	Building	Pa	1	History, 180 points a day (480 sec.)	
1-5TT1	Supply temperature sensor heater air handling unit	Temperature	Building	°C	0,1	History, 180 points a day (480 sec.)	
1-5TZA1	Frost protection thermostat	Temperature	Building	°C	0,1	History, 180 points a day (480 sec.)	Mechanical, switching, and alarming
1-5XT1	Combined temperature and humidity sensor supply air	Temperature and humidity	Building	°C and %r.h.	0,1 / 0,1	History, 180 points a day (480 sec.)	
1-5MS1	Maximum humidistat	Humidity	Building	%r.h.	0,1	History, 180 points a day (480 sec.)	Mechanical, switching
1-5PT1	Pressure sensor supply air	Pressure	Building	Pa	1	History, 180 points a day (480 sec.)	
1-5PdT2	Pressure differential Outlet filter	Pressure	Building	Pa	1	History, 180 points a day (480 sec.)	
1-4TT1	Supply temperature sensor chiller	Temperature	Building	°C	0,1	History, 180 points a day (480 sec.)	
1-4TT2	Return temperature sensor chiller	Temperature	Building	°C	0,1	History, 180 points a day (480 sec.)	
1-4PdA1	Pressure difference switch over chiller	Pressure	Building	on / off	-	History, 180 points a day (480 sec.)	Switching and status of chiller
1-6TT1	Supply air temperature South after cooler	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-6TT2	Exhaust air temperature South	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-7TT1	Supply air temperature North after cooler	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-7TT2	Exhaust air temperature North	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-8TT1	Supply air temperature Electrical engineering room after cooler	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-8TT2	Room temperature sensor Electrical engineering room	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	
1-9TT1	Room temperature sensor storage room	Temperature	Zone/Room	°C	0,1	History, 180 points a day (480 sec.)	

🟩 Room measurement

🟦 Outside measurement

🟧 Process measurement

Appendix D:

D.1 System components list Kropman Breda office

System code	System name	Notes	Level
1-1KK1	Boiler	Remeha Gas 210 Eco Pro 160	Building
1-1CP01	Boiler circulation pump	Grundfos UP 32-80 180 Class F	Building
1-2CV1	Control valve Radiator group NO	Landis & Gyr (Siemens) VXG 44.25-10 kvs=10	Zone/Room
1-2CP1	Circulation pump Radiator group NO	Grundfos Type UPS 25-40 Class F	Zone/Room
1-2CV2	Control valve Radiator group cafeteria		Zone/Room
1-2CV3	Control valve Radiator group meeting room		Zone/Room
1-3CV1	Control valve Radiator group SW	Landis & Gyr (Siemens) VXG 44.25-10 kvs=10	Zone/Room
1-3CP1	Circulation pump Radiator group SW	Grundfos Type UPS 25-40 Class F	Zone/Room
1-5XV1	Intake damper air handling unit		Building
1-5WW1	Heat recovery wheel		Building
1-5CV1	Control valve heater air handling unit	Landis & Gyr (Siemens) VXG 44.40-25 kvs=25	Building
1-5CP1	Circulation pump heater air handling unit	Grundfos Type UM 32-20 200 Class F	Building
1-5TV1	Supply ventilator air handling unit		Building
1-5ST1	Steam humidifier	Vapac VP30 30kg/h	Building
1-5AV1	Exhaust ventilator air handling unit		Building
1-5XV2	Outlet damper air handling unit		Building
1-7LK1	Intake damper cafeteria		Zone/Room
1-7LK2	Outlet damper cafeteria		Zone/Room
1-4KM01	Chiller	York Type: EACC 25 Kap: 70,9 kW	Building
1-4CP01	Circulation pump chiller	GKw pomp Type: UPK40-180F02	Building
1-4XX1	Trace heating		Building
1-9RV1	Recirculation ventilator		Zone/Room
1-10-AV1	Toilet exhaust ventilator		Zone/Room
1-6CV1	Control valve air cooling South		Zone/Room
1-7CV1	Control valve air cooling North		Zone/Room
1-8CV1	Control valve air cooling Electrical engineering room		Zone/Room
	🟥	Heating process	
	🟦	Cooling process	
	🟩	Ventilation process	

Appendix E:

E.1 Floor plans Kropman Breda office

First, the floor plan of the first floor is presented.

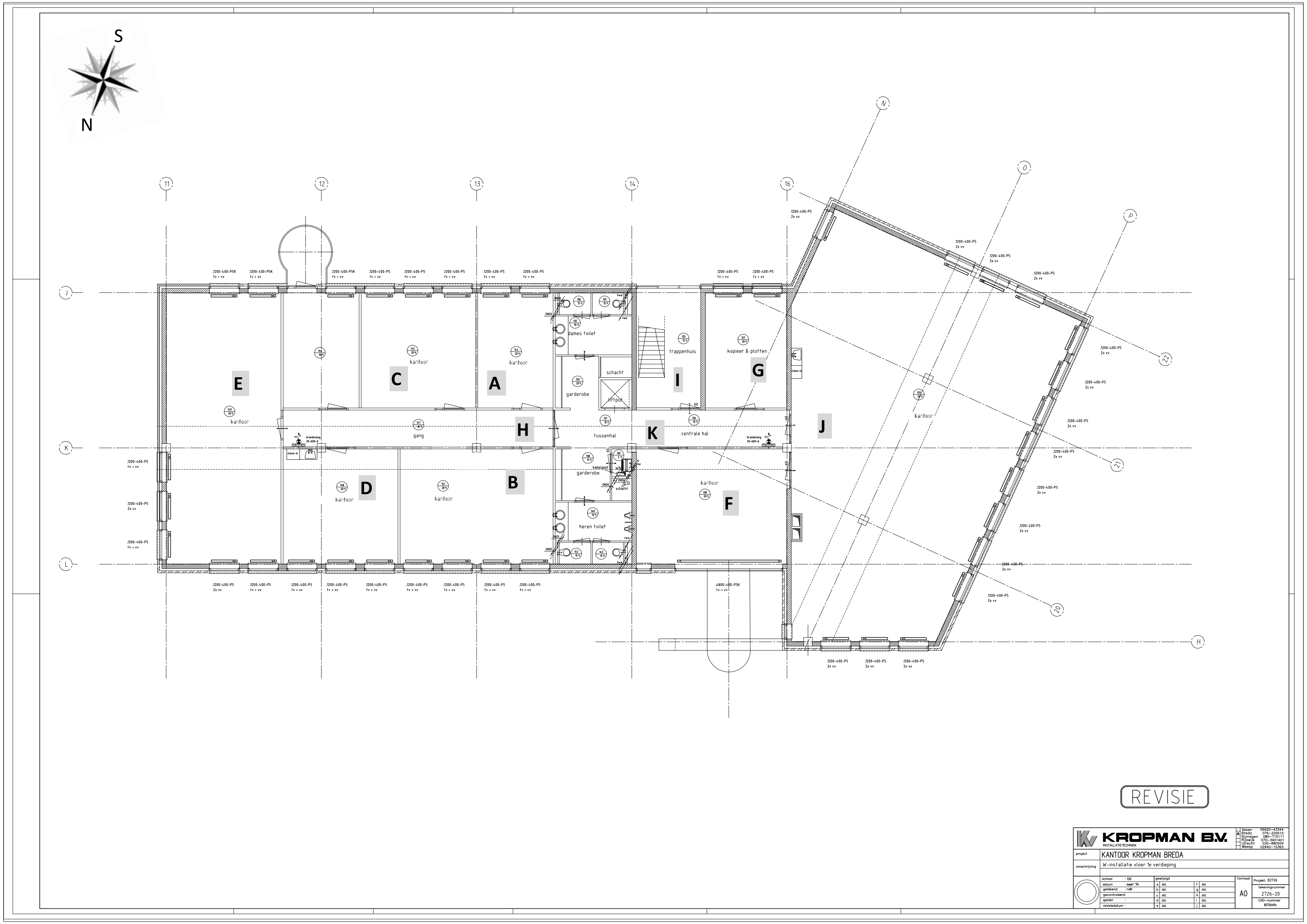
Second, the floor plan of the first floor with the heating (radiators), ventilation (exhaust and supply) systems, and split unit pictured.

Third, the floor plan of the first floor with the positions of additional measurement equipment. Details of the measurement equipment in the rooms can be found in Appendix F.

Fourth, lighting and desks are pictured in the floor plan of the first floor.

Fifth, positions of the PlugWise Circles in the floor plan of the first floor are shown.

