NTNU
Innovation and Creativity

Behovsstyrt ventilasjon i yrkesbygg

Konsekvenser for energibruk og inneklima

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Master of Science in Energy and Environment
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Problem Description

For at DCV-systemer skal fungere i praksis er det en forutsetning at det finnes kommersielt tilgjengelige belastningsfølere som kan tilkoples ventilasjonssystemets styringsautomatikk Det er videre helt avgjørende at de valgte følerelementer i tilstrekkelig grad registrerer den reelle belastningsvariasjon til rett tid og med tilfredsstillende nøyaktighet. Målet er å undersøke anvendeligheten av ulike sensortyper for forskjellige kategorier rom og lokaler. Det er videre et mål å beregne effekt og/eller energibesparelsen som følge av at det velges et DCV-system i forhold til en tradisjonell CAV-løsning i hele eller for deler av et tradisjonelt yrkesbygg av typen kontor- og/eller undervisningsbygg.

Assignment given: 29. January 2007
Supervisor: Sten Olaf Hanssen, EPT

Demand Controlled ventilation in commercial buildings – energy use and indoor climate

Andreas Opsahl Olufsen

Summary and Conclusions

This thesis is a continuation of a project assignment from Fall 2006. The project was named "Demand Controlled Ventilation systems for energy efficiency and good indoor climate".

The main study objectives are:
- Find the utility patent of a specific office floor
- Determine the sensor accuracy
- Develop a computer model for numerical analyses

The work constitutes of two main tasks, i.e.:
- Experimental study
- Numerical simulations

The experimental study formed the basis for assessing the two first objectives. The numerical simulations based on the newly established computer model were used to compare results from experimental study. The numerical simulations performed with minimum and maximum registered occupancy levels suggest that this did not significantly affect the demands for energy, i.e. hot water, cold water and electricity.

The first objective is to find the utility patent of a building at the Norwegian University of Science & Technology. This was performed using logged data from infrared motion sensor readings over a period of twenty nine days.

A main finding is that the average presence is 57% during working hours (8 AM – 3 PM). A utility patent developed, based on the twenty nine days of logged data, shows the expected occupancy at any time during a normal working day. The data also forms the basis for the maximum and minimum occupancy levels found in this building which were used in the numerical simulations.

The second objective, sensor accuracy, is estimated based on comparison of logged data and manual registrations over two days. This information formed a basis for discussion of how well the infrared motion sensors performed. In this building, the conclusion is that ceiling mounted sensors, SWE and MIM, performed better than the wall mounted sensor, SWE-V. Furthermore, the wall mounted SWE sensor gave false readings when office doors were left 00open. The extent of these false readings could not be documented properly because of the limited amount of data. Considering all offices as one zone, any sensor would ensure that enough fresh air is supplied if they were assigned to regulate air flow. When considering air flow to each individual office the SWE-V sensor should have an Off-delay that exceeds 10 minutes in order to ensure that enough fresh air is supplied.

The third objective is to develop a computer model of the building and simulate it with two different ventilation systems. One simulation is of a CAV system, while the other is a VAV system that is able to adjust its minimum OA requirements according to the registered utility patent found in the first objective of the thesis. The computer model was developed with DOE2. The VAV system proved to perform far more efficient than the CAV system for a one year simulation. The hot water demand was reduced by 51%, cold water by 57%, and fan energy dropped by 76%.

Cooling load is the deciding factor for the size of the system, i.e. maximum ventilation rate. Reducing cooling loads can greatly reduce the energy used by the HVAC system. Further, a VAV system with the ability to operate at the lowest possible percentage of maximum flow rate was found to be the most energy efficient system for this building.

This thesis is believed to be the first thesis at NTNU where DOE2 is used. The student has no or little experience with other simulation programs so it is hard to compare DOE2 to other simulation programs. DOE2 requires the user to have some prior experience with the program in order to utilize it in a thesis like this one. Much experience is however needed to utilize the program to its full extent. It is believed that DOE2 can be found in the advanced section of building simulation programs. It was found that DOE2 simulations can be consistent with hand calculations from NS3031. Because DOE2 simulations are so much more advanced than hand calculations, a correct DOE2 model can not be verified based on this comparison.

Abbreviations

List of words appearing in the thesis;

Word	Meaning	Norwegian
CAV	Constant air volume ventilation system.	NA
CFM	Cubic feet per minute. Used to describe flowrates in IP system.	Motparten til SI systemets l/s eller kubikk meter per time.
DCV	Demand Controlled ventilation. Typically a VAV system that is able to meet demands using the minimum amount of energy. Different sources define DCV differently.	Behovsstyrt ventilasjon
DDC	Dual-Duct system. A constant air volume system with two ducts for supply air. One hot and one cold.	To kanal system
DOE	The simulation program used to determine the energy demand.	NA
DrawBDL	A program that gives a graphical presentation of the DOE2 model.	N/A
HVAC	Heating Ventilation Air Conditioning (system)	Varme Ventilasjons (system)
IP-system	Inch-pound system used in US and UK mainly.	N/A
LabView	Software designed for logging data.	N/A
LS-	Loads Summary reports of DOE simualtion outputfile	N/A
LV-	Loads verification reports of DOE simualtion outputfile	N/A
MIM	Ceiling-mounted infrared motion sensor. Model 41-320 Light/vent. Sponsored by Micro Matic AS.	
NS3031	Norwegian standard for estimating energy and effect demands in buildings.	N/A
0&M	Operation and Maintenance	FDVU (forvaltining drift vedlikehold)
OA	Abbreviation of outside air.	Frisk luft
Off-delay	The time between a motion sensors last detected movement and a time selected by the user. The time selected by the user is referred to as off-delay.	N/A
On-delay		N/A
SS-	System Summary reports of DOE simulation outputfile	N/A
SV-	System Verification reports of DOE simuation outputfile	N/A
SWE	Ceiling-mounted infrared motion sensor. Model PIR-TF-25-360.	N/A
SWE-V	Wall-mounted infrared motion sensor. Model PIR-TF-25. Sponsored by Swegon AS	N/A

Utility patent	The pattern of how a space is being occupied over time. Often given as a percentage of maximum capacity versus a time scale.	Bruksmønster
VAV	Variable air volume ventilation system.	N/A
VAVS	What DOE2 calls a VAV system. Variable air volume ventilation system.	N/A

Table of Contents

Introduction

This thesis is a continuation of a project written by the student in Fall 2006. Relevant subjects that were discussed in the project are the up to date codes and standards for ventilation of buildings, system types (i.e. CAV and VAV) and sensors for detecting occupancy.

In the later years the focus on energy savings have lead to the development of ventilation systems that are intended to deliver the correct air flow rate with the right air quality at the right place and time. This of course requires an advanced control system that relies on sensors and actuators. This thesis work considers how infrared motion sensors have reflected the real occupancy in an office building. An assessment to their reliability has been investigated.

The possible energy savings from changing a system from a CAV to a VAV system (controlled partially by infrared motion sensors) was then investigated.

The layout of the thesis is as follows;

Chapter 1 focuses on the practical part of the thesis. This part of the thesis presents how the experiment with infrared motion sensors was conducted and the results that were found. The reason why this has been placed as Chapter 1 is that the results that are found here are used in parts of Chapter 3.

Chapter 2 presents the DOE2 simulation program. It was chosen to simulate a different building than that considered in Chapter 1 and Chapter 3. Chapter 2 focuses on the simulation program rather than detailed results of the simulation. It aims to present DOE2 to the reader and how a hand calculation of the energy demand was performed to compare with the simulated model.

Chapter 3 focuses on DOE2 simulations of the same building as Chapter 1. The intention is to investigate how a CAV system performs compared to a VAV system. The minimum OA requirement in the VAV system is determined by the occupancy found in Chapter 1.

A comment to Chapter 3 is that emphasis has been on simulating expected energy savings rather than operational costs. Some remarks have been made about equipment wear and tear, but the direct links between O&M costs and system types (i.e. CAV or VAV) have not been the focus of this thesis. This was decided in a verbal agreement between the student and the main advisor for the thesis work, Professor Sten Olav Hanssen.

1 Motion sensor experiment

There are three main objectives to this experiment, i.e.:

1) *Find the utility patent of the office floor.*
2) *Determine the accuracy of each sensor to observe the real utility patent.*
3) *Determine how the sensors should be used in this type of environment.*

The outline of this Chapter is as follows. The utility patent is discussed in Section 1.2. Discussion about accuracy is presented in 1.3, and an assessment of the various sensors applicability is given in the summary Section 1.4.

The utility patent found in the experiment is presented in Chapter 1.2 and forms the basis for the occupancy schedule that is used in the simulations in Chapter 3. The simulation in Chapter 3 is of the same office where this experiment took place.

A theory was that a wall-mounted sensor would be more inaccurate in detecting a person doing office work because of the somewhat stationary nature of office work. A shorter off-delay would make this theory more apparent.

Another theory is that a longer off-delay setting will ensure that sensors are less likely to fail at detecting a continuous presence. By choosing two different off-delay settings one might be able to draw some conclusions about its positive and negative affects to the collected data. In a larger scale study it would be possible to have several sensors of the same model with different off-delay settings to check this theory.

Definitions of off-delay and how a sensor fails to detect presence are explained in greater detail in Sections 1.1 and 1.3, respectively.

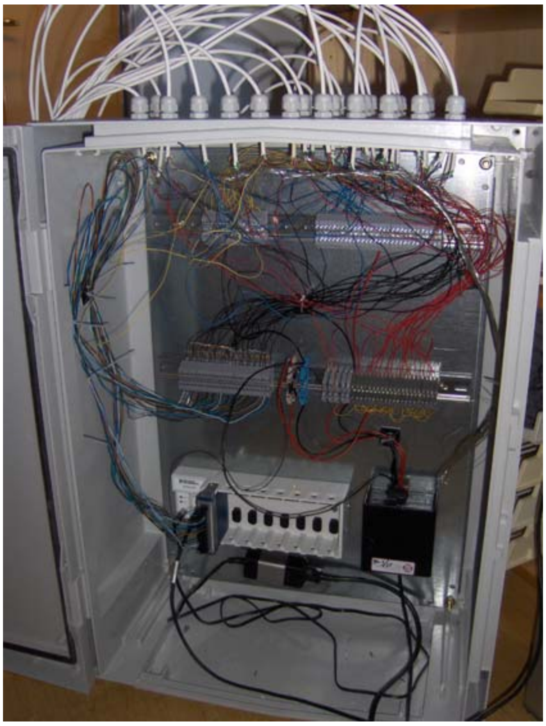
1.1 Description of the experiment

This section presents how the experiment in this thesis work was conducted. A portion of the fifth floor of an office-building at Norwegian University of Science and technology (NTNU) was selected to do the experiment. This building is shared by Sintef and NTNU. The office floor considered consists of two conference rooms, a small coffee-room, two restrooms, a hallway, a storage room for office requisites, a printer room, thirteen one-person offices and three two-person offices. The rooms that are included in the experiment are eleven office rooms and one conference room. All twelve rooms were fitted with infrared motion-sensors to monitor the utility patent of this office environment. The eleven office rooms ranged from 23.9 m^2 – 7.7 m^2, and the conference room is 57.1 m^2.

The office rooms were utilized by either PhD. students, employees of NTNU or Sintef. Four rooms were used by students, two by NTNU employees and six by Sintef employees. During a manuell registration period the utility patent of one of the restrooms was also registered. The manuell registration period lasted for two days and was conducted between 8:00 AM and 13:30 PM on the 22nd and 24th of May 2007.

The main challenge of the experiment was to order and install all the equipment that was needed. Some delays were encountered due to a slow process of planning the equipment needs, assembly and ordering. Mounting of the equipment and design of the software for logging data was performed by the student with technical support from Helge Laukholm, a senior electric engineer at the faculty lab. A picture of the wiring cabinet that was used to provide power to the sensors and to connect them to a computer logger is shown in Picture 1. Due to the delays in the recording of data the period for recording data started on the 16th of Mai and ended on the 30th of June. This was approximately a three week delay compared to the initially planned schedule. Even thought the period of recorded date was shifted, it is not expected to impact the results significantly. No employees had started their long summer vacation during the period when data were collected. This means that the data collected should be representable for the utility patent of normal working hours for this office environment.

The objectives of the experiment are to determine a utility patent for the office, determine the accuracy of the sensors and to determine how the sensors are best utilized in this kind of environment. The utility patent that is found will form the basis for the occupancy schedules used in a simulation of the office.



Picture 1. Left; Connection box for all sensors
Picture 2. Right; Manuell data was recorded from the stationary point at the end of this hall. It offered full visibility of all traffic to and from the rooms.

The equipment that was used is listed below;

-500 m signal/power cable, Draka Norsk Kabel, 1×4×0.6 mmø
-Power supply 12V-24V, Mascot, Type 6823
-Logger, National Instruments, NI 9205 and NI cDAQ 9172
-Computer with windows XP and LabView
-Infrared motion sensors, details on these sensors are found on the next page
-Mounting pads sponsored by Økomar AS.

To determine the accuracy of the sensors one needs the correct utility patent. Manuell registration was used to obtain the most correct utility patent. This could then be compared with the reading of the recorded data. The recorded data was performed using the program LabView. All sensors logged their signals with five minute intervals. The manuell data was collected by sitting continuously in the hallway between 8:00 AM and 13:30 PM on the 22nd and 24th of May 2007. The manuell data was collected using an excel spreadsheet where the room status was registered every five minutes. This is the same interval used by the computer logged data. If a person was present any time during a five minute period he was considered to be occupying that room for the entire five minute interval.
Picture 1. Left; Connection box for all sensors
Picture 2 shows the hallway where the experiment took place with offices to the right and left. Recording the presence of thirteen rooms continuously required a great deal of concentration. Breaks were kept to the absolute minimum to ensure that the results would be as correct as possible. If any uncertainty of the occupancy occurred the student would knock on the door. Routine patrols up and down the hall were preformed approximately every hour to verify occupancy and to keep the student alert.

Four office rooms on this floor were not fitted with any sensors. Three of these rooms were not in use and shortage of cable made it impossible to measure the fourth room. The assumption that three out of sixteen office rooms would be empty on a regular basis seemed unlikely and these rooms have therefore been taken out of the equation when the overall utility patent of the floor is calculated. The same applies for the last room without any sensors. The utility patent for all four rooms is assumed to be the average, thus not affecting the overall calculation of the utility patent. Assuming an average presence in the four unoccupied rooms simply means that the same fraction of occupancy is found in these rooms as for the monitored rooms. A more detailed description of how the utility patent is calculated based on the logged data from the sensors is explained in Section 1.2.

Three different types of sensors were used in the experiment, one wall-mounted and two ceiling-mounted. These sensors will now be presented in an orderly manner;

The wall mounted sensor from Calectro has model number PIR-TF-25. [26] This sensor has been named the SWE-V sensor in the thesis. The name SWE-V was given to the sensor because they were sponsored by Swegon. Swegon is a Swedish company that specializes in ventilation technology. Pictures of the sensor are found in Picture 5 and
Picture 6. The manual for the sensor states the specifications for the sensor. The specifications that have been emphasized are mounting height, detection range, on-delay and off-delay. On-delay and off-delay is explained later in this chapter. On-delay is set to 0 seconds and off-delay is set to 10 minutes by placing a jumper on the appropriate pins in the sensor.

The ceiling mounted sensor from Clectro has model number PIR-TF-25-360. [25] This sensor has been named the SWE sensor in the thesis. Pictures of the sensor are found in Picture 3, Picture 7 and Picture 8. The manual for the sensor states the specifications for the sensor. The specifications that have been emphasized are mounting height, detection range, on-delay and off-delay. On-delay and off-delay are the same for SWE and SWE-V.