Sixth, positions of the Voltcraft energy loggers in the floor plan of the first floor are shown.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schaal : 1:50
datum : maart '94
getekend : rvdh
gecontroleerd:
gezien :
revisiedatum :
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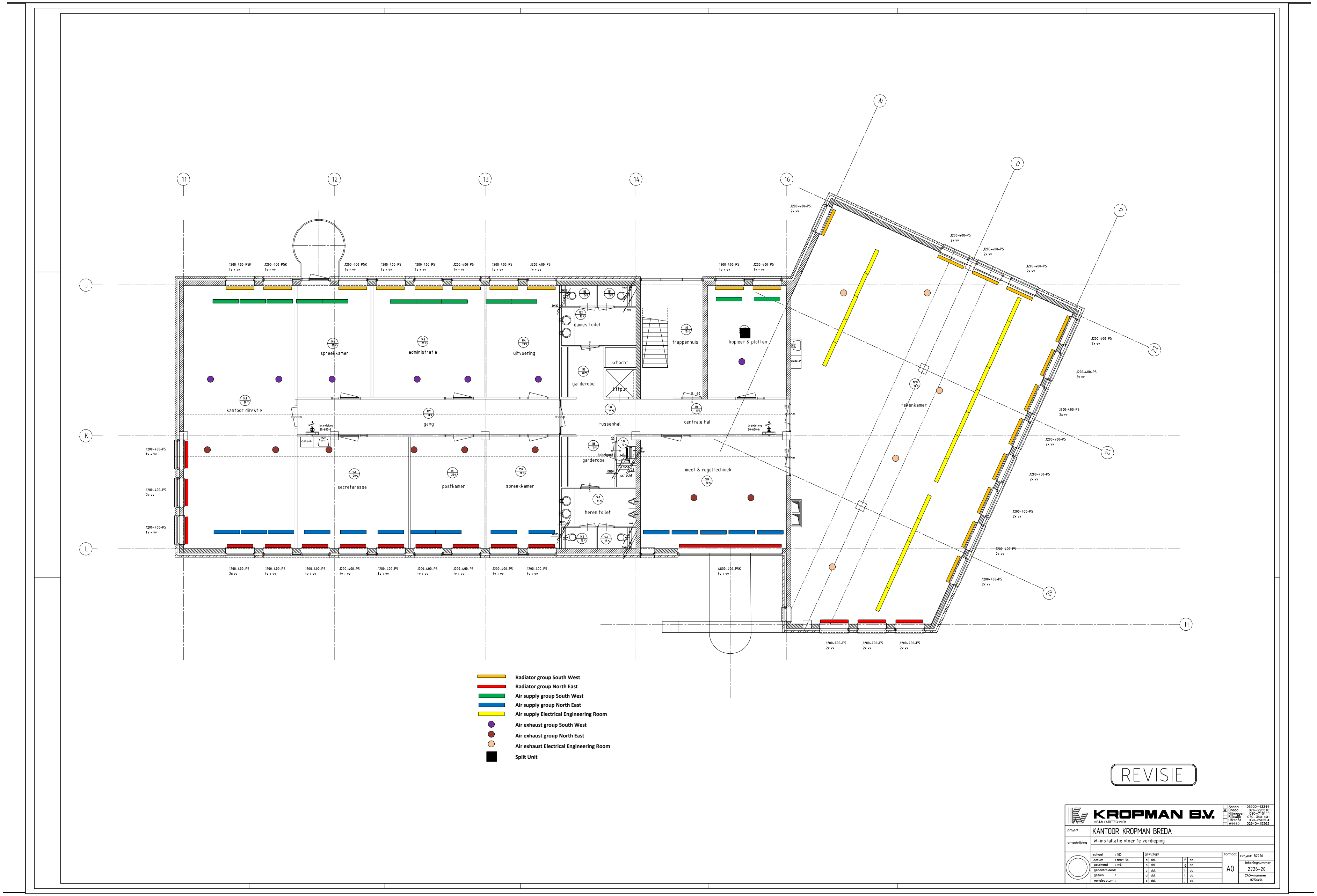
tekeningnummer 2726-20
CAD-nummer B2726V04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Air supply Electrical Engineering Room
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INSTALLATIETECHNIEK
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Breda 076-225510
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Weesp 02940-15363
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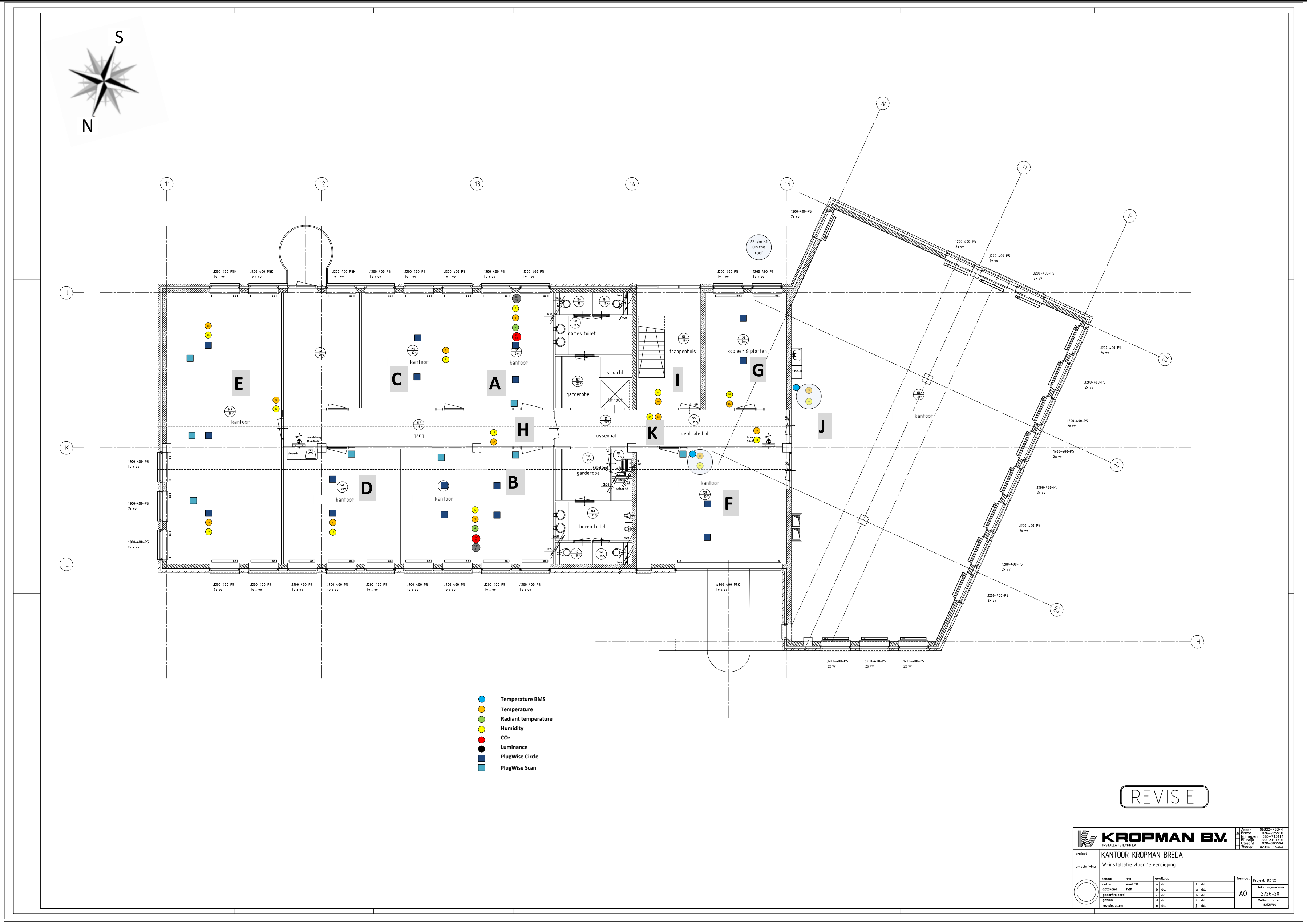
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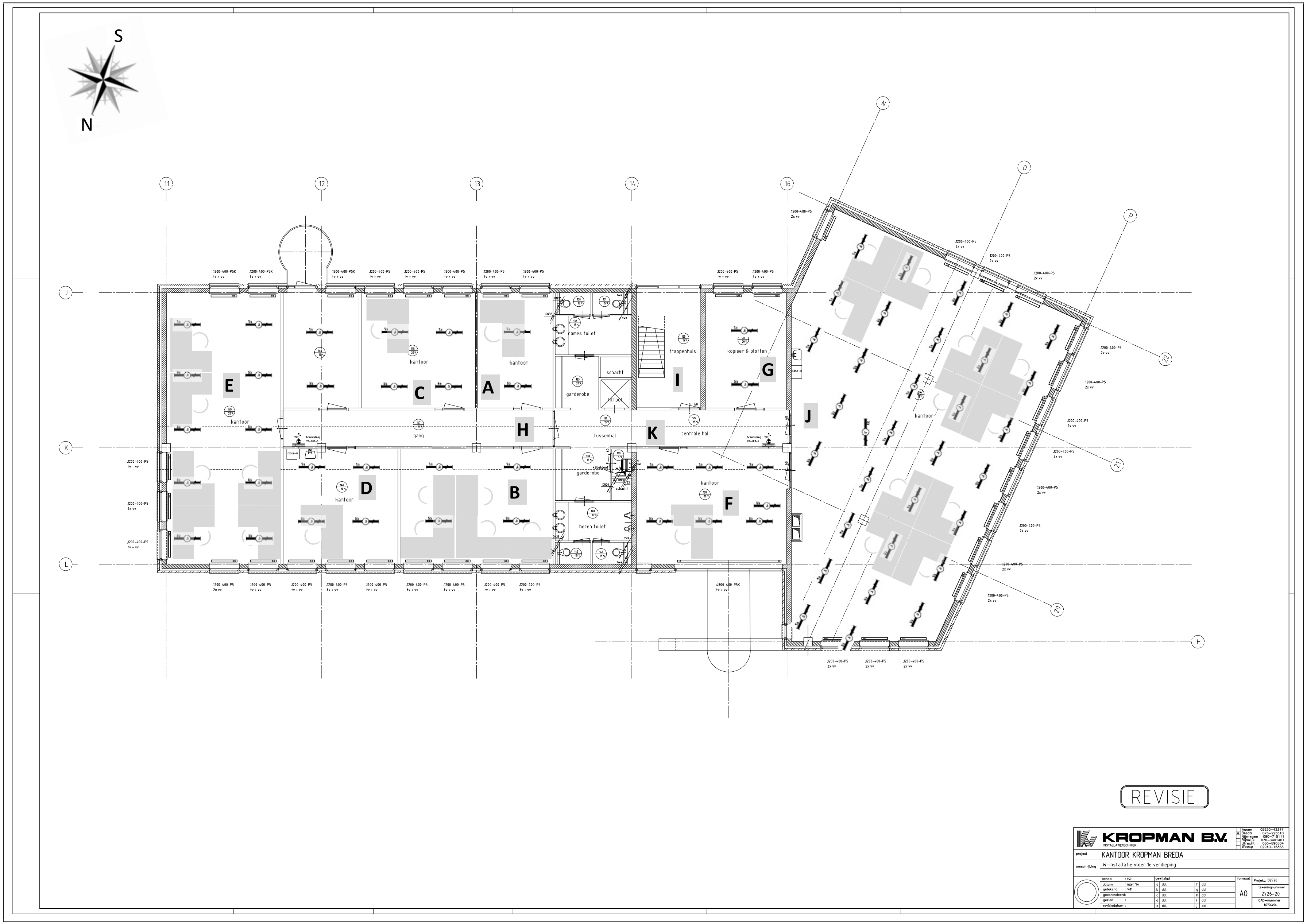
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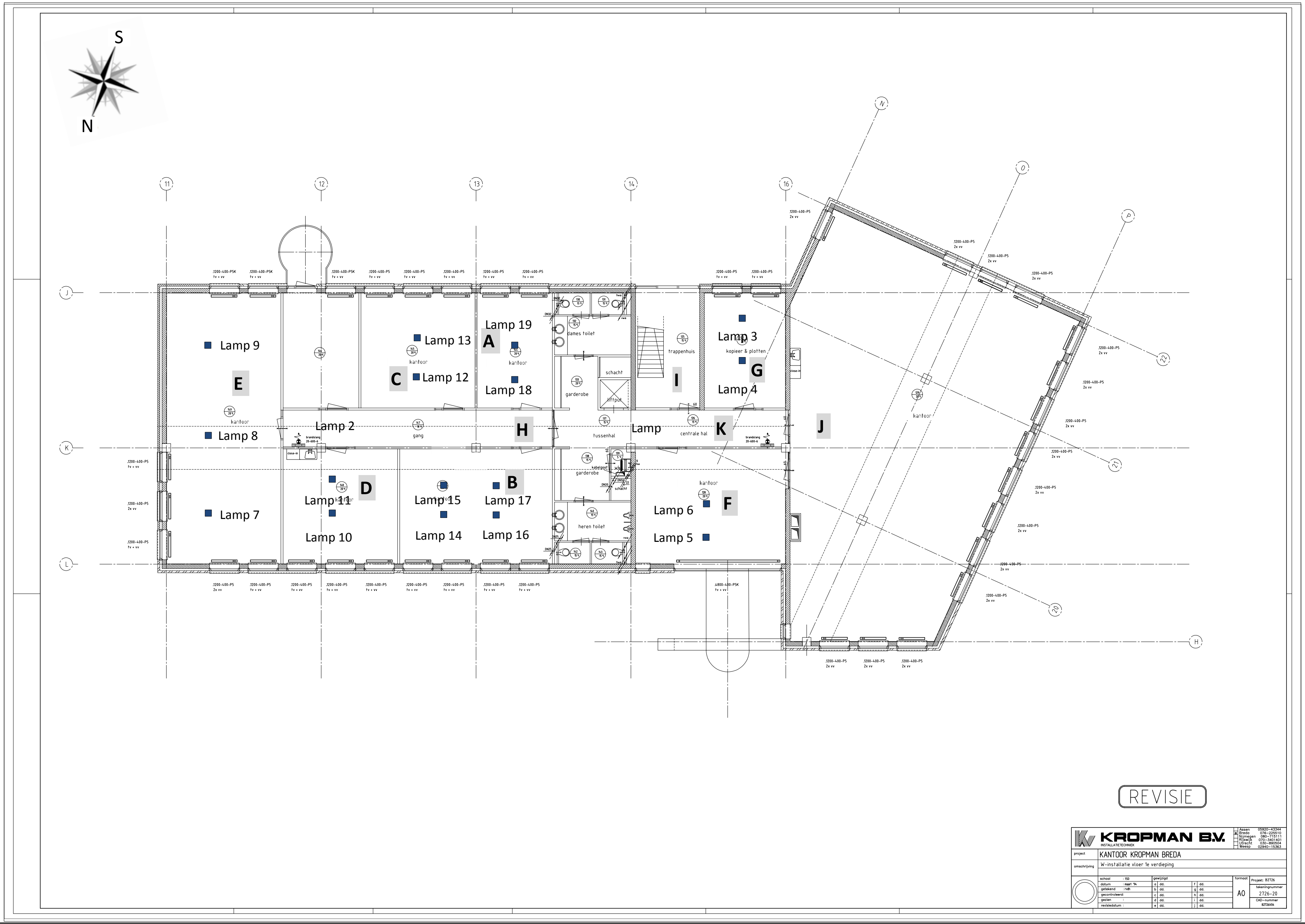
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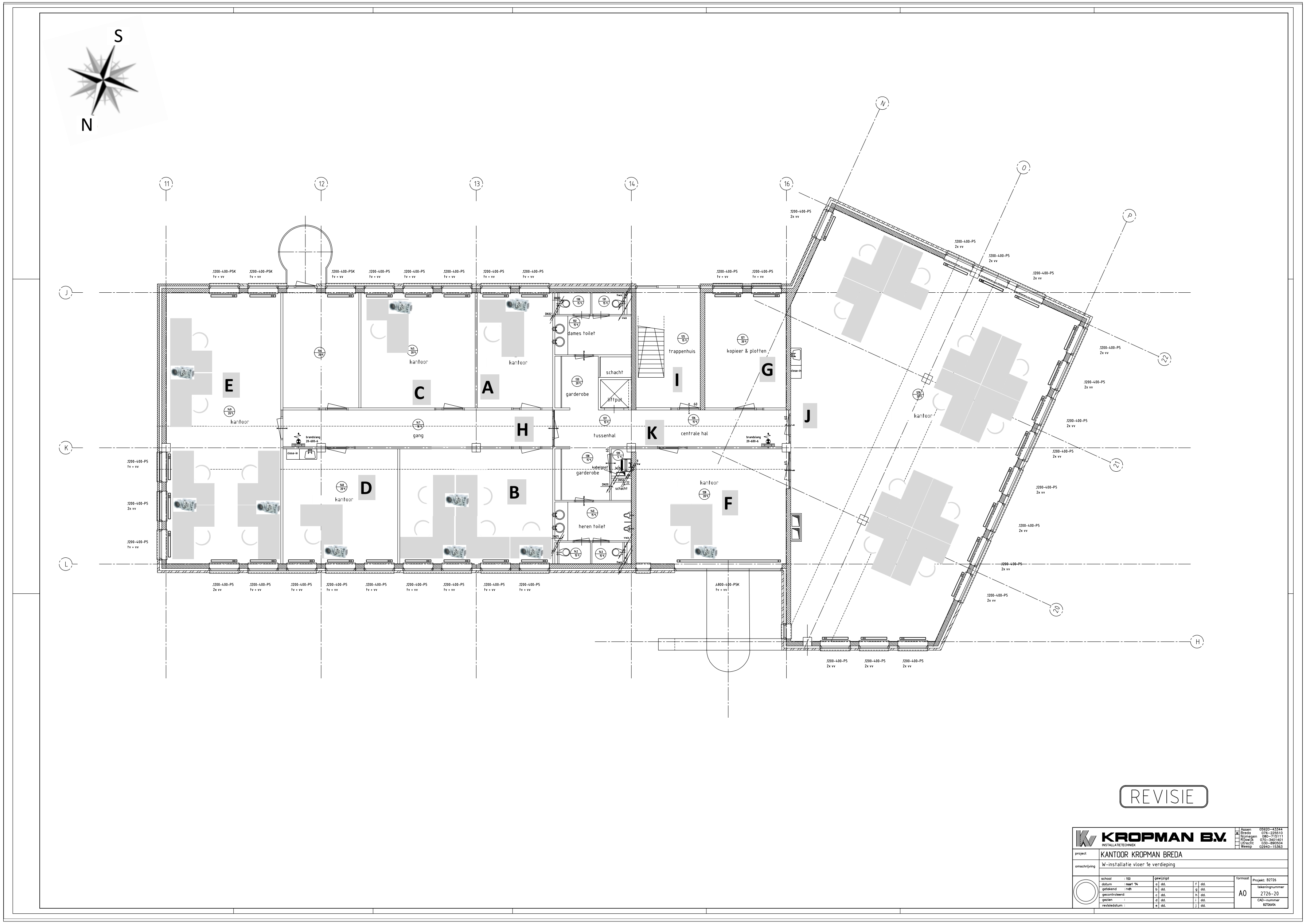
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CAD-nummer B2726V04