The ceiling mounted sensor from Servodan has model number 41-320 Light/vent. [24] Pictures of the sensor are found in Picture 3, Picture 4 and Picture 7. This sensor has been named the MIM sensor in the thesis. This is short for Micro Matic. Micro Matic carries this sensor and gladly sponsored these sensors for this thesis. This model is intended to control both lighting and ventilation. Two separate relays control lighting and ventilation. The off signal from the ventilation relay is 25 % longer that the off signal from the lighting control relay. If the off-delay is set to 15 minutes this means that the ventilation will turn off 18 minutes and 45 seconds after the lights are out. Off-delay for this model is the same as the setting of the Time-wheel that can be observed in Picture 4. On-delay settings are not available for the MIM sensor. A user manual is provided with every sensor. Relevant factory settings are;

-High sensitivity. Changed to Max. sensitivity.
-LED is off. Changed to on.
-Sensor is in automatic mode. This factory setting is not properly explained in the user manuell. Not changed.
-Time-switch is set at the “15min” mark. Not changed.

The Norwegian distributors of this senor, Micro Matic AS Norway, can inform that the lighting control for these sensor require some special attention. Old fluorescent lights with mechanical starter might require the time-switch to be 30 minutes to ensure expected life time of the fluorescent lights. New fluorescent lights with electronic starter require a time-switch setting of minimum 5-10 minutes while incandescent lights can cope with any time-switch setting without reducing life time. [29] Unique to this sensor was its protective cap which allowed the user to adjust the sensors detection area. This allowed the user to limit the detection area to reduce the chance of false readings due to open doors, windows, etc.

Off-delay is the time between the last detection and a time chosen by the installer. Any detection during off-delay will reset an internal timer and thereby indicating a continuous presence. Off-delay for MIM is 1min - 30min determined by a turning the time-wheel on the sensor. The time-wheel can be seen in Picture 4. As mentioned earlier the actual off-delay signal for ventilation purposes add another 25% to the time wheel setting. This means that if the time wheel setting is 15 minutes then the off-delay signal is 18 minutes and 45 seconds. Any detection during this time will reset the timer.

The fact that the time-wheel forces the installer to set off-delay based on an approximate value for MIM sensors is probably not a problem in practical installations. In an experiment the need for accuracy and coherency is greater. This means that the time-wheel was decided to be left at the factory setting of fifteen minutes for all sensors. This was done to avoid differences on the recorded data between individual MIM sensors due to differences in the time wheel position. The off-delay signal from the MIM sensors should in theory all be 18min 45sec. The SWE and SWE-V sensors off-delay was set to ten minutes because there was no jumper setting for 18min 45sec and the next option was 20 min. The choice to set the off-delay to ten minutes for the SWE and SWE-V sensors was done to se the difference in recorded data between a wall-mounted and ceiling-mounted sensor.

An off-delay of about twenty minute is usual for ventilation purposes. [29] According to the provider of the MIM sensor the twenty minute is meant as a blow out period. The blow out period is meant to ensure a proper change of air making for a better indoor climate. This means that after someone leaves a room the ventilation is still running under occupied zone conditions for the whole off-delay period before the system is allowed to run under unoccupied conditions.

On-delay is the time given to the sensor to verify true occupancy. This is how on-delay is defined;
-The sensor starts in standby.
-After one detection a timer is initiated. This timer is set by the user and is referred to as on-delay. Any detection during this time does not reset this timer.
-When the timer expires the sensor goes into a stage known as the 1-minute waiting stage. If the sensor has any detection during the 1-minute waiting stage the off-delay setting is activated. During off-delay the sensor is reporting presence. If no detection is made during the 1-minute waiting stage the sensor returns to standby.

On-delay was only available for SWE and SWE-V and ranged from 0sec - 10min. It was set to 0 sec to correspond with the MIM which does not have an on-delay setting.

All office rooms were fitted with at least two different sensors. The conference room was only fitted with one ceiling-mounted sensor. The combination of sensors was either two ceiling-mounted or one ceiling and one wall. One room was fitted with all three types to see if they behaved differently. SWE-V was fitted in eight rooms. The SWE was fitted in four rooms. And MIM was fitted to all twelve rooms. This means that MIM was the only sensor in the conference room. It also means that MIM was the only single sensor that covered all the rooms. Pictures of how the sensors were mounted in the rooms are shown in Picture 3, Picture 5 and Picture 7.

All sensors were mounted according to recommendation in the product manuals. Certain specifications found in the manuals have not been emphasized. These specifications may affect the accuracy of the sensors. These specifications include detectable speed, price range and what material the sensing material is made of. These specifications may be worth comparing in a continuation of the study.

Picture 3. Left; Typical office room fitted with two ceiling-mounted sensors. Closest sensor is a SWE sensor and the other is a MIM sensor.
Picture 4. Right; Infrared motion sensor by Servodan. Model number 41-320 Light/vent. Shows Lux-wheel and the time wheel.

Picture 5. Left; Mounting of the SWE-V sensor over the door. The picture is taken from the workspace.
Picture 6. Right; Calectro model PIR-TF-25. Wall mounted infrared motion sensor. Named SWE-V in this thesis.

Picture 7. Left; Typical mounting of the SWE and MIM sensors.
Picture 8. Right; SWE sensor. Same as the top sensor in Picture 7.

Some assumptions being made prior to the experiments were that:

a) Wall-mounted sensors are more inaccurate in detecting a person doing office work, because of the somewhat stationary nature of office work. A short off-delay of 10 minutes on the SWE-V sensors may provide evidence of how often and for how long the sensor fails to report presence.

b) Long off-delay setting will ensure that sensors are less likely to fail at detecting a continuous presence. By choosing two different off-delay settings one might be able to draw some conclusions about its positive and negative affects to the collected data.

The main message of this chapter is that on-delay setting was set to 0sec for all sensors. Off-delay was set to 10 minutes for SWE-V and SWE while it was left at the factory setting of 18.75 minutes for MIM.

1.2 Utility patent

There are two objectives of this chapter;

1) *Find the average presence during working hour.*
2) *Determine the utility patent of the office.*

The average presence was calculated using two different approaches. The first approach is based on the average measurement off all sensors. This means that if one sensor showed presence within a five minute interval and the other didn't, the average of these readings would result in a calculated presence of two and a half minutes for the five minute interval. The second approach is based solely on the MIM sensors. As mentioned earlier this sensor was installed in all rooms. Since the off-delay for the SWE-V and SWE sensors are eight minutes and forty-five seconds shorter than the MIM off-delay one can expect the first approach to give a lower value than the second approach.

The first approach is calculated for the normal working hours only. The normal working hours within this period of time is from 8:00 AM to 3:00 PM. The calculated average presence showed that 57% of the office rooms were being used during working hours and that the conference room was being used 37% of the time during working hours. See Figure 1.

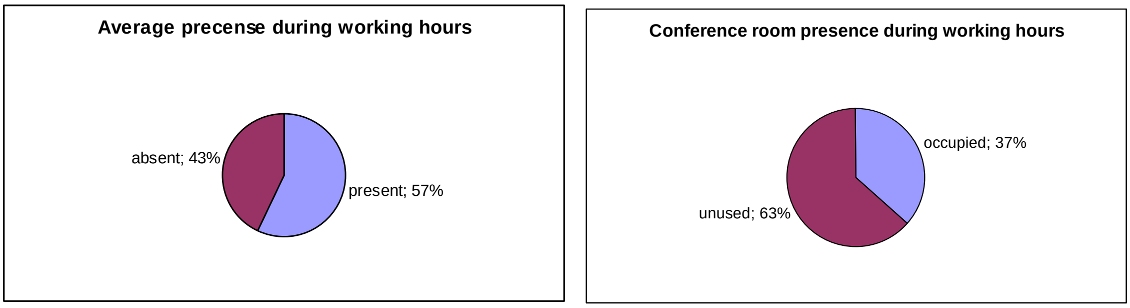


Figure 1. The average presence during working hours based on 29 weekdays. From 16th of May to the 30th of June. Calculated using the average of SWE-V, SWE and MIM sensors.

If we break down the average result into daily values we are able to see how some days are very busy while others have low levels of presence. The extreme values found using the average reading from SWE-V, SWE and MIM yield a maximum presence during working hours to be 71% and a minimum of 41%. The maximum presence was recorded on the June 4th and the minimum value was recorded on May 22nd. Day 10 and day 2, respectively in Figure 2.

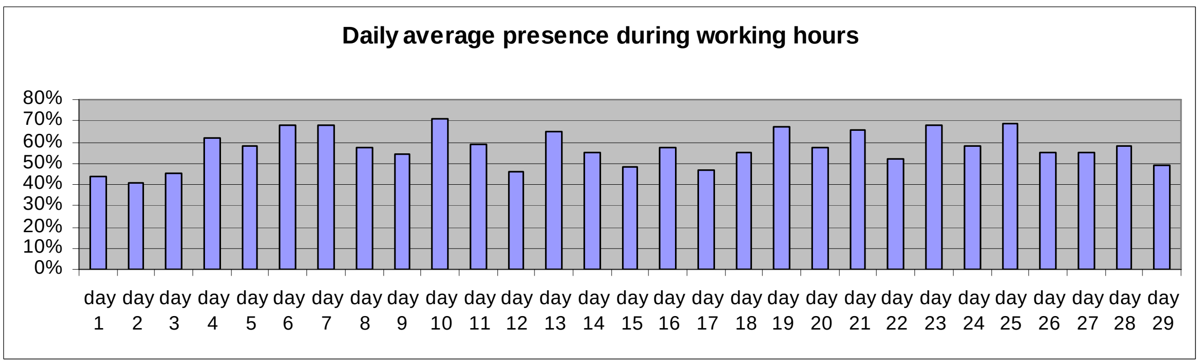


Figure 2. Average overall presence within working hours on a day by day basis. Calculated using the average of SWE-V, SWE and MIM sensors. Y-axis represents the average presence during working hours that particular day.

An average day has many different values of presence due to the fact that people leave their rooms. They may leave for lunch, coffee break, meeting or some other reasons, giving data that is without smooth curves. Not surprisingly, the largest variation in registered presence is around morning at 8 AM, at lunchtime from 11 PM – 1 PM and at the end of regular working hours from 3 PM-4 PM. These variations are depicted in Figure 3.

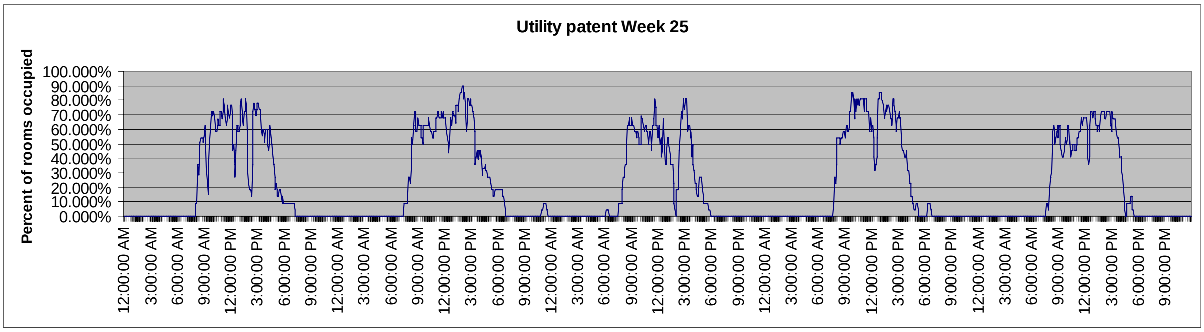


Figure 3. Measured data for five working days in week 25. From June 18th to June 22nd. Calculated using the average of SWE-V, SWE and MIM sensors.

Figure 4 shows the same type of data as Figure 3 but for weekends instead of regular working days on week days.

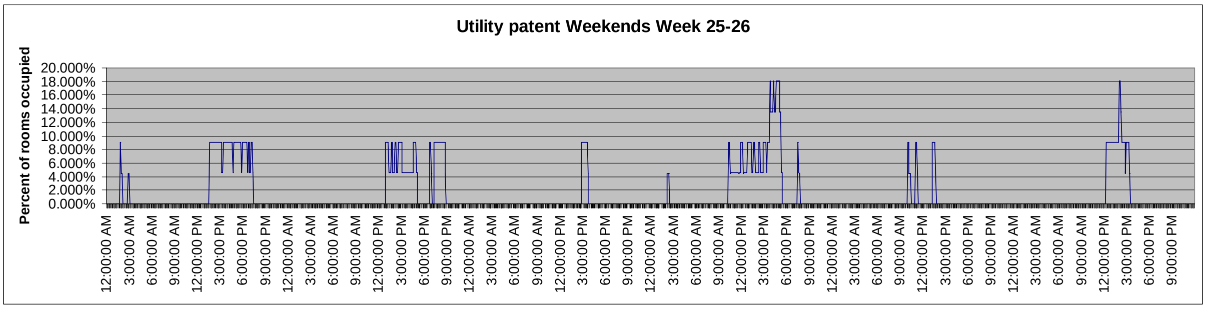


Figure 4. Measured data for two weekends in week 25 and 26. Max value 18% occupancy. Calculated using the average of SWE-V, SWE and MIM sensors. Note that the y-axis only reaches 20%.

The highest level of occupancy recorded was 100%. This happened once between 10.55 AM and 11.00 AM on the 14th of June 2007 and was the only time when all rooms were being used. See Figure 5.

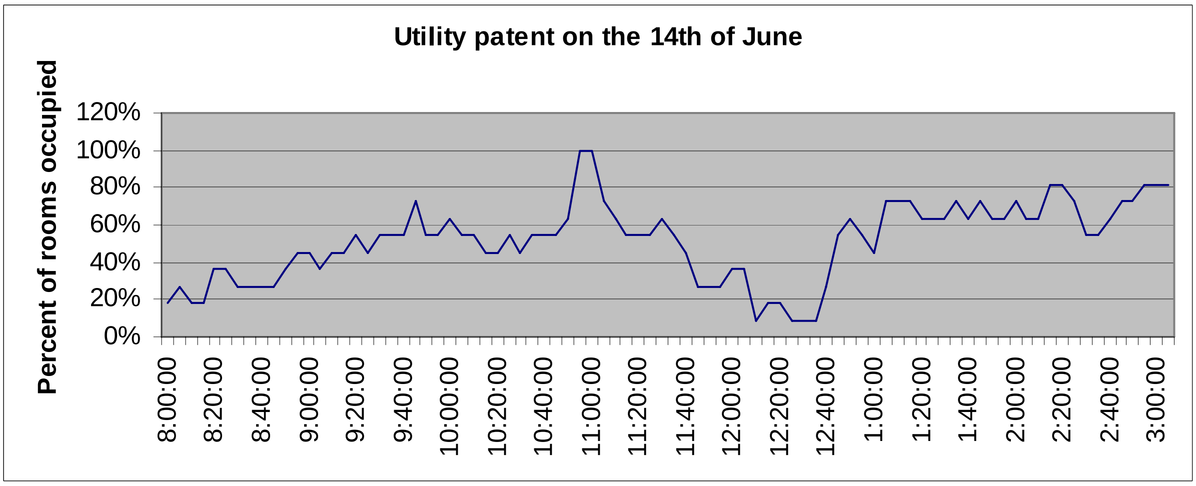
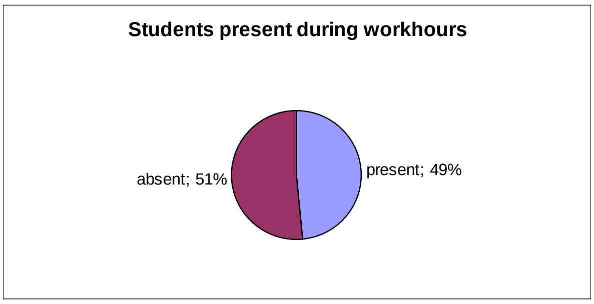


Figure 5. Utility patent on the 14th of June. Calculated using the average of SWE-V, SWE and MIM sensors.

The utility patent for PhD. students compared to that of regular employees was also investigated. It was found that 49% of the students and 62% of the employees were present during working hours. See Figure 6.



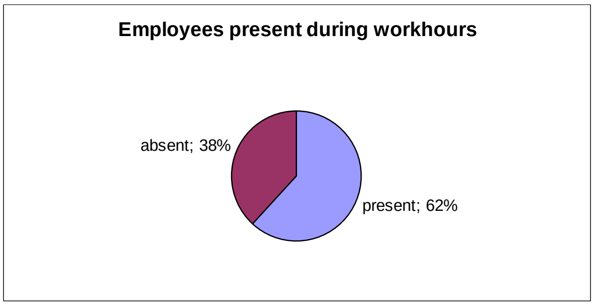


Figure 6. Utility patent for four PhD. students and that of seven employees during working hours. From 8 AM to 3 PM. Calculated using the average of SWE-V, SWE and MIM sensors.

This result does not imply that the PhD. students are working less. The pie-chart might have been very different if the presence for 24 hours had been considered and not only the hours between 8 AM to 3 PM on regular weekdays.

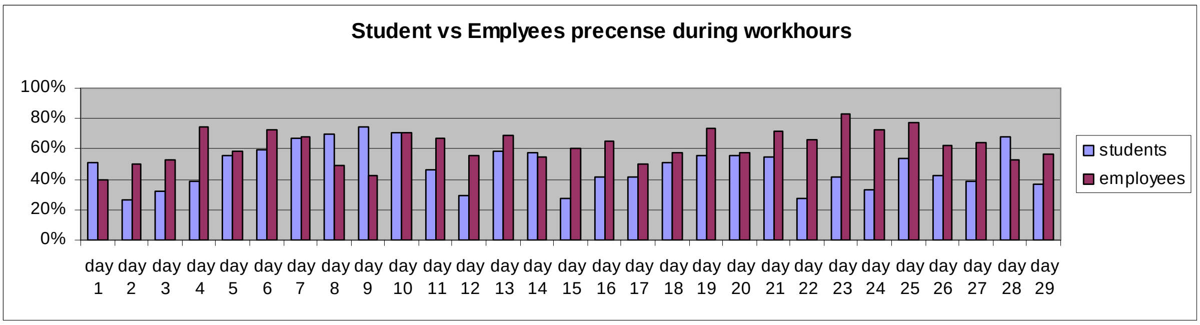


Figure 7. Day by day comparison of the average presence of PhD. students and employees during working hours. Calculated using the average of SWE-V, SWE and MIM sensors.

The second approach to determining the utility patent was to use data from the MIM sensor alone. Because of a longer off-delay setting it was expected that this method would reveal a higher value of recorded presence. A longer off-delay means that the sensor will report presence for a longer time if it works properly. It was therefore expected that this method would yield a higher value for presence during working hours. The increase in average presence during working hours is however quite small. The second approach reveals an average presence during working hours of 59% (Figure 8) while the first approach gave 57%. Working hours are still between 8 AM and 3 PM. The presence recorded in the conference room is of course unaffected by the different approaches, because it was only fitted with the MIM type sensor.

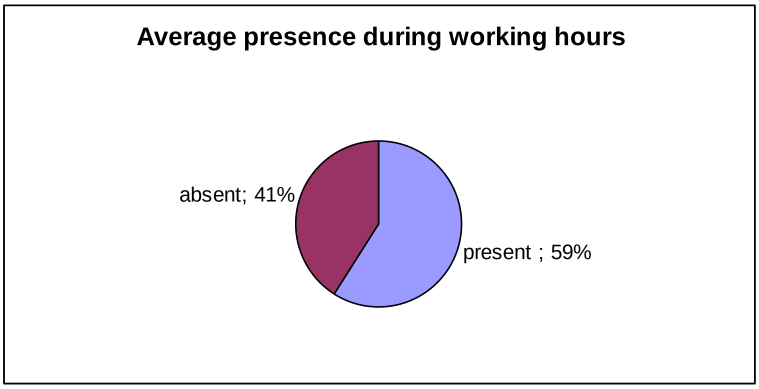


Figure 8. The average presence during working hours based on twenty nine weekdays. From 16th of May to the 30th of June. Calculated using MIM sensors only.

Now we concentrate on the second objective of this chapter. An average utility patent was calculated based on the twenty nine working days. This utility patent is based on the average presence during each five minute interval for all twenty nine days. This graph does therefore not represent one single day but rather an average expected occupancy during any time on any given working day. See Figure 9. The max value is the maximum value found out of all the twenty nine working days for each five minute interval. The minimum was calculated using the minimum value found out of all the twenty nine working days for each five minute interval. These results are later used in the simulation program DOE2 to simulate the office. This is found in Chapter 3.

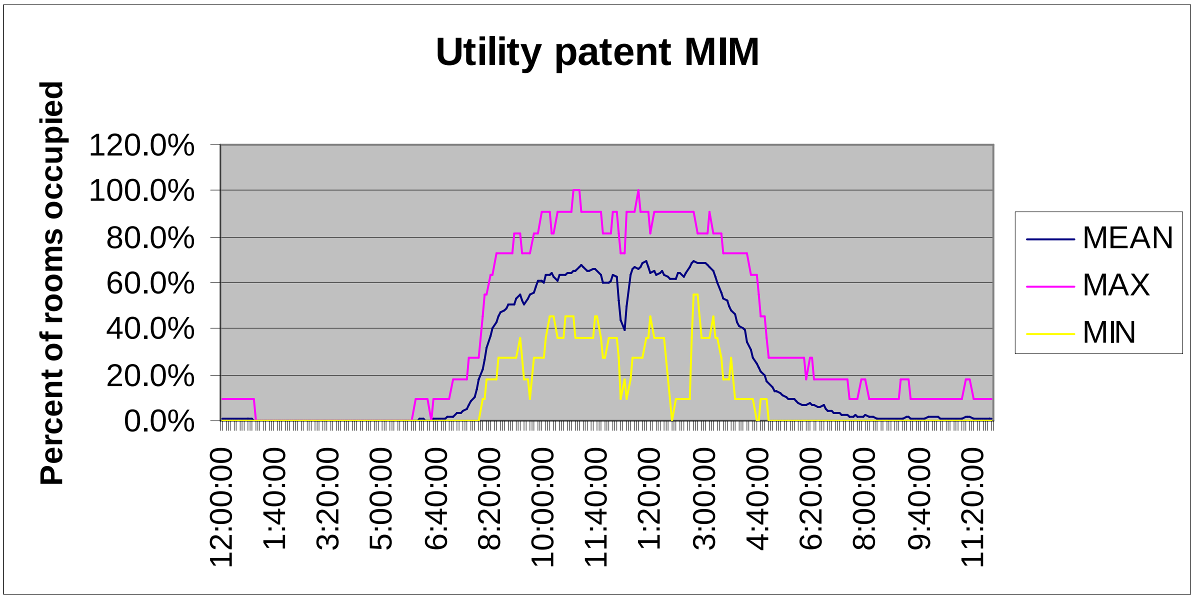


Figure 9. Max, min and average occupancy based on twenty nine working days. Calculated using the data from MIM sensors only.

From the manuell registration it was found that the women's restroom was used for twenty minutes total out of a possible eleven hours. This was distributed on four visits where the longest one was due to cleaning personnel. If this is the regular utility patent of the women restroom it would only be in use 3.8 % of the time during regular working hours. The limited number of hours that data was collected for this room makes the result very inaccurate and might not be applicable for all three restrooms found on this floor. Further it might not be applicable for as an average over a longer period of time. A better picture of the occupancy on the restrooms would be revealed if a sensor had been installed there as well.

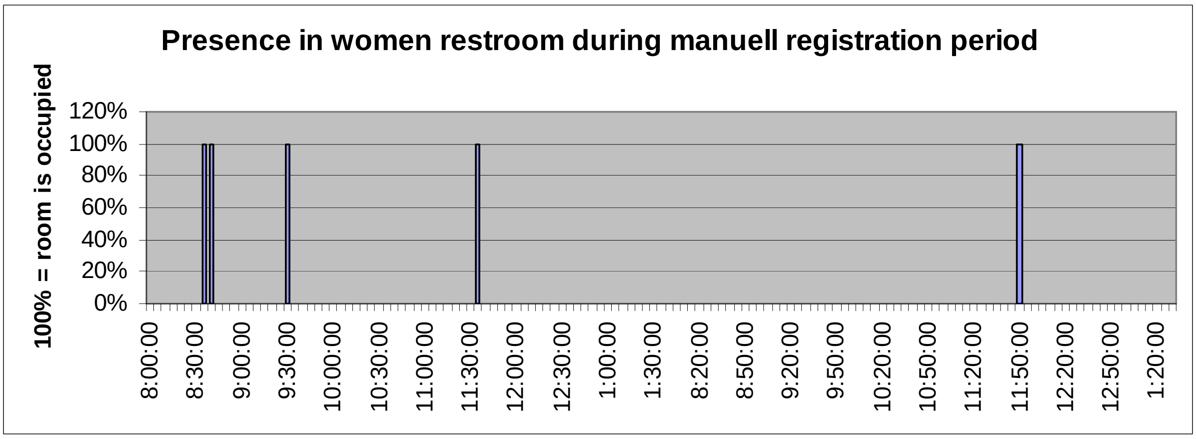


Figure 10. Presence in women restroom recorded during manuell registration period. Between 8:00 AM and 13:30 PM on the 22nd and 24th of May 2007.

The main findings in this chapter were that the presence was 57% in the offices and 37% in the conference room in the hours between 8 AM and 3 PM. The utility patent in Figure 9 forms the basis of the occupancy schedule used in the simulations in Chapter 3, Simulation of the office.

1.3 Accuracy and suitability

In this chapter we seek to determine how well each sensor has performed based on some criteria made by the student. The criteria made by the student to compare the sensors accuracy are “failure to detect presence” and “overestimated time”. This is explained in more detail later in this Section.

In demand controlled ventilation (DCV) systems there are three main choices of sensors for detecting occupancy. These are infrared motion sensors (1) like SWE-V, SWE and the MIM, relative humidity sensors (2) and gas sensor (3) that detect CO_2 and/or VOC. [27] CO_2 sensors and motion sensors are the most commonly used. In connection with a temperature sensor the CO_2 or motion sensor can allow a system to save energy when the need for ventilation is low. The temperature sensor ensures that temperatures are within a specific range while the occupancy sensors allow the system to limit ventilation rates (and/or temperatures) considering whether people are present or not. Note that ventilation rates should not be lowered even though people are not present if the temperature requirements are not met. A gas sensor is able to indicate a varying demand for ventilation between 0-100%. A motion sensor will typically only be able to give fixed minimum demand for ventilation based on whether or not people are present. This is because motion sensors are usually not able to detect the number of people or the quality of the air.

The accuracy and suitability of a sensor can be evaluated using several criteria. The most important criteria for motion sensors are their ability to reflect the real utility patent, i.e. its accuracy. This ability may be affected by factors as placement, sensor sensibility, room location in building and the architecture of the room. The sensors accuracy can thus be evaluated by comparing manually collected data with the output from the sensor.

The suitability of the sensor is determined by other factors as predictability of the occupancy levels of the detection zone and the sensors adaptability to rooms of different architecture.

The MIM sensor had the option of setting the sensitivity to four different levels based on the usage. (Min, Low, High, Max) It also had the option of limiting the sensors detection area. This was achieved with a cover that could be cut into the desired shape. [24] The MIM sensors used in the experiment were all set to maximum sensitivity and had their cover cut to match the desired detection area. This adds to the sensors ability to adapt to room architecture.

Again, the rooms that were fitted with motion sensors were one conference room, eight one-person offices and three two-person offices. The eleven office rooms ranged from 23.9 m^2 – 7.7 m^2, and the conference room is 57.1 m^2. Offices facing north-east have a design flow rate of 540 m^3/h, offices facing south-west have 420 m^3/h and the conference room facing south has a design flow of 520 m^3/h.

A failure to detect presence is defined as a discrepancy between the recorded data and the manually collected data. A single event of failure to detect presence could theoretically last an unlimited amount of time if the recorded data and the manually collected data never have the same value concurrent in time.

The only possible values the sensors and the manually collected data can have are “presence” or “no presence”. In Figure 11 and Figure 12 these values are represented by a number between 1 and 4 or zero, respectively. Because of the off-delay and the time interval that the data is recorded with the SWE and SWE-V sensors should turn off 5-15 minutes after the last manually recorded presence while the MIM sensors should turn off 15-25 minutes after the last manually recorded presence.

Room 3, 5, 6 and 7 represent the south-west offices. During the time of manuell registration, one office was empty the entire time and did therefore not have any readings. The empty room was fitted with one SWE and one MIM sensor. The empty room was left out of the presented data because no false readings were detected. The empty room could be called room 11 but will not be mentioned again. The actual room numbers that these rooms represent are rooms 542, 543, 544, 545 and 546.

Rooms 1, 2, 4, 8, 9 and 10 represent the north-east offices. The recorded data for south-west offices will be presented first then the data for the offices facing north-east. The room numbers that these rooms represent are rooms 530, 533, 534, 538 and 539. One of the requirements for collecting data about presence was that the collected data could not be traced back to a particular room. By giving the rooms a random number between one and eleven instead of the actual room numbers, the anonymity of the collected data is preserved.

Firstly the results from the south-west offices will be presented, then the results from the north-east offices. A summary of the reliability of each sensor for all rooms is presented in the summary at the end of Section 1.4. This summarizes all the failures of the sensors and discusses the differences.

A comparison of manually recorder and measured data is performed to assess the accuracy. Results for the south-west offices are discussed first. A short discussion for each each room is given, followed by a more aggregated comparison for all rooms.

South-west offices; Figure 11.

Room 3:
Event 1, Day 1, 1:00 PM; Manuell recording fail to detect someone entering the room for a short period of time. Both SWE-V and MIM sensors turned on but there was no manuell recording of the incident.
Event 2, Day 2 10:15 AM; SWE-V fails for a 5 minute period.
Event 3, Day 2 11:45 AM; Manuell recording of a 5 minute absence that none of the sensors picked up.
Event 4, Day 2 1:10 PM; Manuell recording of a 10 minute absence that none of the sensors picked up.

Room 5:
Event 5, Day 1, 11:00 AM; SWE-V fails for a 5 minute period.
Event 6, Day 1, 11:50 AM; SWE-V fails for a 5 minute period.
Event 7, Day 2, 8:45 AM; SWE-V fails for a 10 minute period.
Event 8, Day 2 9:10 PM; Manuell recording of a 10 minute absence noted by SWE-V only.
Event 9, Day 2, 9:35 AM; SWE-V fails for a 5 minute period.
Event 10, Day 2, 10:35 AM; SWE-V fails for a 5 minute period.
Event 11, Day 2, 9:35 AM; SWE-V fails for a 15 minute period.

Room 6:
Event 12, Day 2, 11:05 AM; Manuell recording of a 10 minute absence that none of the sensors picked up.

Room 7:
Event 13, Day 1, 12:35 AM; SWE-V fails for a 5 minute period.
Event 14, Day 1, 1:00 PM; SWE-V fails for a 5 minute period.
Event 15, Day 2, 11:25 AM; Manuell recording of a 5 minute absence that none of the sensors picked up.
Event 16, Day 2, 1:10 PM; Manuell recording of a 15 minute absence noted by SWE-V only.

The SWE-V sensor failed to detect presence a total of nine times. Seven of the times the sensor failed to report presence for a 5 minute period, once for a 10 minute period and once for a 15 minute period. This indicates that the sensor would not have failed to detect presence if the off-delay had been twenty minutes instead of ten.

The MIM did not fail to detect presence when someone was in the room. Due to the longer off-delay signal the long breaks, like lunch, were not so well reflected by the MIM sensor as the SWE and SWE-V.

Note that these were the results from the south-west offices.