Appendix F:

F.1 Positioning and details additional measurement equipment

This appendix gives the details and positions of additional measurement equipment for each room.

Room A

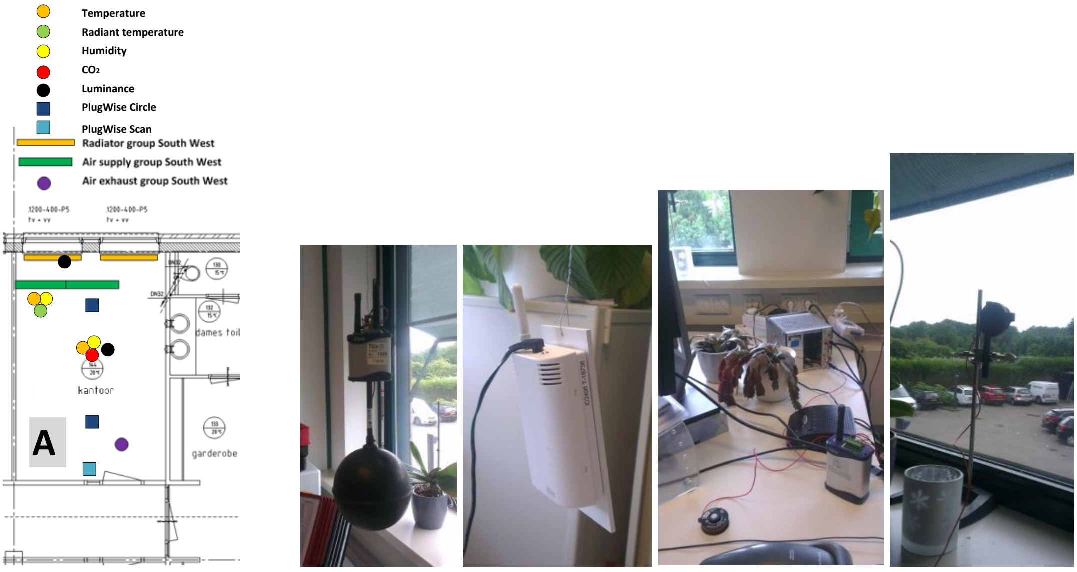


Figure 61: From left to right; measurement positions, black globe temperature and humidity measurement equipment, CO_2 temperature and humidity measurement equipment, illuminance measurement equipment on the desk, illuminance measurement equipment in front of the window.

Table 19: Equipment details room A

Description	ID number TU/e	Network ID	Range	Accuracy
Black globe T/RH	1539	6878	BG: 0 - 50 °C T: -10 – 55 °C RH: 0 -95 %	BG: ± 0.05 °C T: ± 0.2 °C RH: ± 2 %
T/RH/CO_2 transmitter	2498	18738	CO_2: 0 – 5000 ppm T: 5 – 45 °C RH: 0 -100 %	CO_2: ± (50+2%) ppm °C T: ± 0.4 °C RH: ± 2 %
Illuminance	1662 / 924	5311	133.5 pA/lux	
Laptop and data logger	0251			

Room B

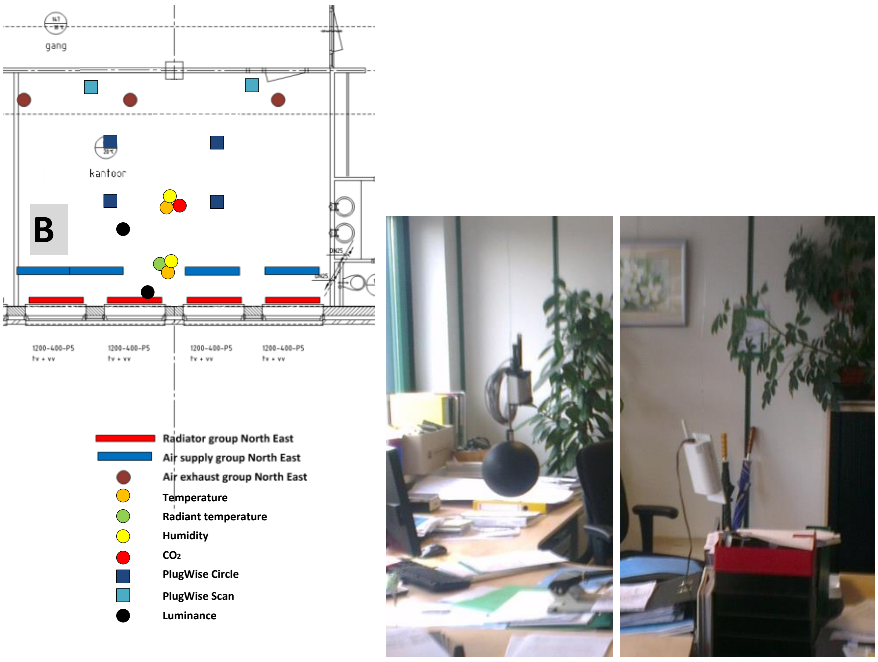


Figure 62: From left to right; measurement positions, black globe temperature and humidity measurement equipment, CO_2 temperature and humidity measurement equipment.

Table 20: Equipment details room B

Description	ID number TU/e	Network ID	Range	Accuracy
Black globe T/RH	1537	6876	BG: 0 - 50 °C T: -10 – 55 °C RH: 0 -95 %	BG: ± 0.05 °C T: ± 0.2 °C RH: ± 2 %
T/RH/CO_2 transmitter	2497	18737	CO_2: 0 – 5000 ppm T: 5 – 45 °C RH: 0 -100 %	CO_2: ± (50+2%) ppm °C T: ± 0.4 °C RH: ± 2 %
Illuminance	979 / 1991	3792	101.8 pA/lux	

Room C

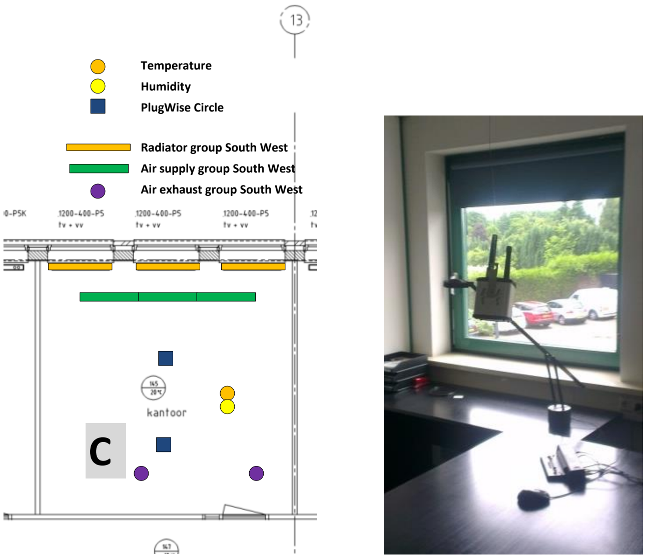


Figure 63: From left to right; measurement positions, temperature and humidity measurement equipment.

Table 21: Equipment details room C

Description	ID number TU/e	Network ID	Range	Accuracy
Temperature / Relative Humidity	1497	6795	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %

Room D

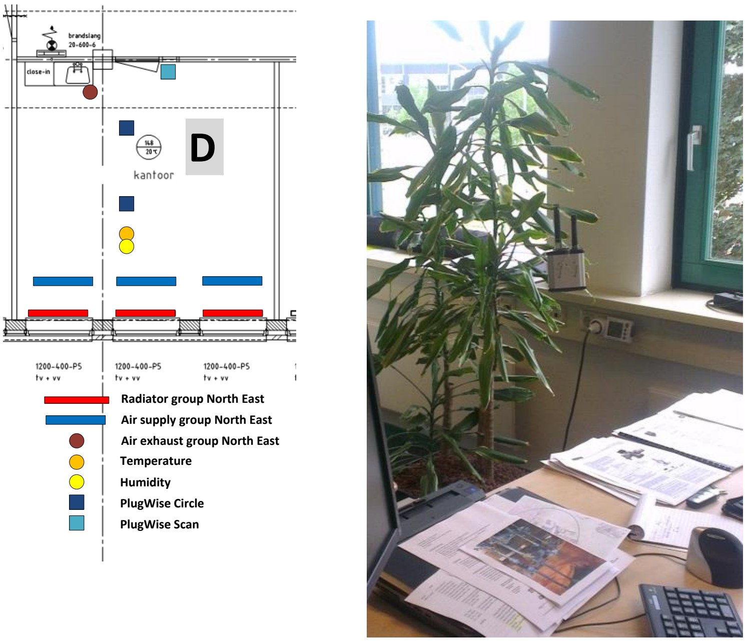


Figure 64: From left to right; measurement positions, temperature and humidity measurement equipment.

Table 22: Equipment details room D

Description	ID number TU/e	Network ID	Range	Accuracy
Temperature / Relative Humidity	1511	6810	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %

Room E

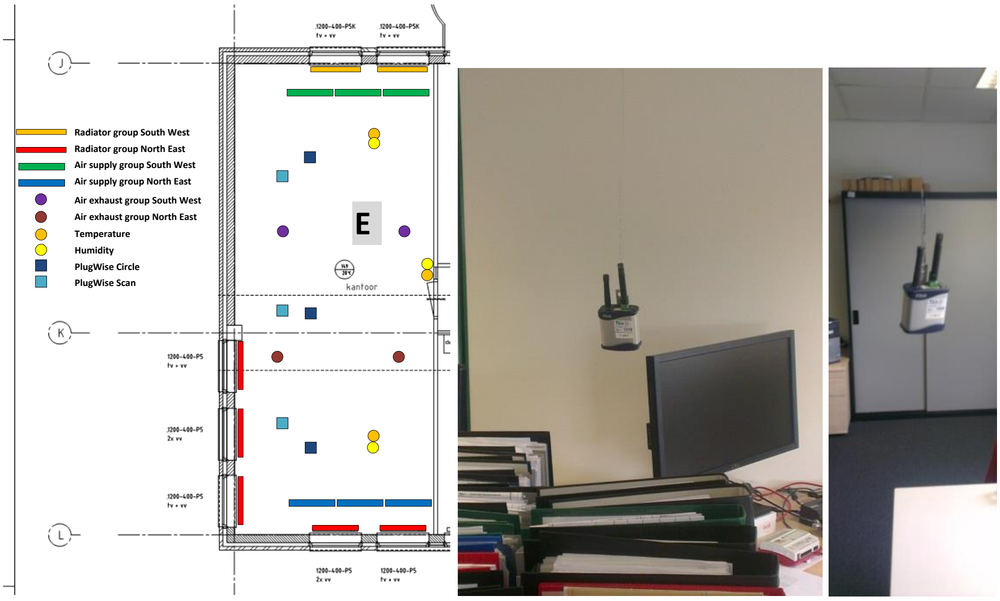


Figure 65: From left to right; measurement positions, temperature and humidity measurement equipment north side of the room, temperature and humidity measurement equipment south side of the room.

Table 23: Equipment details room E

Description	ID number TU/e	Network ID	Range	Accuracy
Temperature / Relative Humidity	1518	6817	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %
Temperature / Relative Humidity	1534	6833	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %
Temperature / Relative Humidity From 16-09-2013	1532	6831	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %

Room F

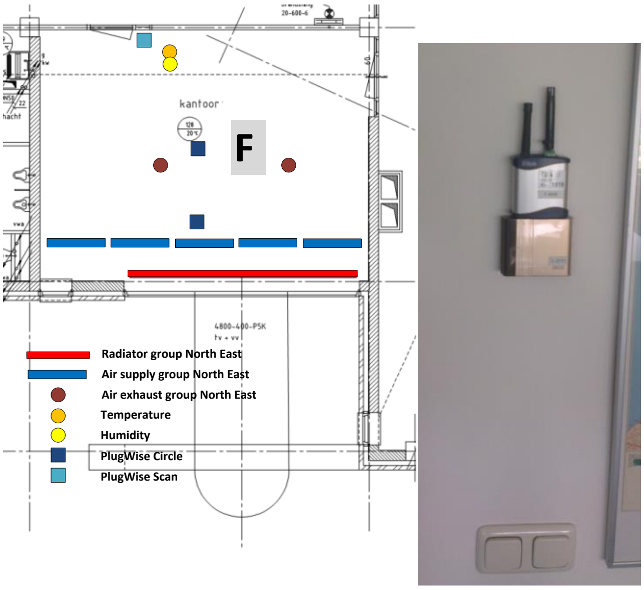


Figure 66: From left to right; measurement positions, temperature and humidity measurement equipment.

Table 24: Equipment details room F

Description	ID number TU/e	Network ID	Range	Accuracy
Temperature / Relative Humidity Till 06-09-2013	1519	6818	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %

Room G

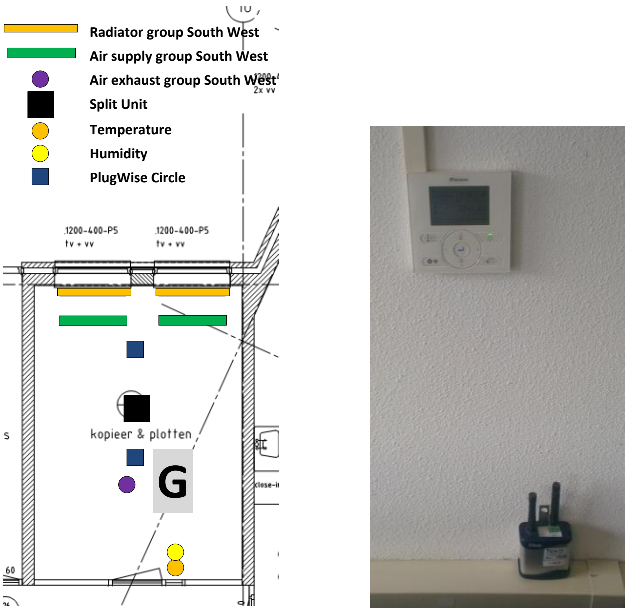


Figure 67: From left to right; measurement positions, temperature and humidity measurement equipment.

Table 25: Equipment details room G

Description	ID number TU/e	Network ID	Range	Accuracy
Temperature / Relative Humidity	1520	6819	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %

Room H

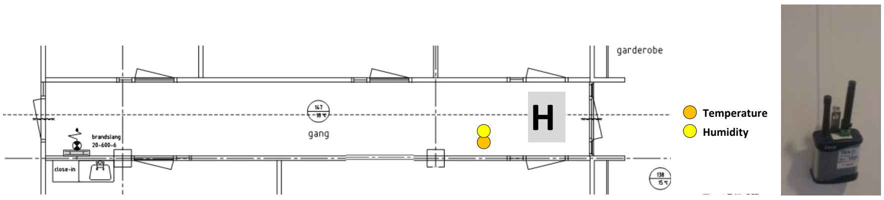


Figure 68: From left to right; measurement positions, temperature and humidity measurement equipment.

Table 26: Equipment details room H

Description	ID number TU/e	Network ID	Range	Accuracy
Temperature / Relative Humidity	1521	6820	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %

Room I

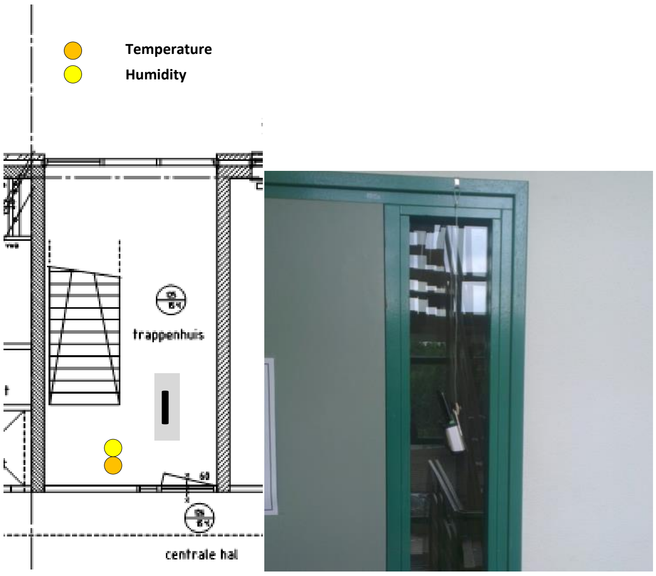


Figure 69: From left to right; measurement positions, temperature and humidity measurement equipment.

Table 27: Equipment details room I

Description	ID number TU/e	Network ID	Range	Accuracy
Temperature / Relative Humidity	1531	6830	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %

Room J

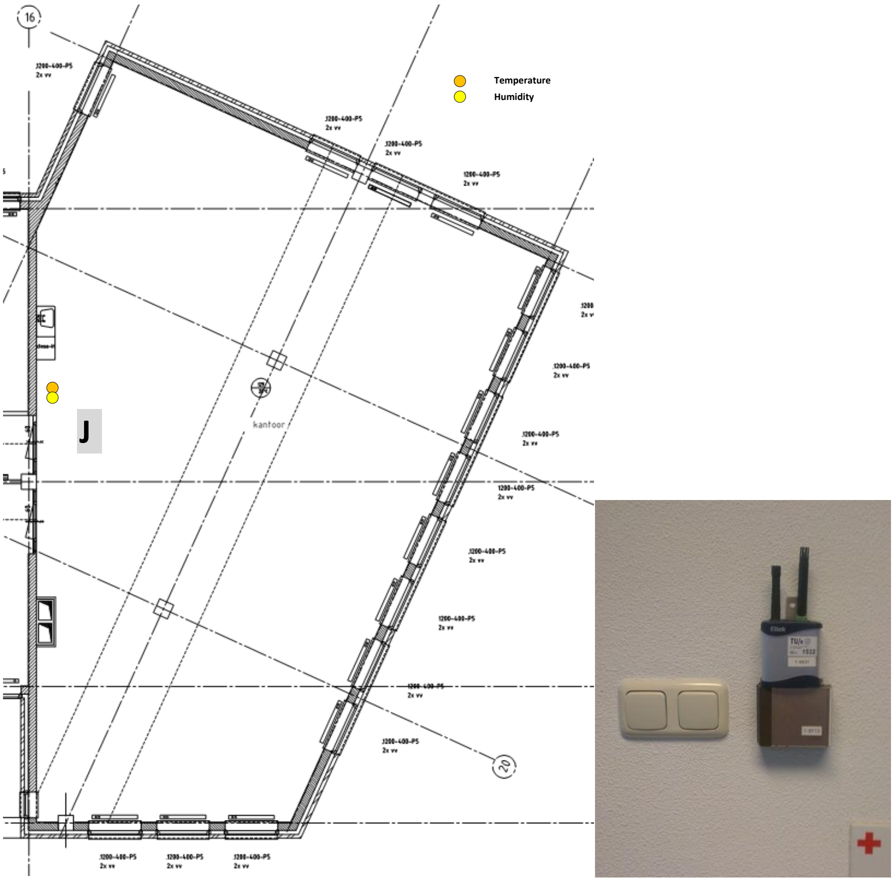


Figure 70: From left to right; measurement positions, temperature and humidity measurement equipment.

Table 28: Equipment details room J

Description	ID number TU/e	Network ID	Range	Accuracy
Temperature / Relative Humidity Till 06-09-2013	1532	6831	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %

Room K

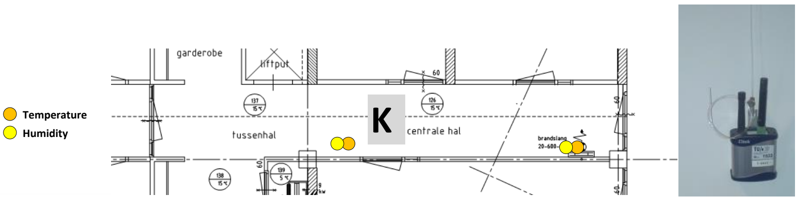


Figure 71: From left to right; measurement positions, temperature and humidity measurement equipment.