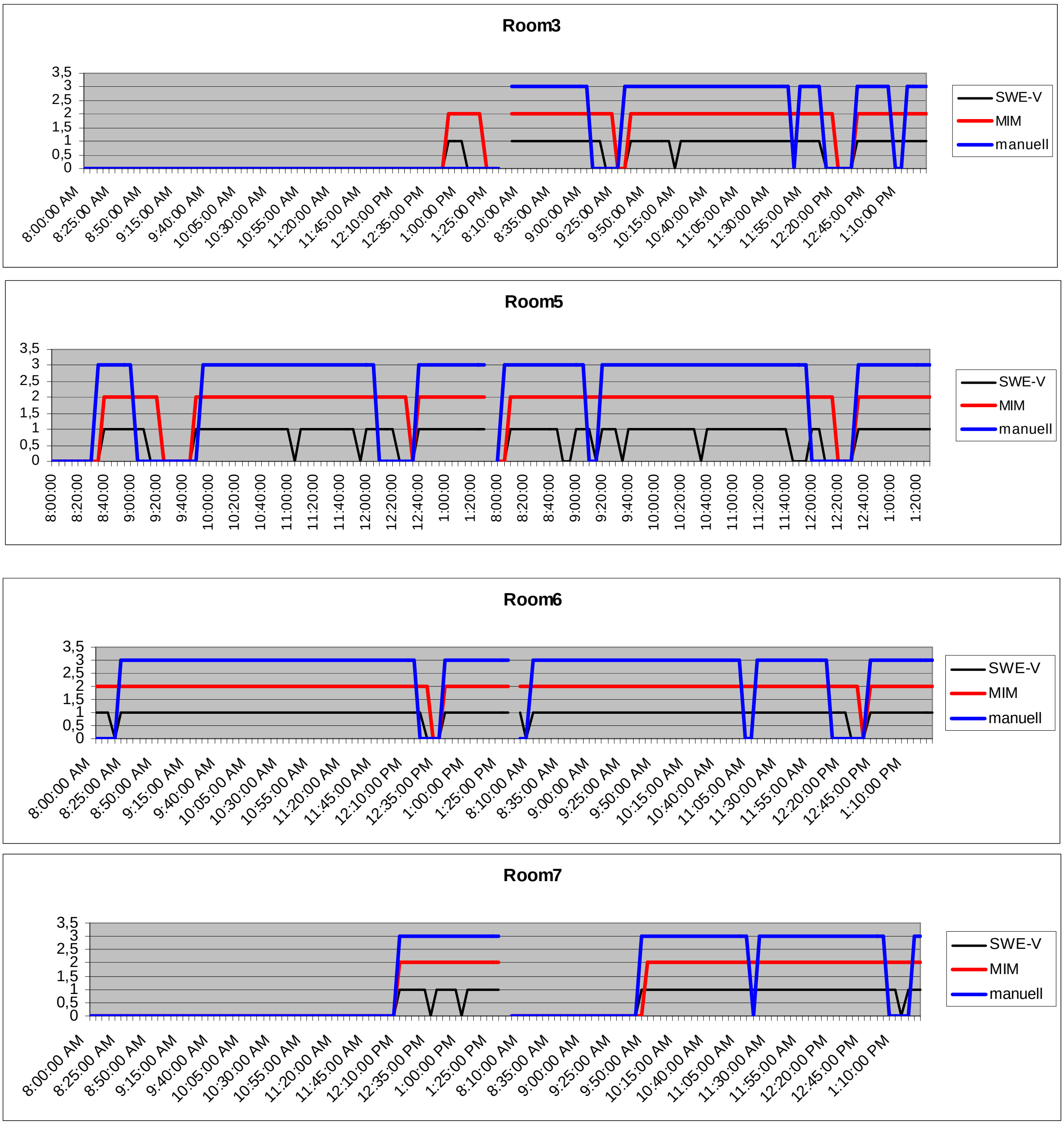


Figure 11. Offices facing south-west.

North-east offices; Figure 12.

Room 1:
Event 17, Day 1, 9:15 AM; Manuell recording started 10 minutes later than SWE-V and MIM.
Event 18, Day 1, 10:15 AM; Manuell recording of a 10 minute absence noted by SWE-V only.
Event 19, Day 1, 11:25 AM; SWE-V and MIM suggest that manuell recording failed to notice that a person returned to the office for a brief time after a 20 minute break.
Event 20, Day 1, 1:00 PM; SWE-V and MIM suggest that manuell recording are 15 minutes late.
Event 21, Day 2, 10:00 AM; SWE-V fails for a 5 minute period.

Event 22, Day 2, 11:55 AM; SWE-V and MIM suggest that manuell recording failed to notice that a person returned to the office for a brief time after a 10 minute break.
Event 23, Day 2, 1:25 PM; SWE-V fails for a 5 minute period.

Room 2:
Event 24, Day 1, 9:15 AM; SWE-V fails for a 10 minute period.
Event 25, Day 1, 10:05 AM; SWE-V fails for a 5 minute period.
Event 26, Day 2, 9:25 AM; Manuell recording of a 5 minute absence that none of the sensors picked up.
Event 27, Day 2, 10:20 AM; Manuell recording of a 5 minute absence that none of the sensors picked up.

Room 4:
Event 28, Day 1, 8:30 AM; SWE-V and MIM suggest that manuell recording failed to notice that a person visited the room for a brief period of time
Event 29, Day 1, 1:15 PM; SWE-V and MIM suggest that manuell recording failed to notice that a person visited the room for a brief period of time

Room 8:
Event 30, Day 1, 10:40 AM; SWE-V fails for a 5 minute period.
Event 31, Day 2, 9:20 AM; SWE-V fails for a 5 minute period.
Event 32, Day 2, 12:20 PM; Manuell and MIM correspond but SWE-V and SWE are indicating presence. This event is eliminated from the evaluation.
Event 33, Day 2, 12:45 PM; SWE-V fails for a 5 minute period.

Room 9:
Event 34, Day 1, 1:00 PM; SWE falsely detects presence for a 10 minute period. Open door.
Event 35, Day 2, 9:40 AM; SWE falsely detects presence for a 10 minute period. Open door.

Room 10:
Event 36, Day 1, 9:30 AM; SWE falsely detects presence for a 10 minute period. Open door.
Event 37, Day 2, 8:40 AM; SWE fails for a 5 minute period.
Event 38, Day 2, 9:00 AM; SWE fails for a 10 minute period.
Event 38, Day 2, 9:20 AM; SWE fails for a 5 minute period.
Event 39, Day 2, 10:50 AM; SWE and MIM suggest that manuell recording failed to record a break, or both sensors failed. SWE off-delay suggests that MIM fail to detect presence for a 20 minute period, while SWE fails a 10 minute period. This event is eliminated from the evaluation.

The SWE-V sensor failed to detect presence a total of seven times. Six of the times the sensor failed to report presence for a 5 minute period and once for a 10 minute period.

The SWE sensor failed to detect presence a total of three times. Two of the times the sensor failed to report presence for a 5 minute period and once for a 10 minute period. Like the SWE-V this shows that the sensor would not have failed to detect presence if the off-delay had been twenty minutes instead of ten.

Note that these were the results from the north-east offices.

Comprehensive results from south-west facing offices and north-east facing offices show that the SWE-V sensor failed a total of 16 times for a total of (5min×13 + 10min×2 +15min×1) 100 minutes. SWE sensor failed a total of 3 times for a total of (5min×2 + 10min×1) 20 min. The MIM sensor was not found to fail at any time.

Finally, some general remarks regarding the observation for the various sensors are given. In room 9 and room 10 the SWE sensor made three detections when it should not have given any signals. All three instances lasted for ten minutes and would imply that only one single motion was detected. This is most likely to be a result of open doors. The doors on these rooms were intentionally left open when there were no occupants there. This was done to see if false readings would happen. The results imply that an open door will cause the SWE sensor to register some false readings. The false reading could however been eliminated by choosing a longer on-delay because this eliminates any single detection. Another alternative solution would be to give the sensor the ability to restrict the detection area, which could be a good alternative solution on future models. At the current setting any single detection would send the SWE and SWE-V into off-delay settings because the on-delay setting was set to zero seconds.

The MIM did not fail to detect presence when someone was in the room. It was also found to be unaffected by the open door. Since the detection area for each MIM sensors were individually adjusted to the room this would eliminate seemed to eliminate the chance of false readings from caused by an open door.

Some data suggests that errors were made when manually recording data. It has been considered to most likely that there is an error in the manuell recordings if two or more sensors suggest that there is a presence. An example of this can be seen in Room 4.

Rooms 5 and 6 are both one-person offices. See Figure 11. The SWE-V in room 5 has the highest number of failures to register presence while there are no failures on the SWE-V in room 6. This shows that wall-mounted sensors are unpredictable when used in offices. It is difficult to say whether or not a wall-mounted sensor will be fit for an office environment because it depends on the person using the office. In general the SWE-V wall-mounted sensors require more motion to detect presence than the SWE ceiling-mounted sensor. This can best be seen on room 8 which was fitted with both types. Here the SWE-V failed four times while SWE had no failures. See Figure 12, Room 8.

A summary of the reliability of each sensor for all rooms is presented in Section 1.4. This section summarizes all the failures of the sensors and discusses the differences.

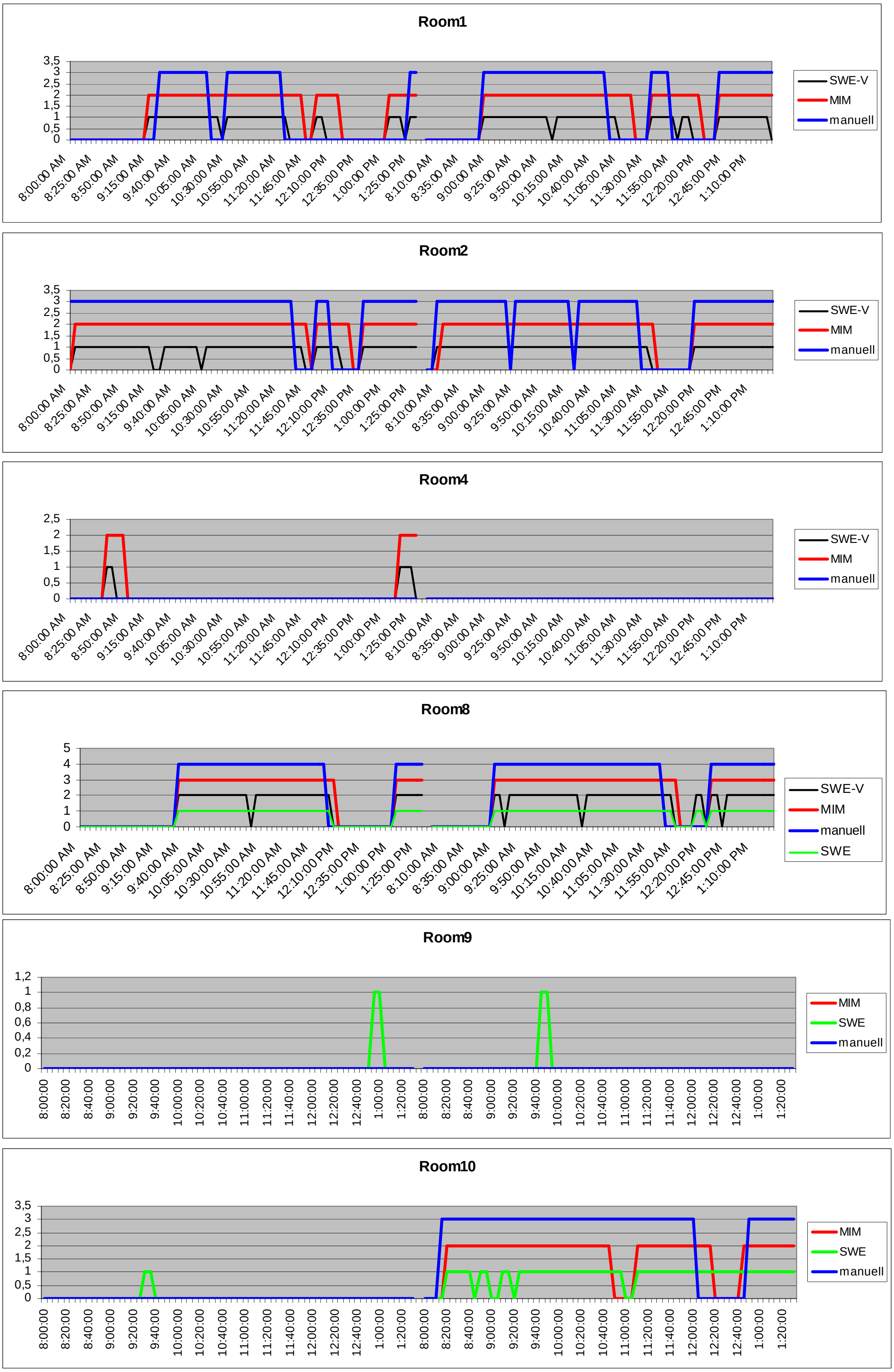


Figure 12. Offices facing north-east.

The findings in this chapter suggest that the SWE sensor is sensitive to room architecture but because of the limited amount of data this can not be stated as a conclusive result. The SWE-V sensor fails to detect presence often while the MIM sensor never fails. The SWE sensor also shows some failures to detect presence but lack of data can not make this a conclusive result.

1.4 Summary of the experiment

In this chapter we wish to present and compare the accuracy of the sensors. The criteria developed by the student “Failed to detect” and “Overestimated time” are explained in greater detail. A recommendation of how the sensors should be used in this office is also given.

The manually recorded data from the office rooms were collected and compared to the logged data. Obvious errors, like data from room 4, were left out of the comparison. In room 4 the measured data and the manuell data are not consistent. Both sensors have detected a presence but the manuell registration did not observe anyone entering the room. In this case it is likely that someone entered the room briefly and that the observer failed to observe it. This error by the observer is therefore corrected for when analyzing the individual sensors ability to reflect the true occupancy. It simply means that obvious errors are left out when analyzing the data. The following events from Section 1.3 have been left out. 17, 18, 19, 20, 22, 28, 29, 32, 34, 35. 36 and 39.

Table 1, Table 2 and Table 3 summarize how the sensors have performed compared to the data from the two days of manuell registration. 8:00 AM and 13:30 PM on the 22nd and 24th of May 2007. The 22nd of May was found to be the day with the lowest level of average occupancy while the 24th of May has an above average overall occupancy during working hours, reference is made to Day 2 (22nd of May) and Day 4 (24th of May) in Figure 2.

The following results are based on the data that was collected from the hours with manuell registration. Data from each sensor type has been extracted and compared to the manuell registration. Each sensor type has been evaluated separately. First we consider the SWE sensor. See Table 1. An explanation of how the evaluation is conducted is found under Table 1.

SWE	Time (minutes)	Percentage
Detected	715	97.3%
Failed to detect	20	2.7%
Total	735	100.0%

SWE, manuell	Time (minutes)	Percentage
Registered	680	100.0%
Overestimated	35	5.1%
Overestimated w/failure	55	8.1%

Table 1. SWE sensor data from rooms 8 and 10 compared to manuell data for the same rooms.

The table is explained from top to bottom, left to right. ***“Detected”*** is a sum of all the minutes for all the sensors of this specific type where they reported presence. This means that if the three SWE sensors in room 8, 9 and 10 reported presence during a five minute period, the “Detected” amount of minutes would be 15 minutes (3*5). By adding all the data from the sensors, and leaving out obvious error (e.g. deliberately open doors), we get a total of 715 minutes of reported detection. Note that the three cases where this sensor turned on because of the open door have also been left out of this sum. This is because the doors were deliberately opened to test for these false detections and is therefore an obvious error. Only room 8 and 10 was considerer for evaluating the SWE sensor.

"Failed to detect" are the number of minutes where the sensor simply fails to detect presence. This can be observed in room 10 and is most likely caused by the fact that the occupant is causing enough motion for the motion sensor to react.

"Total" is the sum of "Detected" and "Failed to Detect"

"Registered" is the sum of all the minutes where presence was manually detected for the rooms with this specific sensor installed. In the first table this is the manuell data from rooms 8, 9 and 10. Room 9 doesn't contribute anything because it was empty.

"Overestimated" is caused by the sensors off-delay setting. It is the sum of the minutes after the manuell registration stops to the time where the sensor stops detecting. This value will increase as the off-delay increases.

"Overestimated w/failure" is a sum of the minutes where the sensor fails to report presence and the time that is overestimated. This number was constructed as a measurement of how the sensor performs compared to the true presence. It represents a kind of overall performance factor. The percentage is how much the overestimated time and failures to detect constitute of the registered number of minutes.

The "failed to detect" percentage, "overestimated" percentage and the "overestimated w/failure" percentage represents factors or measures which may be used to determine a sensors ability to reflect the real utility patent, e.g. its accuracy. It can be used to compare the sensors.