Table 29: Equipment details room K

Description	ID number TU/e	Network ID	Range	Accuracy
Temperature / Relative Humidity	1533	6832	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %
Temperature / Relative Humidity From 16-09-2013	1519	6818	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %

Rooftop weather station

Figure 72: On the left in the picture temperature and humidity measurement equipment and on the right the pyranometer.

Table 30: Equipment details rooftop

Description	ID number TU/e	Network ID	Range	Accuracy
Temperature / Relative Humidity	1456	7023	T: -10 – 55 °C RH: 0 -95 %	T: ± 0.2 °C RH: ± 2 %
Pyranometer	2515	17240	0 – 1500 W/m²	0.375 mW/m²

Appendix G:

G.1 Temperature measurement comparisons

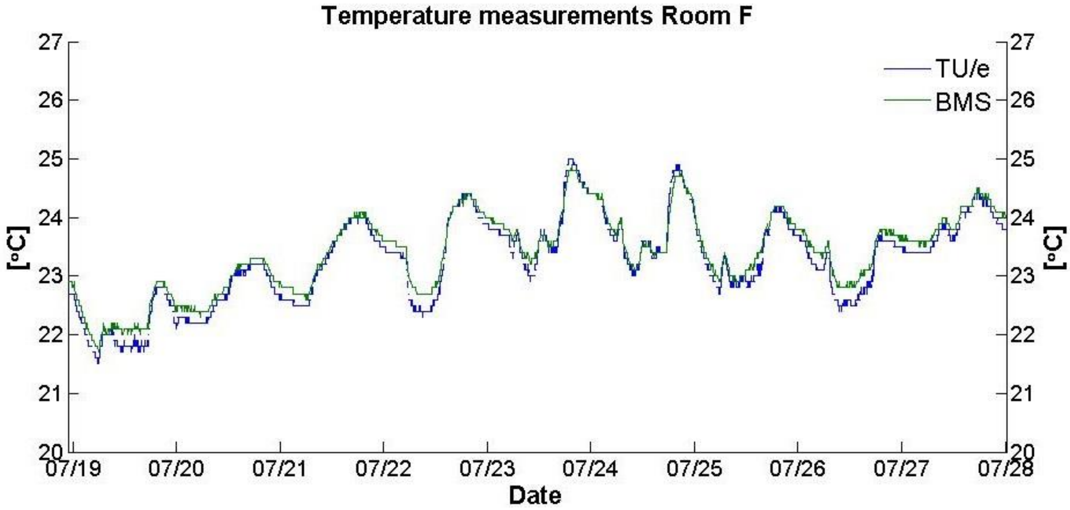


Figure 73: Temperature measurement comparison between the measured values of the BMS and TU/e equipment situated in Room F.

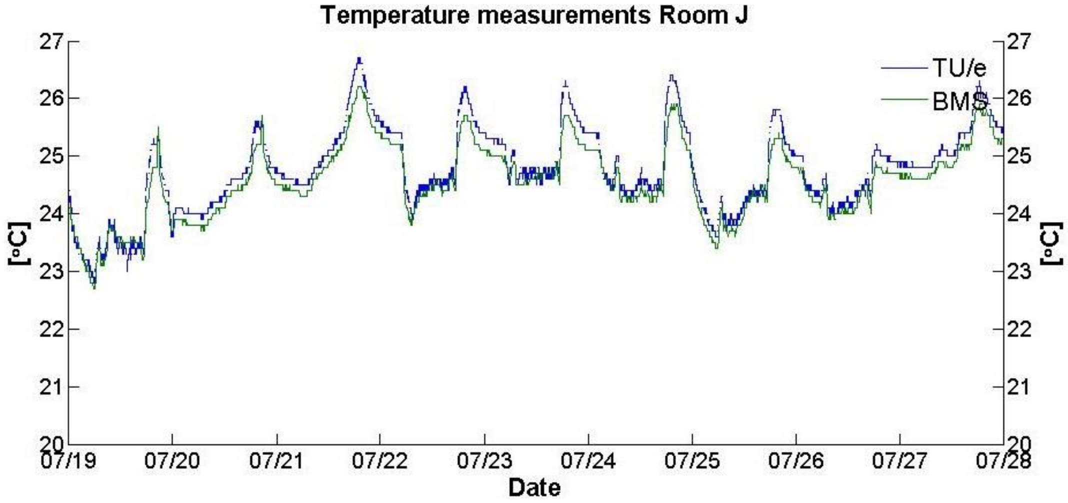


Figure 74: Temperature measurement comparison between the measured values of the BMS and TU/e equipment situated in Room J.

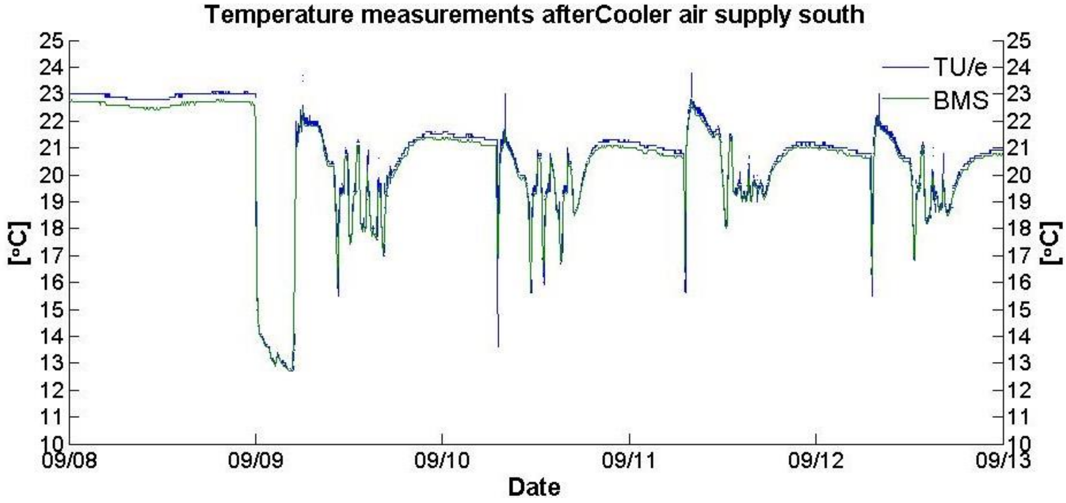


Figure 75: Temperature measurement comparison between the measured values of the BMS and TU/e equipment situated in the air duct directly after the duct cooler of the air supply south.

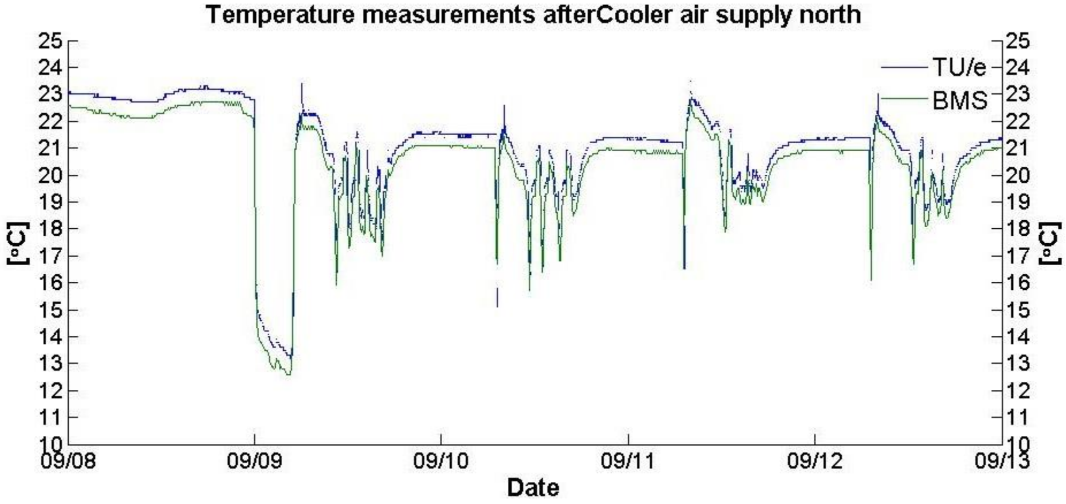


Figure 76: Temperature measurement comparison between the measured values of the BMS and TU/e equipment situated in the air duct directly after the duct cooler of the air supply north.

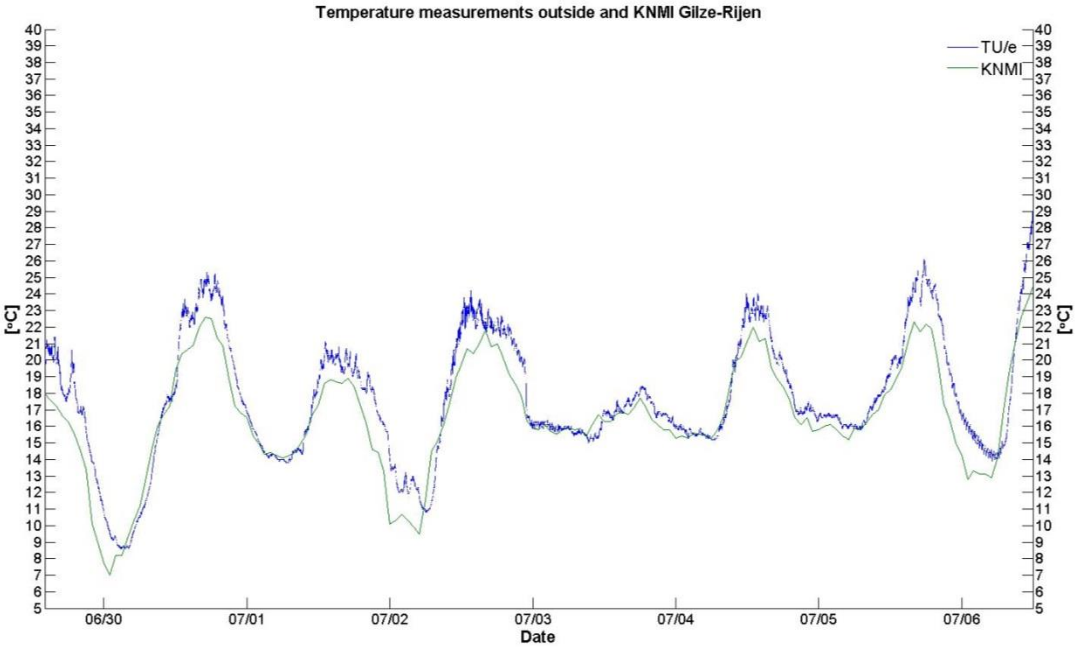


Figure 77: Temperature measurement comparison between the measured values of the KNMI Weather Station Gilze-Rijen and TU/e equipment situated at the roof of the building.

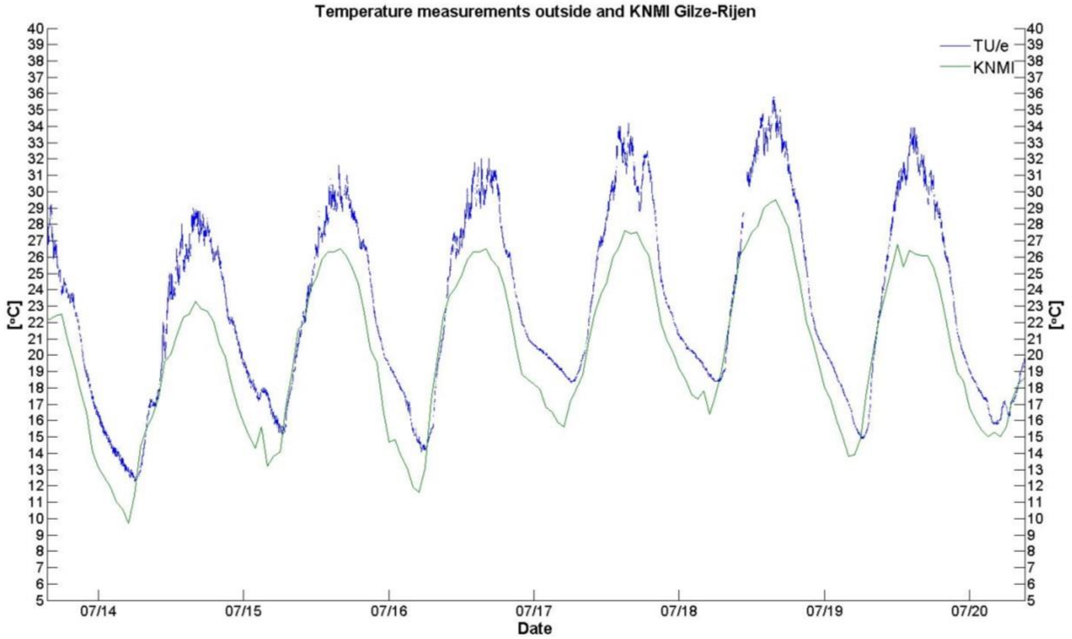


Figure 78: Temperature measurement comparison between the measured values of the KNMI Weather Station Gilze-Rijen and TU/e equipment situated at the roof of the building.

Data synchronised by adjusting the Daylight Saving Time (DST) which the measured data is clocked by since the Windows operation system automatically determines the clock setting based on location and thus takes DST into account, while the KNMI climate file does not change the time due to DST.

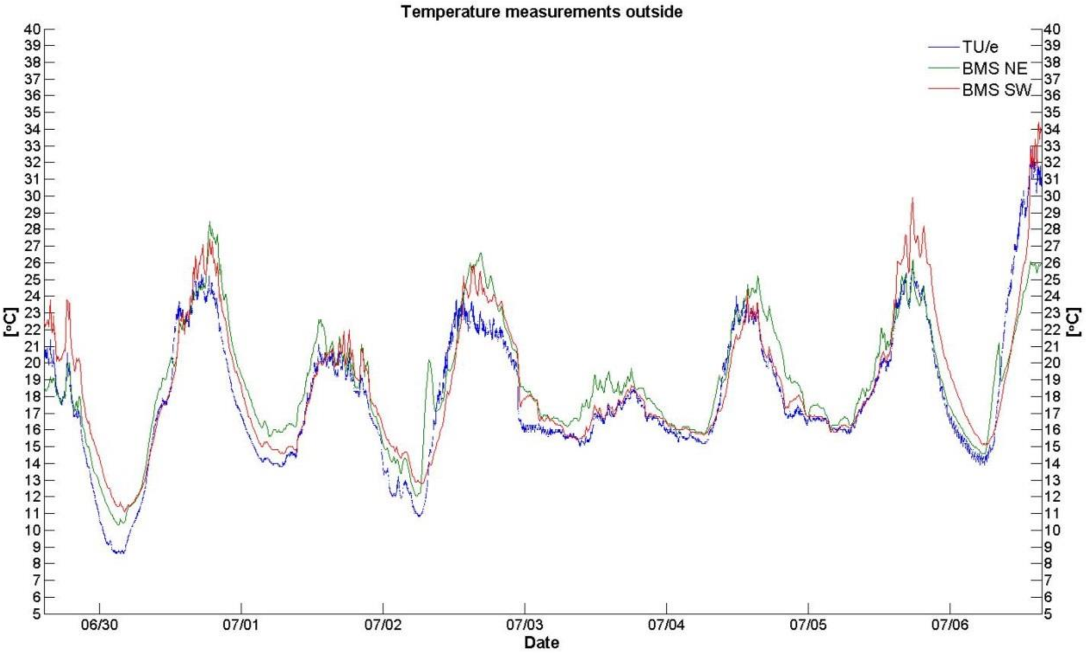


Figure 79: Temperature measurement comparison between the measured values of the BMS and TU/e equipment situated at the roof of the building.

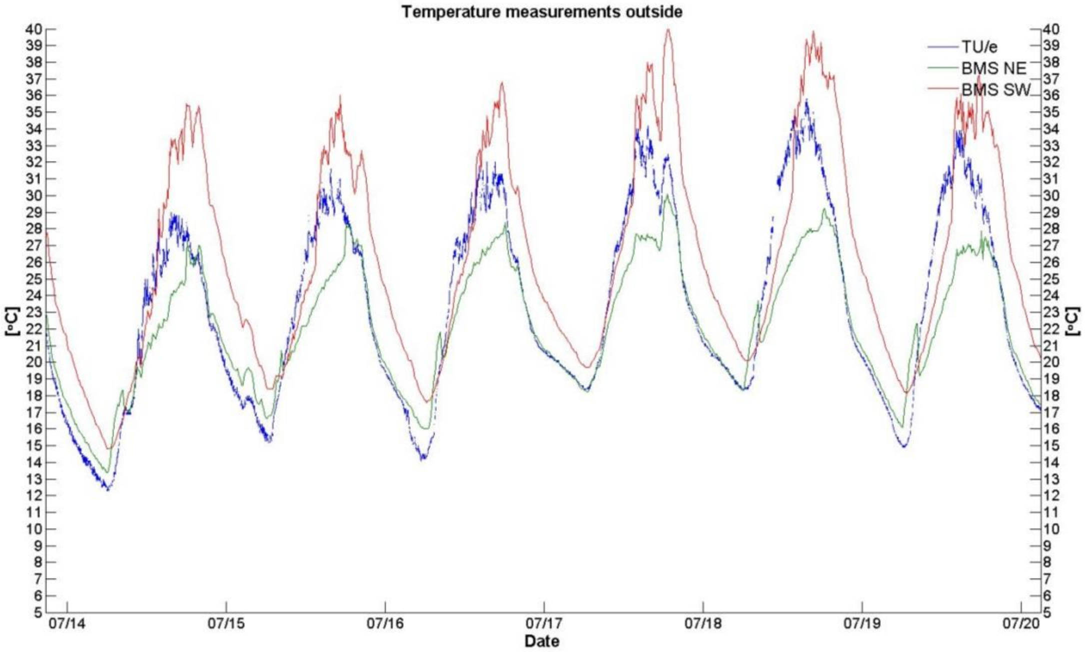


Figure 80: Temperature measurement comparison between the measured values of the BMS and TU/e equipment situated at the roof of the building.

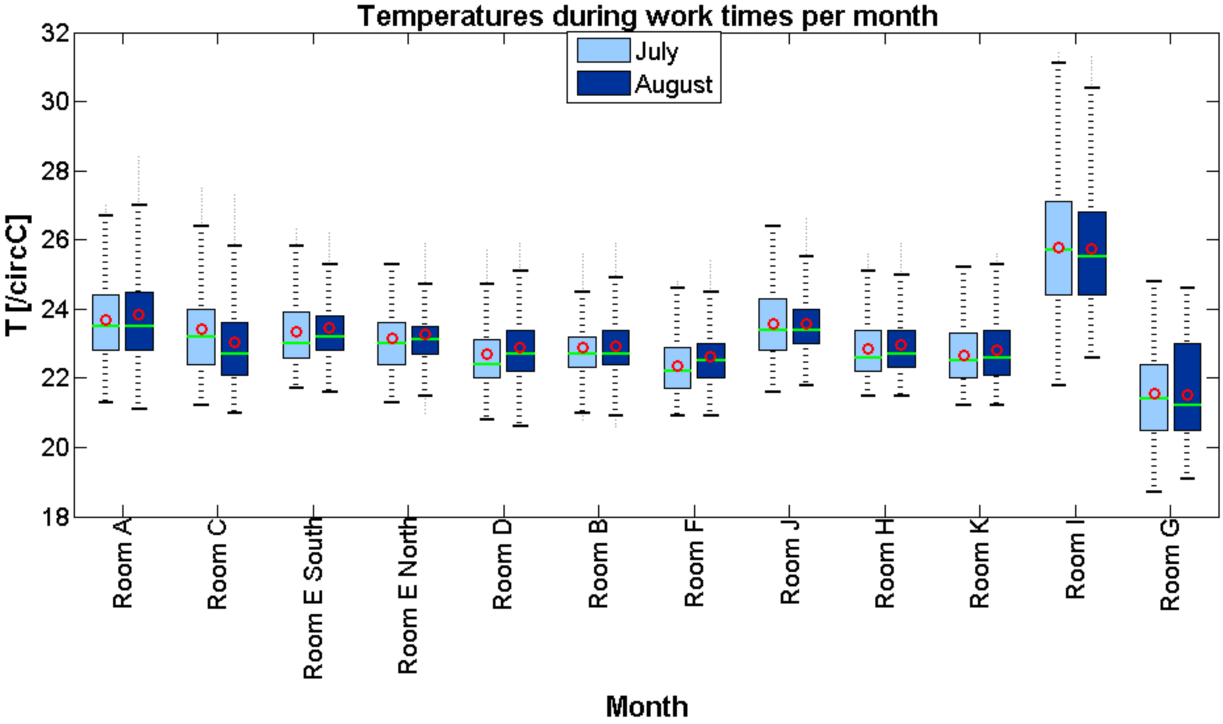


Figure 81: Boxplot of measured temperatures during work times in July and August per room.

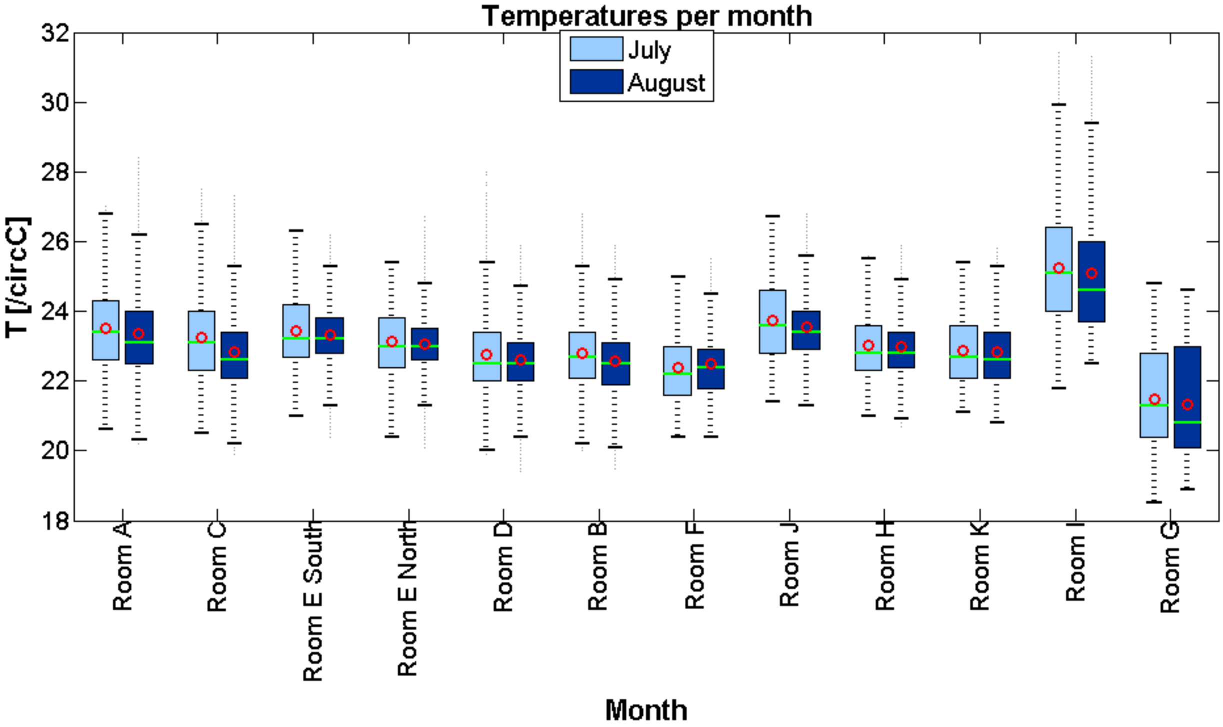


Figure 82: Boxplot of measured temperatures in July and August per room.