SWE-V	Time (minutes)	Percentage
Detected	3105	96.8%
Failed to detect	100	3.2%
Total	3205	100.0%

SWE-V, manuell	Time (minutes)	Percentage
Registered	2935	100.0%
Overestimated	170	5.8%
Overestimated w/failure	270	9.2%

Table 2. SWE-V sensor data from rooms 1, 2, 3, 4, 5, 6, 7 and 8 compared to manuell data for the same rooms.

MIM	Time (minutes)	Percentage
Detected	3675	100.0%
Failed to detect	0	0.0%
Total	3675	100.0%

MIM, manuell	Time (minutes)	Percentage
Registered	3210	0.0%
Overestimated	465	14.5%
Overestimated w/failure	465	14.5%

Table 3. MIM sensor data from rooms 1-10 compared to manuell data for the same rooms.

The failure to detect presence happened fifteen times for the SWE-V sensor and three times for the SWE sensor while no failures could be observed for the MIM sensor. The failed to detect percentage indicates these results more fairly. Keep in mind that the different sensors were not represented in all rooms. SWE was only represented for rooms 8 and 10. For the SWE-V sensor rooms 1, 2, 3, 4, 5, 6, 7 and 8 were represented and the MIM sensor was represented in rooms 1-10. From the data there was no proof that any sensors were reporting detection when people were not present. Only the SWE sensor reported detection when no one was present. This was not considered to be a common registration problem for this building since the rooms were usually locked when people left the office. Also, there were no windows facing the hallway and the windows facing out of the building are on the fifth floor. This means that no pedestrians would pass by to trigger the sensor. Further analyzes of the SWE sensor in offices with a different architecture and/or different routines of closing the office doors might reveal other results.

The overestimated percentage is how many percent the overestimated minutes are compared to the minutes the sensor is expected to detect, includes off-delay. Overestimated minutes w/failure to detect includes the minutes where the sensor should have detected motion but didn't. The MIM sensor with an off-delay of eighteen minutes and forty-five seconds had the highest overestimated time. It also had the lowest amount of failures to detect presence. A theory about these results is that shortening the off-delay will increase the frequency of failures to detect presence. This relation should be investigated further.

For this office environment it likely that a long off-delay results in a higher overestimated time and fewer failures to detect presence. The downside of a long off-delay could be fewer savings. This is however not proven since the failure to detect presence may result in more wear and tear on components in the ventilation system.

Unfortunately the conference room was not used at all during the manuell registration period. It was only victim of random visits and was therefore not suitable to be compared with manually recorded data. See Figure 13.

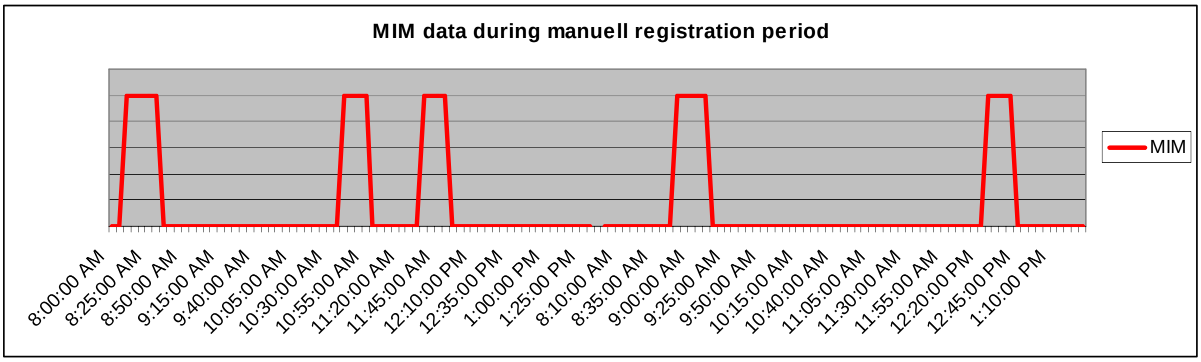


Figure 13 MIM data recorded in conference room during manuell registration period. Shows only random visits.

The women restroom was only use 3.8% of the time during manuell registration period. This would indicate that controlling lighting and ventilation in this facility with motion sensor would be advisable.

For the conference room it would be advisable to use a CO_2 sensor. This would eliminate the effect of random visits and should give a better estimate of the need for OA. If one of the motion sensors from this experiment is used in the conference room it is not possible to determine how many people are using it. It could however be suited to control lighting only.

For both one and two-person offices the ceiling-mounted SWE or MIM with its current settings perform a good job at detecting presence. For two-person offices a CO^2 sensor can theoretically give slightly higher savings because it can determine the ventilation rate more accurately. The ceiling-mounted SWE and MIM sensors are accurate enough to also control lighting. With an off-delay of twenty minutes one could expect that there would be no failures to detect presence. A shorter off-delay will theoretically give higher savings but might cause frustration if lighting is controlled by the same sensor. From the logged and manuell data it was found that a 10 minute off-delay will give an overestimated time where the system calls for ventilation of 5-6 % while a 20 min-delay will gives 14-15%. A 10-minute delay is therefore sufficient to meet the demands for OA.

In general, the student realise that there are large uncertainties associated with the analyses being undertaken. This makes it impossible to draw any firm conclusions. The most important issue is probably the limited amount of measured data, which creates a significant statistical uncertainty. Furthermore, various error sources are weakly discussed with respect to how they may impact the measured data, such as being random versus creating a biased value.

However, the study work outlines a possible way to assess utility pattern, sensor accuracy and compare sensors. The study work would greatly benefit from including more statistical data and analysis, which unfortunately is outside the topics being studied by the student.

It is important to keep in mind that the manually collected data was only carried out for two days. A future study might consider having more days of manually collected data to give the results better statistical validity.

The main findings in Chapter 1 is the average presence of 57% in the offices and 37% in the conference room in the hours between 8AM and 3 PM and the utility patent on Figure 9. Increasing the off-delay decreases the number of failures to detect presence but increases the overestimated time. Further, motion sensor are best used in rooms were the number of occupants are fairly predictable whenever the room is in use.

2 DOE2.1E Simulation program

This Chapter aims to present the DOE2 simulation program and a building at the Norwegian University of Science and Technology, Gløshaugen (NTNU) campus that was simulated using the program. The work done in this part of the thesis was conducted to prepare the student for further use of DOE2. It was necessary to refresh the students' familiarity with DOE2 to perform the simulations found later in Chapter 3 and to show that the program was capable of simulating a simple building in Norwegian climate. In Chapter 3 another building from the NTNU campus is simulated.

Section 2.1 will present some detail of DOE2 and its history. Section 2.2 focuses on some general assumptions that have been made when the models in this thesis have been created. Section 2.2 subchapters explain how a specific model was created to fit the cantina floor in one of the buildings on the NTNU campus. The subchapters of Section 2.2 present the energy demand for the simulated model and compare this to a hand calculation of the energy demand for the building. A short summary is found in Section 2.3.

2.1 Computer simulations and DOE2.1E

The goal of this section is to present DOE2 to the reader.

DOE2 is a computer simulation program for evaluating the energy performance and associated operating costs of buildings. The first version of DOE-2 was released by the Lawrence Berkeley Laboratory (LBL) in 1978. [1] Since then several new versions of the program have been released. The latest version is the DOE-2.1e-121 from 2003. The model in this thesis is run on the DOE-2.1e-119 version from 2002. [2][3][4]

To comprehend how a simulation with DOE2 works it's necessary to know the basics of how the program works and its limitations. A simulation is always an estimate of how the real building may behave. It therefore follows that bad programming result in a bad model. This principle is often referred to as "Garbage in Garbage out". Creating a calibrated and accurate model with DOE2 is time consuming and requires some experience with the program and knowledge about building physics and ventilation systems.

In a project undertaken during an exchange visit to Texas A&M University, College Station, the student used DOE2 to create a model of one of the buildings on that campus. The DOE2 model in this project was calibrated using an hourly baseline of the buildings electric consumption. In DOE2 models the baseline of the electric consumption helps to determine the internal loads in the building. This will in turn yield a model that better estimates the cooling and heating loads in that particular building.

A good model can be a useful tool when retrofitting buildings or when planning new buildings. An interesting question is to what extent computer models are being used today. How good are we to estimate the energy consumption of new buildings and retrofits? This question is however not part of this thesis.

The DOE2.1E program requires the user to create an input-file. This contains all the information about the building which the program needs. The input-file can be written in notepad and must be consistent with the DOE2 language and DOE2 version. [6] Another essential part of the program is the weather-file. The weather-file contains hourly data about such factors as sun, wind, humidity and temperature, i.e. it determines the climate where the building is located. This allows the user to test his/her building in different climates. The buildings selected for this thesis are situated in Trondheim, Norway.

Two floors in a large building on NTNU, Gløshaugen campus were selected as part of the simulations. The cafeteria, which is the focus of this chapter, is situated on the sixth floor in this building. The other floor is an office on the fifth floor. Both floors are part of the same large building on the campus. The cantina and the office are however simulated as two separate buildings. The sections are simulated as two separate buildings and are not connected in any way in the simulations. The office simulation is presented in chapter 3. The cantina is considered in this Chapter.

The goal of simulating the cafeteria is to establish the validity of DOE2 since this is an unfamiliar program at NTNU. It is also meant to refresh the student familiarity with the program.

The goal of simulating the office building is to find the potential savings with different ventilation strategies. The results from the Chapter 1 will be used to simulate the office with different levels of occupancy. Again, the office simulation is found in Chapter 3. The office is mentioned here because several of the assumptions made in the model of the cantina have been made in the model of the office.

2.2 Assumptions in the input-file

The two building that were simulated have some common assumptions and some specific. The common assumptions done in the simulations will be presented here. The specific assumptions made can be found in the buildings individual chapters. i.e. Chapter 2 for the cantina and Chapter 3 for the office.

DOE2 uses a fixed schematic technique to simulate HVAC systems. This means that program uses a set of built-in curve-fits of how much energy a component uses to perform a specific task. The equipment curve-fits can be found in ref [6]. It's assumed that the built-in curve-fits are representable for the systems we're looking at.

DOE2 is able to calculate many system parameters based on the loads on the building. Since there was little data available on these systems it's chosen to let the program find the suitable equipment. The fan size, cooling and heating coils are some of the equipment that DOE2 sizes. The equipment has corresponding operating curve-fits that can be user specific, but it's assumed that the default curves are applicable.

Norway uses daylight-savings. In the program this forces one 23-hour day in the spring and one 25-hour day in the fall. This has minimal effect on the energy consumption and it's turned off in the simulations. [7] The simulation has turned off holidays. This will basically have little effect on the overall energy consumption.

Where there has been doubt about the construction of the buildings the construction has followed the requirements for thermal insulation of the building codes of 1969. Infiltration is also set according to these codes. [14] The requirements in the building codes state that infiltration is not to exceed 1.5 m^3 per square meter per hour when the difference in pressure is 50 Pa between the outside air and the inside air. This definition of infiltration does not compute with DOE2 and an approximation has been used based on NS3031. [16]. The coefficient of surface conductance is 0.45 W/m^2 °C for outer walls including the windows and 0.23 W/m^2 °C for the roof. All internal walls have U-values of 1.17 W/m^2 °C.

The duct air loss is assumed to be zero. There are no temperature losses or gains in the ductwork.

The baseboards are assumed to be controlled after the principle of thermostatic-control. This is the default control-method. Thermostatic control means that the baseboards are controlled by a thermostat in the zone. Heat is added proportionally to the difference between desired and actual zone temperature. The alternative is to control the baseboards with a thermostat located outside the building. This is called a reverse-action control. This requires more information about the buildings performance according to outside temperatures. [21]

The control of heating and cooling supplied by the ventilation system is controlled after the principle of proportional control. A throttling-range is specified which determines the amount of heating or cooling that is delivered from the system as a function of the difference between the desired temperature in the zone and the actual temperature. [21] Section 2.2.2, Figure 19, explains this in greater detail.

2.2.1 Simulation of the cantina

The objective of this section is to explain how the model of the cantina was created.

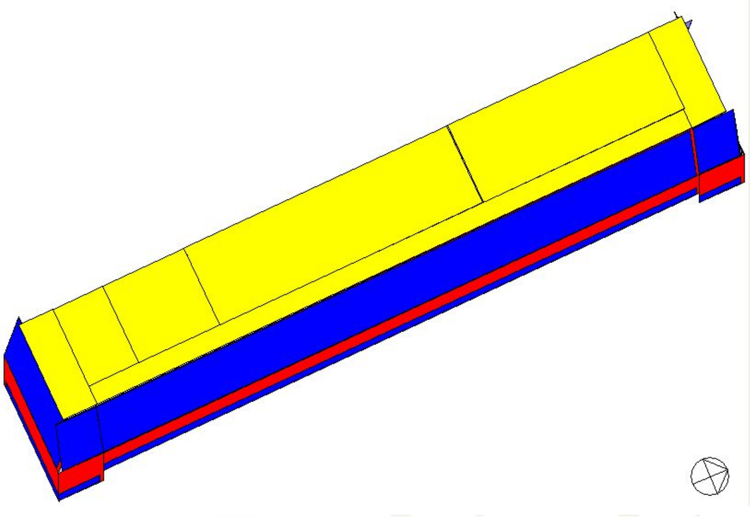


Figure 14. DrawBDL of cantina

The cantina is divided into several rooms. In the simulation this is represented by dividing the floor into six different zones. The zones were divided according to Figure 15. The numbers on the picture represents the numbers that the zones were given in the program input-file. Zone 1 is called space-1-1, zone 2 is space-2-1, etc [17]. The black lines in Figure 15 represent either internal or external walls.

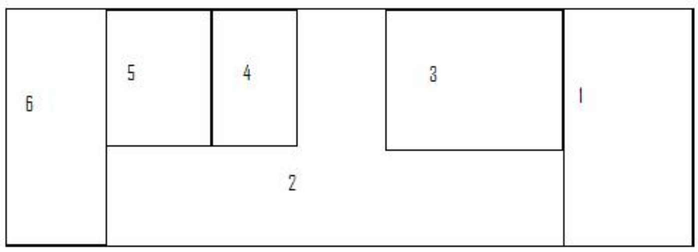


Figure 15. Zoning of the cantina

For those familiar with this building, zone 2 is the largest room in the cantina where people eat lunch. Zone 3 is the kitchen, zones 4 is a conference room, zone 5 is a storage room and zones 1 and 6 are the stairways.

According to the maintenance personnel and employees who work in the cantina there are great difficulties of maintaining the temperatures during winter and summer. [23][30] In the summertime the temperatures are too high and in the wintertime too low. Some of the reasons for this are that the system does not offer cooling. It only uses outside air for cooling. The system is a dual-duct system, and it allows return air to be utilized. This kind of system is not very common in Norway. In a dual-duct system hot and cold air are lead to a terminal box in separate ducts. The hot and cold air is then mixed before entering the space. The hot deck set-temperature is set at 30 ºC and the cold deck to 16 ºC in the simulations. [17] Figure 16 shows the DOE2 schematics of a Dual-Duct system.

The heat recovery unit is a rotating heat recovery unit with an effectiveness set to 75%. RECOVERY-EFFICIENCY is the codeword in DOE2 language and refers to the energy recovered over the total recoverable energy. If the difference between exhaust and outside air temperatures is less than 5.6 ºC, no recovery is simulated. How DOE2 calculates heat-exchangers is discussed in greater detail in ref [10]. In the simulation of the cantina the recovery-efficiency was found to have little effect. This might be because the system allows the use of return air. Instead of using the recovery-efficiency it was decided to set the MIN-OUTSIDE-AIR= 0.25. This allows the system to reuse 75% of return air. This parameter has a huge effect on the energy consumption of the system and it was assumed that this assumption would mimic heat recovery unit of ~75%.

Even though the real system in the cantina does not incorporate a cooling coil the simulation does. After some initial runs it was decided to incorporate cooling to the system because room temperatures became very high. There was also trouble getting DOE2 to run properly when the system did not have any cooling capacity. It simply crashed.

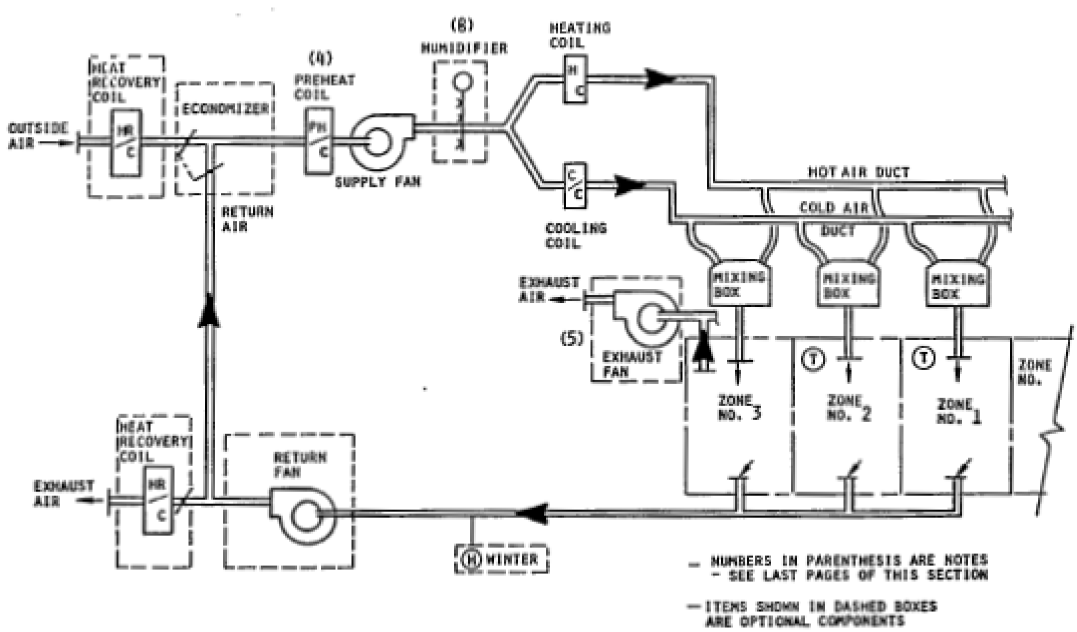


Figure 16 Air mixing system (DDS, Dual-Duct System) [8]

The DDS is considered to be energy intensive. For example; the hot deck temperature is set to 30 ºC and the cold deck temperature is set to 12 ºC. The room temperature is set to 21 ºC and the system is operating on constant volume and there are no loads on the conditioned space. In this case the system would require an equal amount of hot and cold air is to satisfy the room temperature.

It is however possible to make the systems more energy efficient by resetting the hot and cold deck temperatures. Reset of hot and cold deck temperatures will minimize temperature difference between the hot and cold decks based on outside temperatures or time and can therefore minimize energy consumption in these systems. This is applied in the simulation of the cantina and is explained later in the text.

In the maintenance control-room the hot deck temperature showed 27.4 ºC and the cold deck 12.7 ºC. In the simulation it's assumed that the system is in perfect working condition. According to maintenance personnel this is not the case. [30]

The windows used in the simulation are double paned window with reflective coating. This type of window has less solar gains than windows without reflective coating. From the DrawDBL portrait of the building we can observe that this building has an incredibly large amount of windows.

According to the manual in ref#[8] the size of the supply fan for the DDC system is calculated as 0.000642 kW/(m^3/h) if its not given a specific value. The ventilation capacity is 1700 m^3/h and a cross reference of the SV-A report in the output file confirmed a fan size of 1.1 kW. [18]

Delta T across the supply fan is 2.3 °C by default. The supply static pressure and efficiency is calculated based on the supply delta T and the supply kW. Exhaust fan efficiency is 0.75. The duct air loss is assumed to be zero. There are no temperature losses or gains in the ductwork.

Heating and cooling capacity is calculated by DOE2. These values are calculated using the peak loads on the building.

Equipment like coils use prefixed standard curves to determine their heat exchange rates and efficiencies. The appropriate curves can be found by cross-referencing between references [8] and [13].

2.2.2 Details of the simulated DDS system

This section describes further details of the information that is incorporated in the simulated model of the cantina.

Design temperatures for the ventilation system are 21 ºC for heating and 23 ºC for cooling. The design temperatures are one degree Celsius higher and lower than the desired room-temperatures. Design temperatures are used by DOE2 to determine the required ventilation rates to satisfy the peak heating and cooling loads. Heating and cooling schedules are used to lower or raise the acceptable room temperatures at different hours. Allowing high and low temperatures during hours outside operating hours is quite normal practice. The high and low temperatures that are acceptable outside operating hours are called set back temperatures. This allows for less energy consumption at hours when the building is assumed to have a low occupancy or be completely unoccupied.

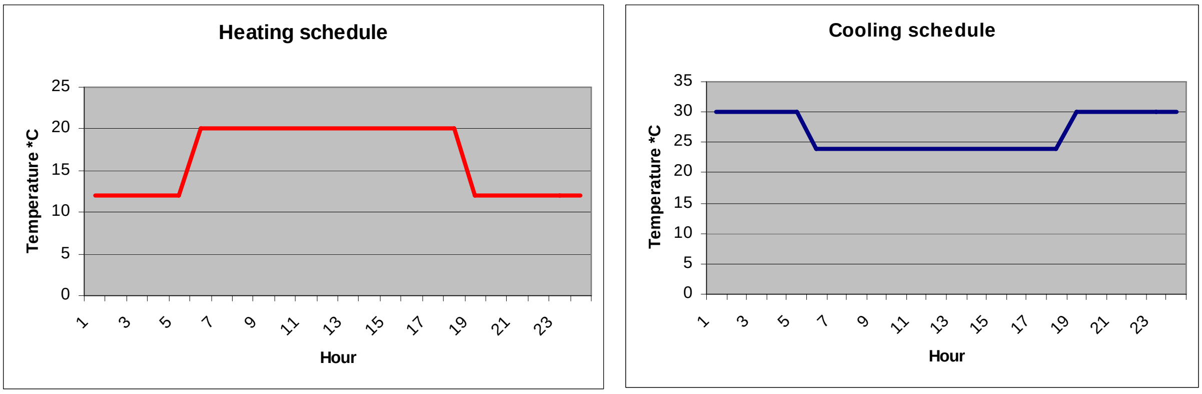


Figure 17 Heating and cooling schedules, cantina

The schedule in Figure 17 is valid for weekdays. During weekends the heating and cooling is set to 12 ºC and 30 ºC respectively. These values are the minimum/maximum temperatures that are allowed. The system will turn on if these temperatures are exceeded.

The fans are available according to Table 4 and Figure 18. The DDC ventilation system is a type of CAV system. The fans run constantly with a fixed airflow rate when the system is on. Even though the fans are turned off outside normal operating hours they are still available if the loads on zone 2 cause it to exceed the minimum or maximum temperature, i.e. Figure 17. We can imagine that temperatures beneath or above the minimum/maximum temperatures can damage equipment in zone 2 and we therefore want the fans to be turned on if it is required. This function is called NIGHT-CYCLE-CTRL in DOE2 and makes sure that temperatures are within the scheduled range even outside normal operational hours. In the simulation the system turns on to meet the loads if the largest zone (zone 2) is out of the scheduled minimum/maximum temperatures. The system will then continue to run for the specific hour it was turned on. If the temperature is still not within scheduled range at the end of this hour the system will continue to run. The Yes/No in Table 4 simply specifies whether or not the fans are within the normal operating hours. The graphical presentation of the table is Figure 17. If the minimum/maximum temperature of zone 2 is within its limits during a “no”-period the fans will be off. Weekends are set to “no” for all hours.

Hour	ON
1-5	no
6-18	yes
19-24	no

Table 4 Normal fan operating hours

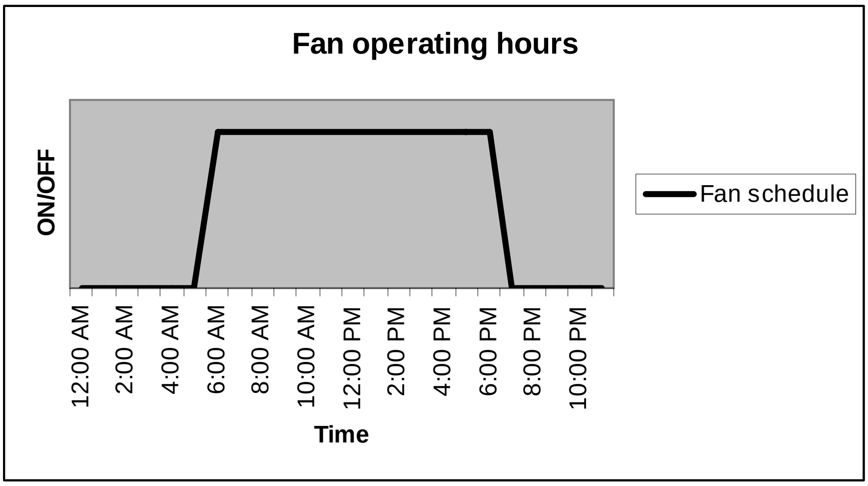


Figure 18. Fan normal operating hours.

Heating is supplied by baseboards and by the ventilation system. The baseboard heating capacity is specified for each zone. Zone 1 and 6 are unconditioned. This means that they are passive and do not receive ventilation or heating/cooling. This is a simplification of the real building. These zones are stairways that run from the first floor and all the way up to the cantina on the sixth floor. Zone 2 is equipped with 17 baseboards. All baseboards are considered to consume hot water. The total heat delivered by these baseboards was initially approximated to be 8.5 kW. The approximation was done by observing the type and number of radiators that were installed in the different zones. Zone 3, 4 and 5 are each equipped with baseboards that were assumed to be able to deliver 3kW per zone. These assumptions did not satisfy the demand for heating and therefore had to be changed. The assumed values for the baseboards resulted in a system that was below the scheduled temperature for many hours during January and December. By running the program with oversized baseboard capacities it was found that the zones would need the following baseboard heating installed to satisfy the desired temperature schedule, see Table 5.

Zone	baseboard heating (kW)
2	36.0
3	20.0
4	8.8
5	5.0

Table 5. Installed baseboard heating per zone in kW

The estimated baseboard heating in Table 5 assure that the heating loads are met.

Baseboards will add to the hot water supply that is required to condition the cantina. The other consumers of hot water are the heat exchanger and the pre heat coil in the ventilation system. The baseboards are assumed to be controlled after the principle of thermostatic-control. This is the default control-method. Thermostatic control means that the baseboards are controlled by a thermostat in the zone. Heat is added proportionally to the difference between desired and actual zone temperature. The alternative is to control the baseboards with a thermostat located outside the building. This is called a reverse-action control. This requires more information about the buildings performance according to outside temperatures. [21]

The control of heating and cooling supplied by the ventilation system is controlled after the principle of proportional control. A throttling-range is specified which determines the amount of heating or cooling that is delivered from the system as a function of the difference between the desired temperature in the zone and the actual temperature. [21] The black line in Figure 19 is the "dead-band". In this temperature-range the system delivers no heating or cooling. The desired room temperatures for the cantina are 20 ºC and 24 ºC for the heating and cooling periods, respectively.

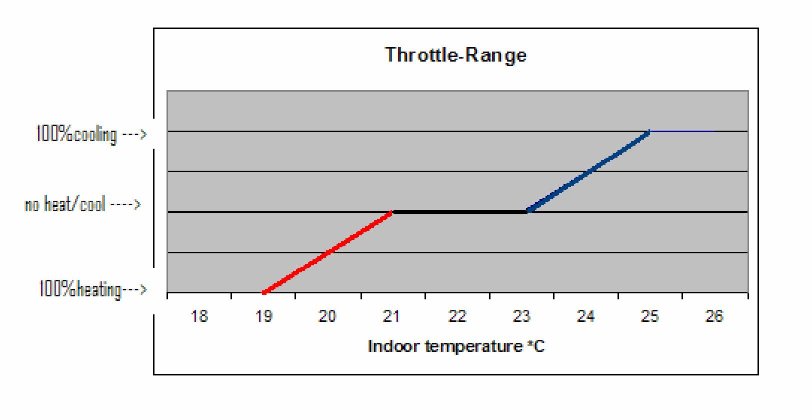


Figure 19. Throttling-range for the cantina HVAC system

The maximum supply temperature for this system is 25 ºC and the minimum is 16 ºC. These values will be important to DOE2 if the program is used to calculate the ventilation capacity to meet the loads. Keep in mind that this is not the values of the hot and cold deck temperatures in the system.

The system is fitted with a preheating coil. The preheating coils main purpose is to protect components against frost. The default in DOE2 for the DDC system is a preheat coil which is capable of maintaining 7.2 ºC for the OA pulled in by the system before it reaches other components. Its location can be seen on Figure 16.

Min-outside-air fraction is the minimum fraction of outside air that is mixed with return air before it becomes supply air. This factor has a great impact on energy use in a system. By allowing 75% of the air extracted from the zones to be reused it will greatly reduces the energy needed to heat or cool outside air when this is significantly different from the return air temperature. In the SS-J report of the output file for the cantina it can be observed that minimum OA happens during peak heating while maximum OA happens during peak cooling. Minimum OA per person is 2.9 cfm. This is equivalent to 3.9 m^3/h or 1.1 l/s and is far below the recommended 10 l/s.

Each zone can be assigned its own schedules for different parameters. Some main parameters are occupancy, lighting, electric loads, infiltration and ventilation. For the cantina it is also relevant to use the shading-schedule option to simulate the effect of blinders. The blinders are not applied during the wintertime until the 15^{th} of May unless the solar-gains exceed 317 W/m^2. This option helps to decreases the peak cooling and the real system incorporates blinders. Between 15^{th} of May and 15^{th} of September the blinders will be applied when the solar-gains exceed 6 W/m^2. This means that the blinders are applied almost all summer long. Only the windows in zone 2 are fitted with blinders. See Figure 15.

The occupancy schedule used for the cantina is based on information from the cafeteria lady. [23] The occupancy schedule used for the conference rooms are based on an estimate made on how the rooms have been booked in March 2007. For the hallways and restrooms common sense has been applied to determine the occupancy schedule. The schedules for occupancy are valid for weekdays only. During the weekends it is considered to be empty.