Appendix H:

H.1 Results questionnaire

The questionnaire held during the project is in Dutch.

Geslacht

Man	92.31 %
Vrouw	7.69 %

n = 13
# 13

Leeftijdscategorie

< 20 jaar	0 %
20 – 30 jaar	0 %
31 – 40 jaar	38.46 %
41 – 50 jaar	53.85 %
51 – 60 jaar	7.69 %
> 60 jaar	0 %

n = 13
# 13

Verdieping werkplek:

2e verdieping	15.38 %
1e verdieping	84.62 %
Begane Grond	0 %

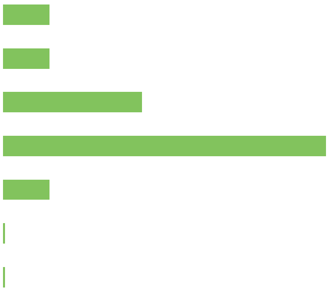
n = 13
# 13

Temperatuur in kantoor in de winter van 'Comfortabel' tot 'Oncomfortabel' (-)

1 Comfortabel	23.08 %
2	46.15 %
3	15.38 %
4 Neutraal	7.69 %
5	7.69 %
6	0 %
7 Oncomfortabel	0 %

n = 13
# 13

Temperatuur in kantoor in de winter
van 'Te warm' tot 'Te koud' (-)



1 Te warm	7.69 %
2	7.69 %
3	23.08 %
4	53.85 %
5	7.69 %
6	0 %
7 Te koud	0 %

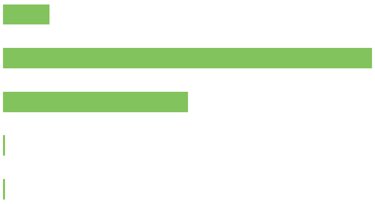
n = 13
# 13

Temperatuur in kantoor in de winter
van 'Gehele dag stabiel' tot 'Variërend gedurende de dag' (-)

1 Gehele dag stabiel	15.38 %
2	30.77 %
3	15.38 %
4	23.08 %
5	15.38 %
6	0 %
7 Variërend gedurende de dag	0 %

n = 13
# 13

Luchtkwaliteit in kantoor in de winter
van 'Droog' tot 'Vochtig' (-)



1 Droog	7.69 %
2	61.54 %
3	30.77 %
4	0 %
5 Vochtig	0 %

n = 13
# 13

Luchtkwaliteit in kantoor in de winter
van 'Fris' tot 'Bedompt' (-)

1 Fris	7.69 %
2	23.08 %
3	61.54 %
4	7.69 %
5 Bedompt	0 %

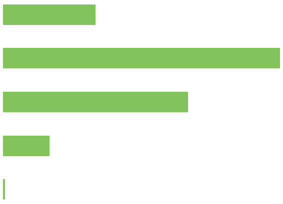
n = 13
# 13

Luchtkwaliteit in kantoor in de winter van 'Geurloos' tot 'Stinkend' (-)

1 Geurloos	23.08 %
2	30.77 %
3	46.15 %
4	0 %
5 Stinkend	0 %

n = 13
# 13

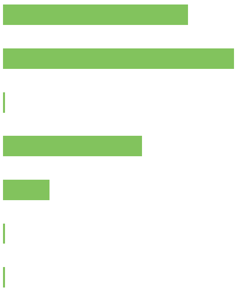
Luchtkwaliteit in kantoor in de winter van 'Bevredigend' tot 'Onbevredigend' (-)



1 Bevredigend	15.38 %
2	46.15 %
3	30.77 %
4	7.69 %
5 Onbevredigend	0 %

n = 13
# 13

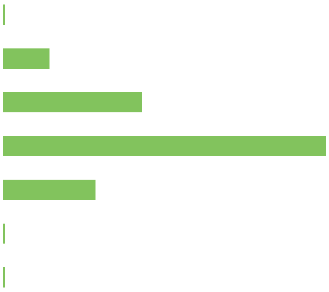
Temperatuur in kantoor in de zomer van 'Comfortabel' tot 'Oncomfortabel' (-)



1 Comfortabel	30.77 %
2	38.46 %
3	0 %
4 Neutraal	23.08 %
5	7.69 %
6	0 %
7 Oncomfortabel	0 %

n = 13
# 13

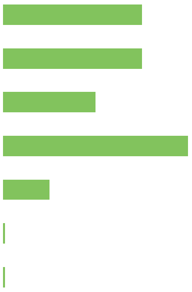
Temperatuur in kantoor in de zomer van 'Te warm' tot 'Te koud' (-)



1 Te warm	0 %
2	7.69 %
3	23.08 %
4	53.85 %
5	15.38 %
6	0 %
7 Te koud	0 %

n = 13
# 13

Temperatuur in kantoor in de zomer
van 'Gehele dag stabiel' tot 'Variërend gedurende de dag' (-)



1 Gehele dag stabiel	23.08 %
2	23.08 %
3	15.38 %
4	30.77 %
5	7.69 %
6	0 %
7 Variërend gedurende de dag	0 %

n = 13
# 13

Luchtkwaliteit in kantoor in de zomer
van 'Droog' tot 'Vochtig' (-)

1 Droog	0 %
2	38.46 %
3	53.85 %
4	7.69 %
5 Vochtig	0 %

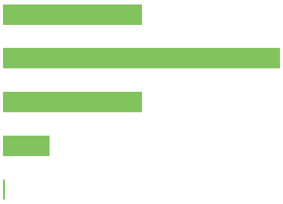
n = 13
# 13

Luchtkwaliteit in kantoor in de zomer
van 'Fris' tot 'Bedompt' (-)

1 Fris	7.69 %
2	30.77 %
3	53.85 %
4	7.69 %
5 Bedompt	0 %

n = 13
# 13

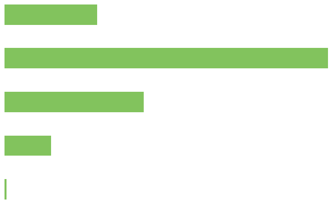
Luchtkwaliteit in kantoor in de zomer
van 'Geurloos' tot 'Stinkend' (-)



1 Geurloos	23.08 %
2	46.15 %
3	23.08 %
4	7.69 %
5 Stinkend	0 %

n = 13
# 13

Luchtkwaliteit in kantoor in de zomer van 'Bevredigend' tot 'Onbevredigend' (-)



1 Bevredigend	15.38 %
2	53.85 %
3	23.08 %
4	7.69 %
5 Onbevredigend	0 %

n = 13
# 13

Om welke redenen laat U bewust de deur dicht tijdens werktijd?

Tocht	0 %
Geluidoverlast	7.69 %
Anders, nl……(volgende tekst regel gebruiken AUB)	92.31 %

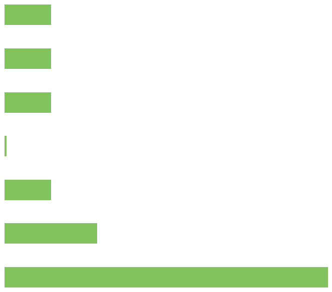
n = 13
# 13

Om welke redenen laat U bewust de deur dicht buiten werktijd?

Warmteverlies	0 %
Inbraakveiligheid	15.38 %
Anders, nl……(volgende tekst regel gebruiken AUB)	84.62 %

n = 13
# 13

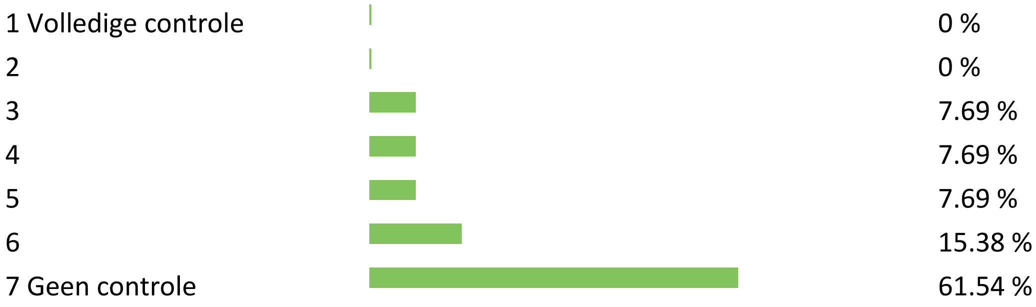
Regelbaarheid (thermostaat, ventilatie en/of roosters) per kantoor Temperatuur: (Volledige controle - geen controle)



1 Volledige controle	7.69 %
2	7.69 %
3	7.69 %
4	0 %
5	7.69 %
6	15.38 %
7 Geen controle	53.85 %

n = 13
# 13

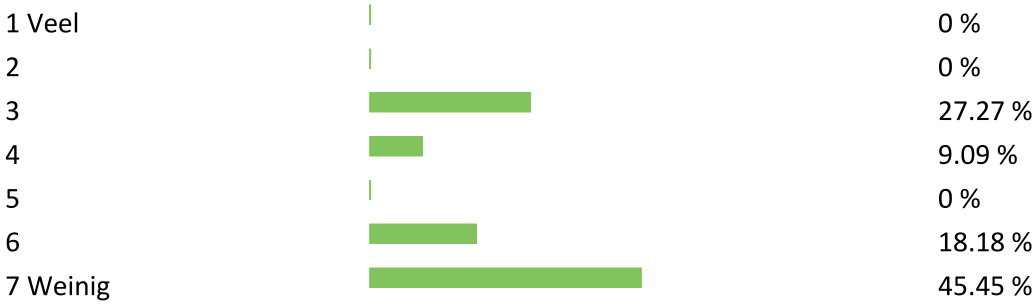
Regelbaarheid (thermostaat, ventilatie en/of roosters) per kantoor
Luchtafvoer (ventilatie): (Volledige controle - geen controle)



1 Volledige controle	0 %
2	0 %
3	7.69 %
4	7.69 %
5	7.69 %
6	15.38 %
7 Geen controle	61.54 %

n = 13
# 13

Zijn er gezondheidsklachten van u en uw collega's gerelateerd aan de luchtk...
Hoofdpijn (Veel - Weinig)



1 Veel	0 %
2	0 %
3	27.27 %
4	9.09 %
5	0 %
6	18.18 %
7 Weinig	45.45 %

n = 11
# 11

Zijn er gezondheidsklachten van u en uw collega's gerelateerd aan de luchtk...
Dufheid/vermoeidheid (Veel - Weinig)

1 Veel	0 %
2	0 %
3	18.18 %
4	27.27 %
5	9.09 %
6	18.18 %
7 Weinig	27.27 %

n = 11
# 11

Zijn er gezondheidsklachten van u en uw collega's gerelateerd aan de luchtk...
Ademhaling (hoesten) (Veel - Weinig)

1 Veel	0 %
2	9.09 %
3	9.09 %
4	27.27 %
5	9.09 %
6	27.27 %
7 Weinig	18.18 %

n = 11
# 11

Hoe zou U de reinheid van Uw kantoor willen omschrijven? (t.a.v. stof, hygi...
Reinheid (Voldoende - Onvoldoende)

1 Voldoende	7.69 %
2	30.77 %
3	15.38 %
4 Neutraal	7.69 %
5	23.08 %
6	0 %
7 Onvoldoende	15.38 %

n = 13
# 13

Heeft u weleens last van ademhalingsklachten en/of last van allergische rea...

Ja	30.77 %
Nee	69.23 %

n = 13
# 13

Komen deze klachten vaker voor op kantoor of thuis?

Vaker thuis	0 %
Vaker op kantoor	15.38 %
Even vaak	38.46 %
N.v.t.	46.15 %

n = 13
# 13

Legenda:
n = aantal respondenten dat de vraag heeft gezien
# = aantal ontvangen antwoorden

65 % of the people working, on the first floor, during the period the questionnaire was held participated.

	Heeft u verder nog opmerkingen of wensen ten aanzien van het klimaat op uw ...
respondent 1	
respondent 2	geen opmerkingen\r\n
respondent 3	
respondent 4	
respondent 5	
respondent 6	
respondent 7	Nee, vind het comfortabel genoeg
respondent 8	Prettige werkomgeving, soms wat last van tocht uit plafond.
respondent 9	
respondent 10	
respondent 11	
respondent 12	
respondent 13	Soms is de lucht droog/last van contactlenzen.

Appendix I:

I.1 Design and measured ventilation capacities

Ground floor

Ventilation capacities in [m^3/h]

Room	Design	Measured as built	Measured 2006	Measured 2013	Reduced
Small office 1	-	-	-	201	146
Small office 2	266	274	-	195	143
Small office 3	200	212	-	201	145
large office 1	-	-	-	699	515
Workshop office	266	274	-	195	143
Workshop storage	360	371	-	370	277,5
Meeting room	560	568	-	571	428,25
Kitchen / Cafeteria	2975	2825	-	2837	2127,75

First floor

Ventilation capacities in [m^3/h]

Room	Design	Measured as built	Measured 2006	Measured 2013	Reduced
Open plan office 1	2412	2405	2099	2169	1612
Large office 1	399	381	247	359	271
Large office 2	318	324	236	309	228
Large office 3	460	458	366,4	386	310
large office 4	366	358	295	424	319
large office 5	792	786	620	726	544
Small office 1	266	260	183	229	170
Storage room	266	260	181	199	152
Server / plotter room	266	52	80	125	47
Hallway	88	86	-	-	-

Second floor

Ventilation capacities in [m^3/h]

Room	Design	Measured as built	Measured 2006	Measured 2013	Reduced
Open plan office 1	3102	3200	1328	2603	1925
Large office 1	282	294	210	225	164
Large office 2	282	290	-	235	170

Ground floor

Ventilation capacities in [l/s pp]		
Room	Measured 2013	Reduced
Small office 1	27,9	20,3
Small office 2	54,2	39,7
Small office 3	18,6	13,4
large office 1	38,8	28,6
Workshop office	54,2	39,7
Workshop storage	102,8	77,1
Meeting room	15,9	11,9
Kitchen / Cafeteria	39,4	29,6

First floor

Ventilation capacities in [l/s pp]		
Room	Measured 2013	Reduced
Open plan office 1	66,9	49,8
Large office 1	99,7	75,3
Large office 2	85,8	63,3
Large office 3	107,2	86,1
large office 4	39,3	29,5
large office 5	40,3	30,2
Small office 1	63,6	47,2

Second floor

Ventilation capacities in [l/s pp]		
Room	Measured 2013	Reduced
Open plan office 1	60,3	44,6
Large office 1	62,5	45,6
Large office 2	65,3	47,2

This table is based on the amount of people who used to work in the corresponding room during the measurement period.

Ground floor

Ventilation capacities in [m³/h pp]

Room	Measured 2013	Reduced
Small office 1	100,5	73,0
Small office 2	195,0	143,0
Small office 3	67,0	48,3
large office 1	139,8	103,0
Workshop office	195,0	143,0
Workshop storage	370,0	277,5
Meeting room	57,1	42,8
Kitchen / Cafeteria	141,9	106,4

First floor

Ventilation capacities in [m³/h pp]

Room	Measured 2013	Reduced
Open plan office 1	241,0	179,1
Large office 1	359,0	271,0
Large office 2	309,0	228,0
Large office 3	386,0	310,0
large office 4	141,3	106,3
large office 5	145,2	108,8
Small office 1	229,0	170,0

Second floor

Ventilation capacities in [m³/h pp]

Room	Measured 2013	Reduced
Open plan office 1	216,9	160,4
Large office 1	225,0	164,0
Large office 2	235,0	170,0

This table is based on the amount of people who used to work in the corresponding room during the measurement period.

Appendix J:

J.1 Energy consumption tables

A better insight in the variation of energy use over the time periods is given by Table 31 and Table 32. The firs presents the kWh consumption per connection per month. While the second presents the energy consumption for each connection per calendar week.

Experiments with the HVAC could explain the reduction of energy use of the HVAC in the month September compared to the other months. The experiments where modulated operation of HVAC AHU fans.

The impact of night ventilation by the AHU can be seen from the energy consumption of the HVAC comparing August with October.

Humidifiers energy consumption is also presented in these tables despite of the inactivity during the measurement period. The energy usage by the system on standby is still 7 kWh per month which seems worth mentioning.

Table 31: Energy consumption per appliance by month [kWh].

Appliance	July	August	September ***	October
③ Chiller*	1533	1090	485	113
④ HVAC*	1388	1829	1421	1513
⑤ Lighting**	-	-	2547	2979
② Humidifier*	4	7	7	7
① Remaining appliances**	-	-	2449	2476

* 10-07-2013 start of measurements.

** 01-09-2013 start of measurements.

*** Experiments with HVAC where done.

Table 32: Energy consumption per appliance by calendar week [kWh].

Appliance	Wn 29	Wn 30	Wn 31	Wn 32	Wn 33	Wn 34	Wn 35	Wn 36	Wn 37	Wn 38	Wn 39	Wn 40	Wn 41	Wn 42	Wn 43	Wn 44
③ Chiller	552	675	435	291	190	180	202	395	21	10	57	42	17	11	37	11
④ HVAC	453	407	434	474	349	381	475	344	340	334	326	323	329	337	331	337
⑤ Lighting	-	-	-	-	-	-	-	567	600	607	641	654	613	669	648	675
② Humidifier	1	2	1	1	2	1	2	1	2	1	2	2	1	2	1	2
① Remaining appliances	-	-	-	-	-	-	-	586	570	569	575	560	562	534	564	552

Appendix K:

K.1 VABI Elements model

The model will be provided digital on DVD. The model can also be requested by mail, mail to: t.p.w.thomassen@outlook.com.

Vabi rekenkern Gebouwsimulatie versie 3.1.0

Algemene gegevens

Klimaatfile:	C:\PROGRAMDATA\VABI\ELEMENTS\DATA\CLIMATE FILES\GRN2013.KLN
Startdatum:	01-01-2013
Aantal rekendagen:	322

Er wordt gerekend met zomertijd (laatste zondag maart-laatste zondag oktober)
De overschrijdingsuren worden alleen tijdens teluren geteld
LET OP: Vakantie- en feestdagen zijn niet opgegeven; alle dagen tellen mee
De overschrijdingsniveaus zijn 25.00 en 28.00 ºC

Grondreflectie

De grondreflectie m.b.t. zonnestraling bedraagt 0.20

Installatiegegevens

Er is een centrale luchtbehandelingsinstallatie aanwezig
Er is een lokale installatie aanwezig
Er wordt een constant volume systeem toegepast
Er treedt een mechanische onbalans op

Beschaduwing

Er wordt geen beschaduwing meegenomen t.g.v. omliggende gebouwen
Er wordt geen beschaduwing meegenomen t.g.v. omliggende vertrekken
Er wordt altijd beschaduwing meegenomen t.g.v. gebouwdelen berekende vertrekken
Er wordt geen beschaduwing meegenomen t.g.v. uitstekende geveldelen
Er wordt wel beschaduwing meegenomen t.g.v. verzonken ligging
LET OP: Bij de berekening wordt alleen de beschaduwing meegenomen van externe zonnestraling op transparante bouwdelen (ramen e.d.), vooralsnog niet die op overige bouwdelen (niet-transparante wanden, daken, e.d.)

Infiltratie en natuurlijke ventilatie

Opgave via infiltratiedebieten
De ventilatiestromen worden opgegeven
Er zijn geen te openen raamdelen aanwezig

Appendix L:

L.1 Energy use chiller in relation with temperature and solar irradiation

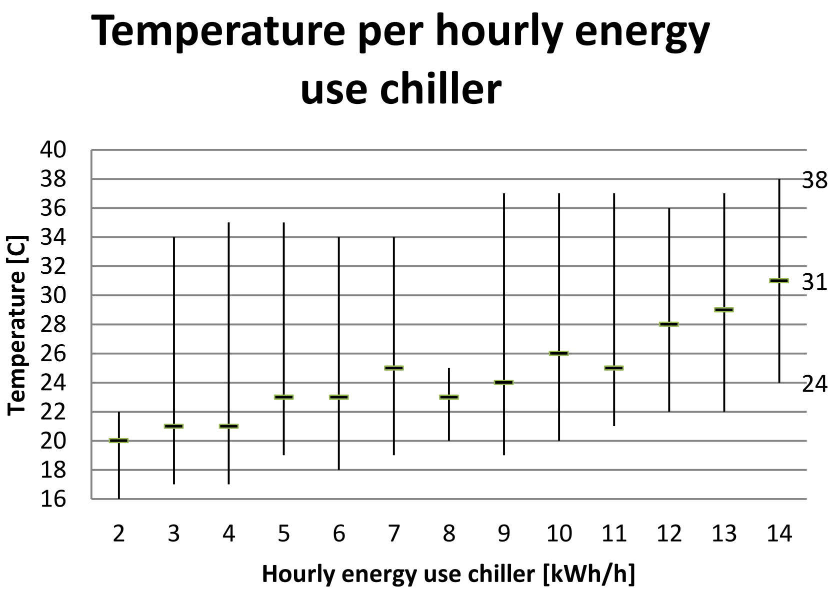


Figure 83: Outside temperature ranges and mean outside temperature sorted by the hourly energy consumption of the chiller.

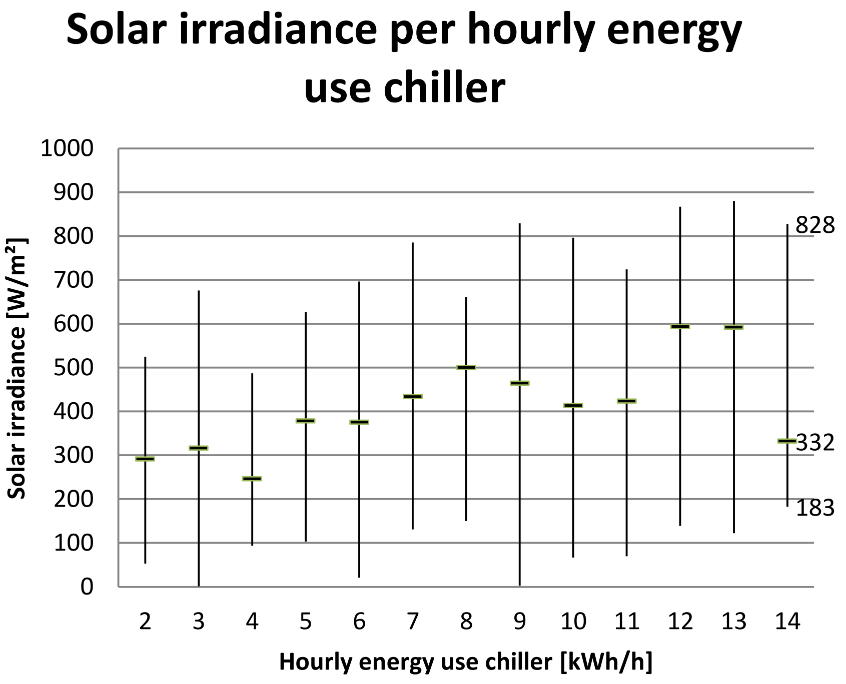


Figure 84: Solar irradiation ranges and mean solar irradiation sorted by the hourly energy consumption of the chiller.