Zones 1, 3, 5 and 6 share the same occupancy schedules. Maximum occupancy here is one person. Figure 20

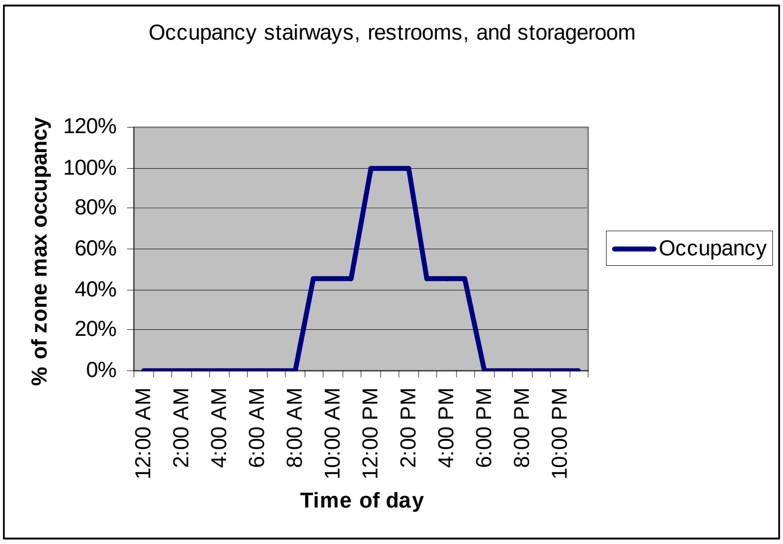


Figure 20. Occupancy zone 1, 3, 5 and 6

Maximum occupancy for the conference room, zone 4, is twelve persons. Figure 21

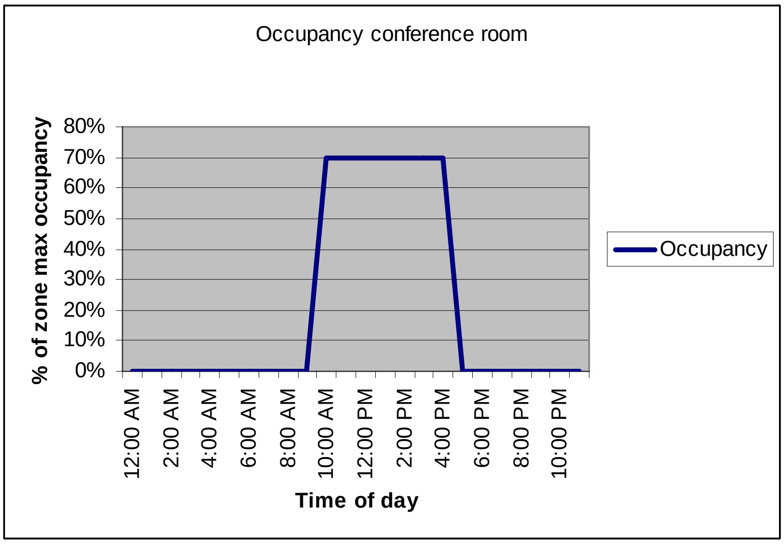


Figure 21. Occupancy zone 4

Maximum occupancy for the cafeteria room, zone 2, is seventy persons. Figure 22

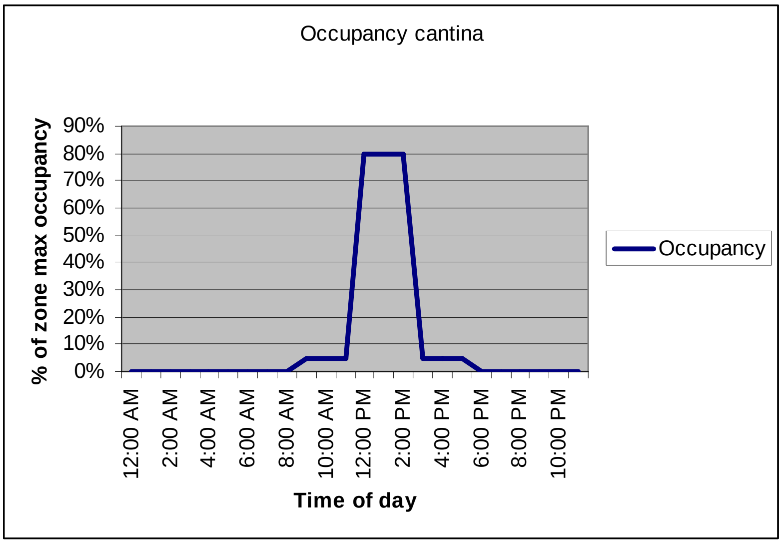


Figure 22. Occupancy zone 2

The simulated occupancy is the maximum occupancy multiplied with the occupancy schedule.

The ventilation capacity for each zone and ultimately the system is based on the HVAC plans for the building. Zone 1 and zone 6 are unconditioned. Total ventilation capacity is 1700 m^3/h. Table 6

Zone #	Vent.capacity m^3/h
zone 1	N/A
zone 2	1000
zone 3	200
zone 4	250
zone 5	250
zone 6	N/A

Table 6. Ventilation capacity for each zone based on HVAC plans.

The infiltration schedule is set to one for the entire year except for May, June, July and August. To simulate the effect of extra infiltration during the hot months as a result of people opening windows the infiltration schedule had the value 4 in May, June, July and August. It was believed that this would reduce the room temperatures. This means that infiltration is four times higher during these summer months compared to the rest of the year. The rest of the year the infiltration is 0.25 air-changes per hour. The simulation uses the air-changes per hour method to account for the infiltration. This method is wind-sensitive. The method allows the user to assume a value for the infiltration but will increase this value with increasing wind speed.

Lighting for the entire cantina is assumed to be 16 W/m^2. The lights are assumed to be controlled similarly for all zones. During weekends the lighting is set to 5% which is the same as it is on weekdays between hours 22 and 8. The office equipment is considered to have the same schedule as the lighting schedule. The assumed value for office equipment is 11 W/m^2.

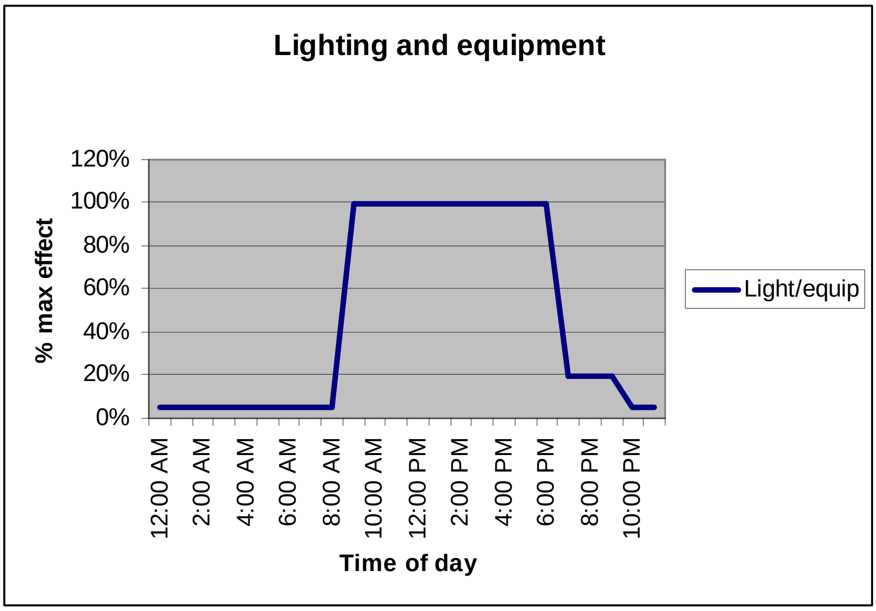


Figure 23. Lighting and equipment schedule for the cantina.

During summer there is less need for heating. To conserve energy the hot deck is therefore reset based on the outside temperature. This is achieved in DOE2 with a reset-schedule. The hot deck set temperatures increase linearly from 20 to 30 degrees Celsius as outside temperatures decrease from 15 to 10 degrees Celsius. Cold deck set temperatures decreases linearly from 20 to 16 degrees Celsius as outside temperatures increase from 10 to 15 degrees Celsius. See Figure 24.

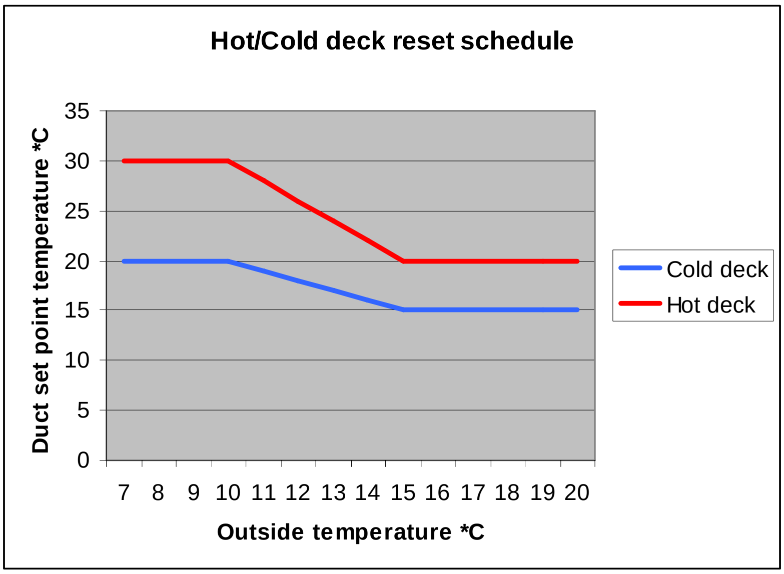


Figure 24. Hot and Cold deck reset schedule based on outside air temperature.

It is not certain that this is the optimal hot and cold duct reset schedule for this model but it serves its main purpose, which is to show how the function works.

2.2.3 Simulated results

A hand calculation of the energy demand for the month January was performed for of this building based on NS3031. [Appendix C] [15]. This suggests an energy demand of 2811 kWh. The simulated system showed a hot water demand of 2262.9 kWh and an electric demand of 1939.9 kWh. The SS-M report of the DOE output file showed that 356.0 kWh of the electric demand was needed for fan operation. [18].

As mentioned earlier this system does not have enough cooling. This is very visible in the SS-F report of the DOE output file. [18] For example, during July the coldest temperature in zone 2 was 33.6 degrees Celsius. The hottest temperature for the same zone and month was a staggering 51 degrees Celsius. These temperatures increased even more when the infiltration rates were left at the year average of 0.25 air-changes/hr.

We will call the original system Simulation 1. The energy demands for hot water, cold water and electric energy for one year is shown in the table below.

	Hot water (kWh)	Cold water (kWh)	Electric energy (kWh)
Simulation 1	5844.5	2800.5	25369.8

Table 7. A one year simulation of the energy demands of Simulation 1.

If we let DOE adjust the ventilation capacity to meet cooling loads the system becomes unrealistically large. The program suggests a ventilation capacity of 17989 m^3/h to meet the cooling loads. This is ten times more that Simulation 1 and the HVAC system plans. For a one year simulation it is possible to se how this has a huge impact on the energy demand. We will call the DOE sized system Simulation 2.

	Hot water (kWh)	Cold water (kWh)	Electric energy (kWh)
Simulation 2	37303.9	16937.1	63557.9

Table 8. A one year simulation of the energy demands of Simulation 2.

2.3 Summary

The current system is therefore is therefore not suited for this building. It does provide enough heating but the cooling demands are far from being met.

Looking at the energy demands found for Simulation 1 and Simulation 2, Table 7 and Table 8, it is suspected that there is some kind of problem with the input file when DOE sizes the system in Simulation 2. This is then causing DOE2 to demand the high ventilation capacity to meet the cooling loads. Either that, or the DDS system is unfit for this building. The students' untrained eye is unable to make a conclusive statement as to the exact reason why the ventilation rates and energy demands increase so dramatically. The increased energy demand is probably a result of the system being a constant air volume system and that the increased ventilation capacity causes the system to heat, cool and move large amounts of air. The real problem is why the system has to be so huge to condition a building which only has a conditioned area of 372 m^2.

Assuming that the input file is correct according to all the parameters that have been mentioned earlier in this chapter we can draw a set of conclusions about the building:
-The building has too many windows which cause a high demand for cooling. This in turn results in a high ventilation capacity and a very ineffective system.
-Blinders should be applied in all zones and turned on during hours of high solar radiation.
-A VAV system could dramatically reduce energy demand and still meet the loads.
-Simulation 1 corresponds to NS3031 calculations which strengthen the belief that the model is correct.
-Better insulation could help reduce heating demand
-Alternative methods of cooling the building should be considered and/or replacing windows with walls.

The main purpose of this chapter was to familiarize with functions and behaviors of DOE2 simulation. Building a model based on manuals and gathered data. All in all this portion of the thesis was a success. A much stronger confidence about how to build and manipulate an input file in DOE2 was achieved. Important parameters that determine the energy demands were discovered. These include ventilation capacity and the minimum OA ratio amongst others. These parameters might change when the system is changed. In the next chapter we will take a closer look at how some of these parameters and how they change the energy demands.

3 Simulation of the office

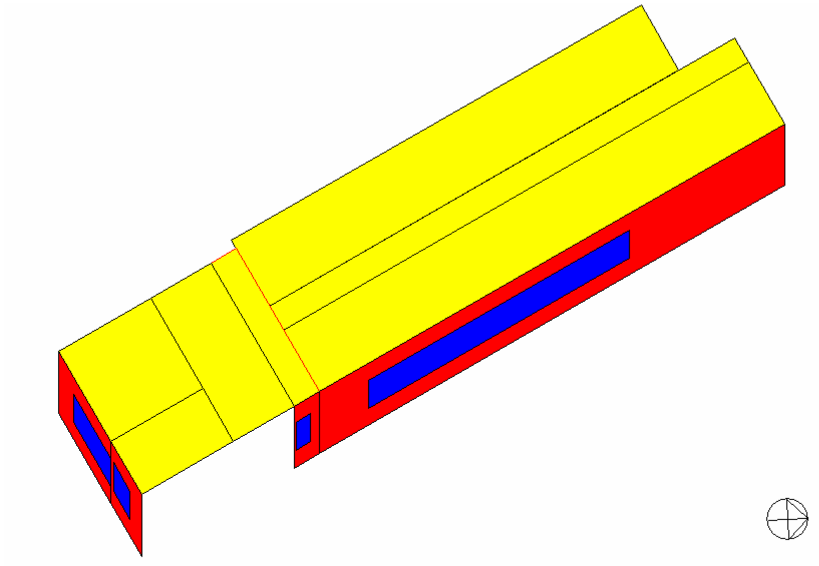


Figure 25 DrawBDL of the office

The goal of the simulation is to investigate what energy savings we might expect when ventilating the office floor with a CAV compared to a VAV which is partially controlled by motion sensors to limit the outside air intake. The two different solutions are called Case 1 and Case 2. In this simulation the results from Chapter 0 will be used. Section 3.1 focuses on describing the model that forms the basis for Case 1 and Case 2 simulations. In Sections 3.2.1 and 3.2.2 the results from each case are presented and some general conclusions about the state of this system are made. Section 3.3 discusses how the utility patent found in Chapter 0 affects the simulation and introduces two alternative systems called Case 3 and Case 4. Finally, Section 3.4 summarizes the main conclusions of the chapter. Some of the questions being evaluated are; What conclusions can be drawn? What are the causes of the differences? What changes can be made to improve the model? Why should we control the system according to the occupancy level? These questions are given their own subchapter.

Case 1 is a CAV system. A CAV (constant air volume) system is a system where the ventilation rates are kept at a constant rate when the system is operational. It can be viewed as an on/off system in the sense that the ventilation rates are kept constant. Constant ventilation rates make the CAV system the simplest type of ventilation systems. It generally requires fewer components and has the lowest initial cost.

Case 2 is a VAV system. A VAV (variable air volume) system is recognized by its ability to vary the ventilation rates. A rather simple adjustment to the DOE2 model transforms the Case1 model from a CAV to a VAV system. The main reason why we find VAV systems is that reduced airflow rates give reduced energy demand. The downside of VAV systems is that they require a higher initial cost and more mechanical parts. This will typically mean higher costs for down payment of the system and can make it more prone to mechanical failures.

Both cases are based on the same DOE2 model but with two important differences. In Case 1 the terminal boxes are locked in a 100% open position and outside air intake is 100%. This represents the current CAV system that serves the office. In Case 2 the terminal boxes can limit the air flow to 10% of maximum airflow and the lower limit for outside air intake is controlled by the number of people in the zone. The limit is set to 10 l/s per person. The outside air intake is the parameter that can be presumed to be controlled by a motion sensor.

3.1 About the model

This Section focuses on presenting the system that is found in the office and how the DOE2 simulation model is built.

The general building specifications and the general system specifications are the same for Case 1 and Case 2. As mentioned earlier only the OA intake and minimum allowed flow through the terminal boxes was changed from Case 1 to Case 2.

General building specifications;

Latitude 42.0
Longitude 88.0
No holidays
No daylight savings
U-value for roof is 0.23 W/m^2 °C
U-value for windows and walls are 0.45W/m^2 °C
Windows have reflective coating and are double pane
U-values are based on the building codes of 69' [14]
Heat gain from people is 400W per person
Lighting is 11.8 W/m^2 (multiplied with lighting schedule)
Equipment is 4.3 W/m^2 (multiplied with equipment schedule)
Infiltration is 0.25 air-changes per hour (wind dependent)
Building volume 1086 m^3
Building floor area 356 m^2

General system specifications;
Figure 26 shows the layout of the system that DOE simulates when the user wants a VAV system. Components shown in dashed lines are optional. Note that the return fan is optional. No return fan was selected for Case 1 and Case 2.
System type: Variable-Volume Fan System w/optional Reheat (VAVS)

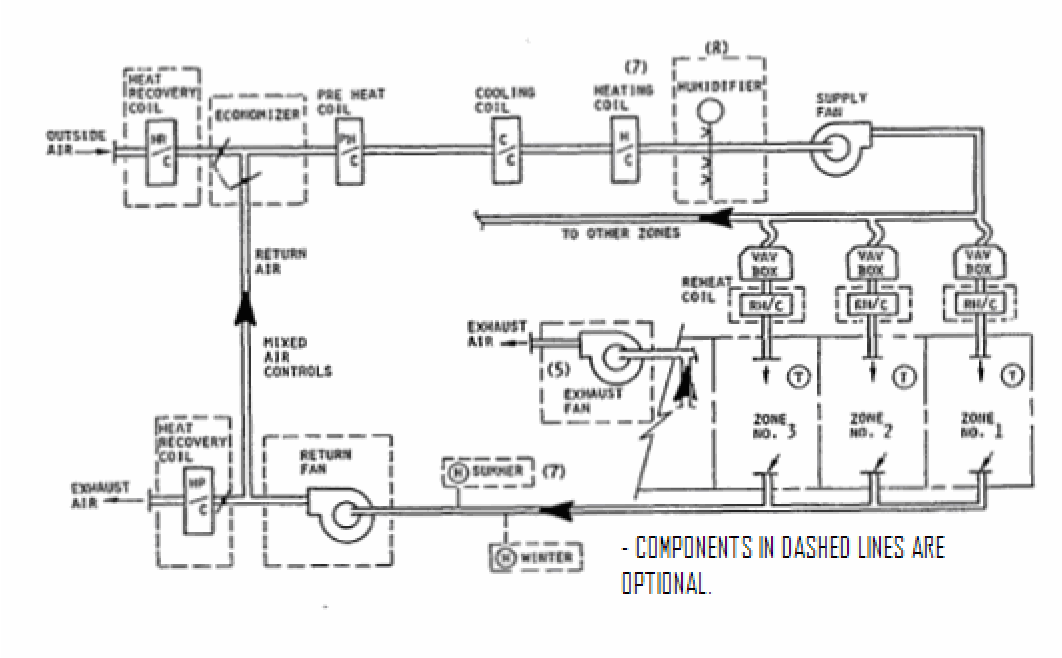


Figure 26. DOE2.1E VAVS system

Design heating temp 21°C (Used when DOE2 sizes equipment)
Design cooling temp 23°C (Used when DOE2 sizes equipment)
Thermostat control is type PROPORTIONAL w/THROTTLING-RANGE=4
Outside air-control is 10 l/s per person or by temperature for Case 2 and 100% in Case 1
Maximum supply temperature of air is 20 °C
Minimum supply temperature of air is 16 °C
Ventilation capacity 2286.6 m^3/h (design flow rate)
Supply fan static pressure 5.5 psi
Supply fan efficiency is 55%
Fan effect 1.6 kW (calculated by DOE2)
Minimum airflow through terminal boxes is 10% in Case 2 and 100% in Case 1
No night cycle control (fans are always off outside operating hours)
Cooling capacity is 7.6 kW
Maximum baseboard heating is 52 kW.
Heat recovery efficiency is 70%

The effect of the fan is calculated by DOE based on the fan static pressure, fan efficiency and the ventilation capacity. DOE uses standard curves that can be modified by the user to fit a specific fan. This model uses the standard fan found in the user manual. The fan static pressure is defined as the total pressure produced by the system supply fan at design flow rate. The ventilation rates are taken from the HVAC plans for the office floor. [12] [Appendix B]

Cooling capacity is calculated by DOE based on peak-loads. However it is limited by the ventilation capacity and the minimum allowed supply temperature. In Case 1 and Case 2 the ventilation capacity is specified. The DOE manual explains calculation of cooling capacity in greater detail when both ventilation capacity and cooling capacity is sized by DOE. [11]

Schedules and zoning;

Schedules in this DOE2 model describe occupancy, lighting, electric equipment, fans, heating and cooling. Parameters like shade and infiltration is also possible to schedule.

The conference room was found to be used in use 37% of the time during working hours, between 8 AM and 3 PM. This amounts to 4505 minutes of presence during working hours calculated for twenty nine days. A total of 5 385 minutes of presence was detected during twenty nine working days. For the simulation part it is assumed that the remaining 880 minutes that were recorded happened between 3 PM and 6 PM. 880 minutes during these hours corresponds to 17% occupancy. This is not 100% correct compared to the recorded data for the conference room, but is a reasonable assumption when doing a simulation of the building. Weekends and all other hours are considered to have no occupancy. Of the two conference rooms in this building only one was equipped with a motion sensor. The two rooms are divided into separate zones when the building was simulated. It is assumed that the occupancy for both rooms is the same. In the input-file for DOE2 the conference rooms are called Space 1-1 and Space 2-1. The Case 2 line on Figure 27 shows the percentage of occupancy in the conference rooms that are used in the simulations. The Case 1 and Case 2 line represent the minimum allowed airflow rate as a percentage of the ventilation capacity to the specific conference room during operating hours.

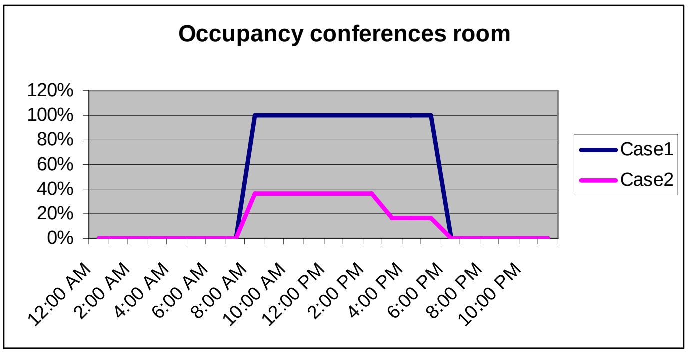


Figure 27. Ventilation and occupancy in the conference zones

A small coffee-room and two restrooms are considered to be one zone called Space 3-1. This zone has the same occupancy percentage as the Case 2 line.

The hallway is considered to be a zone. This is called Space 4-1. It is considered to have no occupancy.

All office rooms are considered to follow the utility patent measured by the MIM sensor. In the simulation the office rooms are split into two zones. One zone is for the offices facing south-west and another for those facing north-east. In the input-file these are called Space 5-1 and Space 6-1, respectively. Space5-1 also features a storage room for office requisites and a printer room. The Case 1 and Case 2 lines in Figure 28 indicates the minimum allowed air flow rate as a percentage of ventilation capacity to the specific office zone. The Case 2 line also represents the level of occupancy that affects the internal loads for the office zones.

All zones are shown in Figure 29. The maximum number of occupants in each zone is listed below. Zone 1=15, Zone 2=8, Zone 3=2, Zone 4=0, Zone 5=11, Zone 6=10. The actual number of occupants is this number multiplied by the schedule.

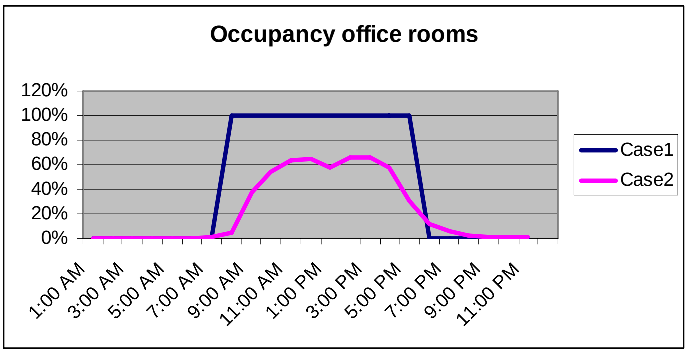


Figure 28. Minimum ventilation rate as a percentage of the zones ventilation capacity. Case 2 line represents the occupancy in the office zones based on the results from chapter 0

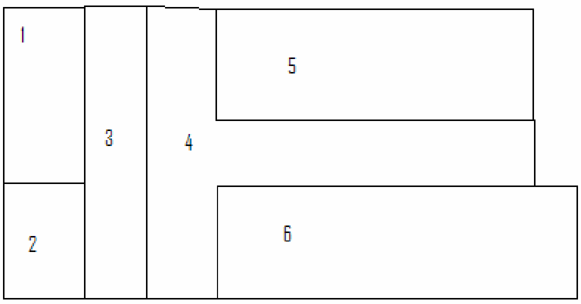


Figure 29. Zoning of the office

For those familiar with this building zone 5 includes room numbers 530, 533, etc. while zone 6 include room number 541, 542, etc. Zone 1 is the largest conference room.

In Case 1 the DOE2.1E model is forced to run on 100% OA (outside air) while in Case 2 the system only takes in 10 l/s of OA per person. This should give a reduction in energy demand for heating of air. Further the terminal boxes in Case 1 are locked at 100% open to simulate a CAV system. In Case 2 the terminal boxes allow reduced airflow down to 10%. 10% airflow is however only possible if the demand for OA is met. A function to control the airflow to one zone based on the level of occupancy alone was not found in DOE2.1E. An alternative to such a function in DOE2 is the "OA-CFM/PER= x " which states that the minimum outside air intake is x cubic feet per minute per person (Case 2 uses 21.2 cfm = 10 l/s). In Case 2 this means that minimum airflow is only possible if the OA-CFM/PER and temperature requirement in the zone allows it. The DOE manual explains that minimum has to be larger than the total outside air quantity to all zones divided by the sum of the supply air to all zones. [9] This ensures that the minimum amount of OA is supplied to the zones. The only drawback with Case 2 is that it will allow return air which is uncommon for Norwegian buildings. It was attempted to set the outside air fraction =1. This had however no effect on Case 1 and Case 2. Further analysis of the outside air fraction will be considered in a later chapter. Case 1 runs with 100% OA and consequently 0% return air. Case 1 and Case 2 include a heat recovery unit with an efficiency of 70%. It was believed that allowing return air might yield some higher energy savings. Systems that incorporate a heat recovery unit seem to have little changes to their energy demand whether they allow return air or not. As the heat recovery unit efficiency increases, this becomes even clearer. This relation is shown in chapter 3.3.2.

Heating is provided with baseboards in each zone. Each zone was fitted with a large baseboard capacity for heating to ensure that all zones would be within desired temperatures during heating season. The maximum supply air temperature has been set to 20 degrees Celsius to ensure that the supply air does not contribute a whole lot to the heating of any of the zones. 20 degrees Celsius is the same as the set temperature for the zones when the system is in heating mode. Minimum supply temperature is 16 degrees Celsius. The desired temperature when the system is in cooling mode is 24 degrees. Night set back temperatures are 12 degrees Celsius for heating and 30 degrees Celsius for cooling. Night set back temperatures can be optimized to fit for a particular building. This is discussed further later in this Section. A default preheating coil ensures that the minimum temperature into the system is 7.2 degrees Celsius. See Figure 30.

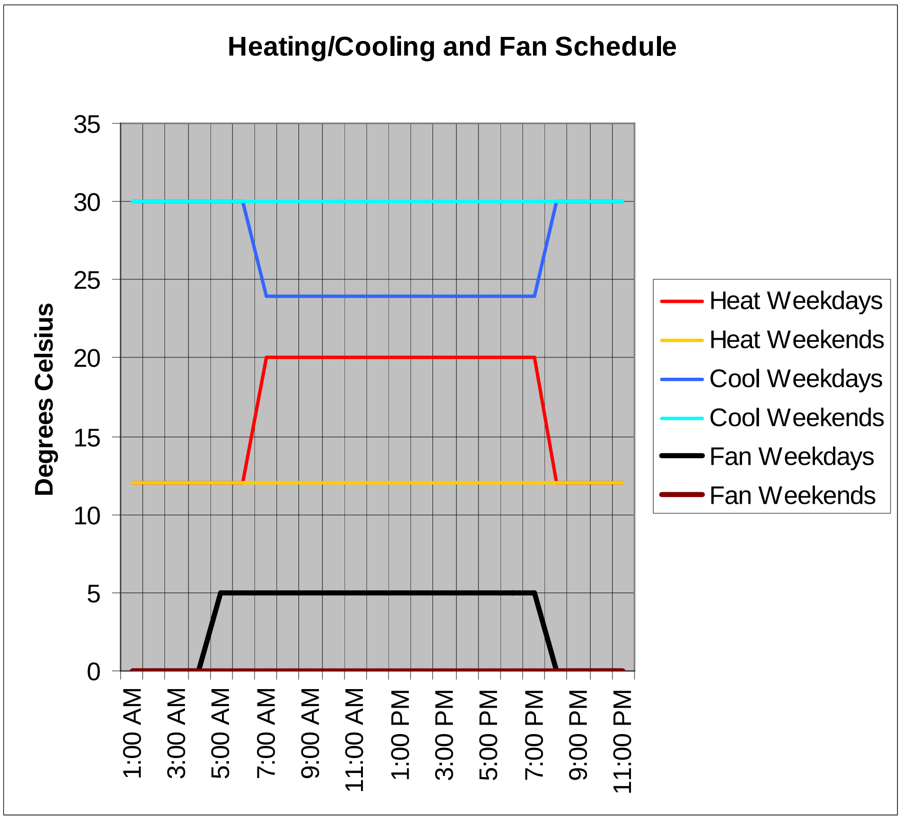


Figure 30. Heating/Cooling and fan schedule. The fan is turned on at 5 AM and off at 8PM.

Heat gains and losses in the ducts have been eliminated. This is a rather unrealistic for a real system, but serves as a simplification of the model. Experimenting with reset schedules for the duct set temperatures when the system changes between heating and cooling modes may reveal some potential savings. Changing duct set temperatures to an optimum requires very little capital expenditure and payback can therefore be immediate. Changes are also easy to undo if there should be any unexpected side effects. [5]

In Figure 30 the desired room temperatures are presented. The fan is only available between 7 AM and 8 PM. However it has a start up period from 5 AM to 7 AM. This means that the system is only able to deliver cooling during the hours where the fans are on regardless of room temperatures. This may cause room to reach temperatures above thirty degrees Celsius outside the hours between 7 AM and 8 PM even though the system has sufficient cooling capacity. For the Case 1 and Case 2 models it was found that the current cooling capacity is not sufficient to maintain desired room temperatures during cooling season. A variation of the Case 2 model was simulated were temperatures were allowed to rise to forty tree degrees Celsius outside the fan operating hours. It was then possible to determine that Zone 6 was the hottest zone with the highest solar gains. During July this zone was under cooled for all hours between 7 AM and 8PM with a minimum temperature of twenty seven degrees Celsius. Zone 6 is the office zone that faces north-east. This seemed very high.

A separate simulation where DOE2 sizes the ventilation rates and cooling capacities will be presented in Chapter 3.3.2. It was chosen not to change the ventilation rates from the original plans for Case 1 and Case 2 even though the system was unable to meet cooling demands.

By turning off the fans outside occupied hours it becomes easier to determine how occupancy levels affect the energy demand. The fan start up period from 5 AM and 7 AM was set to make sure that the zones were properly ventilated before anyone arrives at the office. It also gave the system the opportunity to allow cooling two hours before anyone arrives. This was a bit unexpected since the cooling schedule starts at 7 AM. This should mean that the current cooling schedule allows thirty degrees Celsius during the start up period. This could be adjusted to a lower value if the system need more time to cool the building to the desired temperature after the high night set back temperature. Allowing cooling with night-cycle-control would also be an alternative to compensate for the high temperatures. Night-cycle-control simply allows cooling outside normal operating hours. Because of the same reason as stated at the beginning of this paragraph these measures were not simulated.

Heating is provided mainly by baseboards and is always available. No zones were ever below the desired temperatures. High demands for heating could be observed during fan start up period during the cold months of December and January.

The hourly dry bulb temperature from the weather file was extracted and processed in Excel to show how the temperatures vary during the year, reference is made to Figure 31. This was done to confirm that the weather file seemed reasonable. As far as I know, no DOE2 weather file existed for Trondheim prior to this thesis work. Juan Carlos Baltazar at Texas A&M University, College Station created the weather file based on a weather file with a different format. One conversion program was found during the research period, but this program failed to give reasonable values and was therefore discarded.

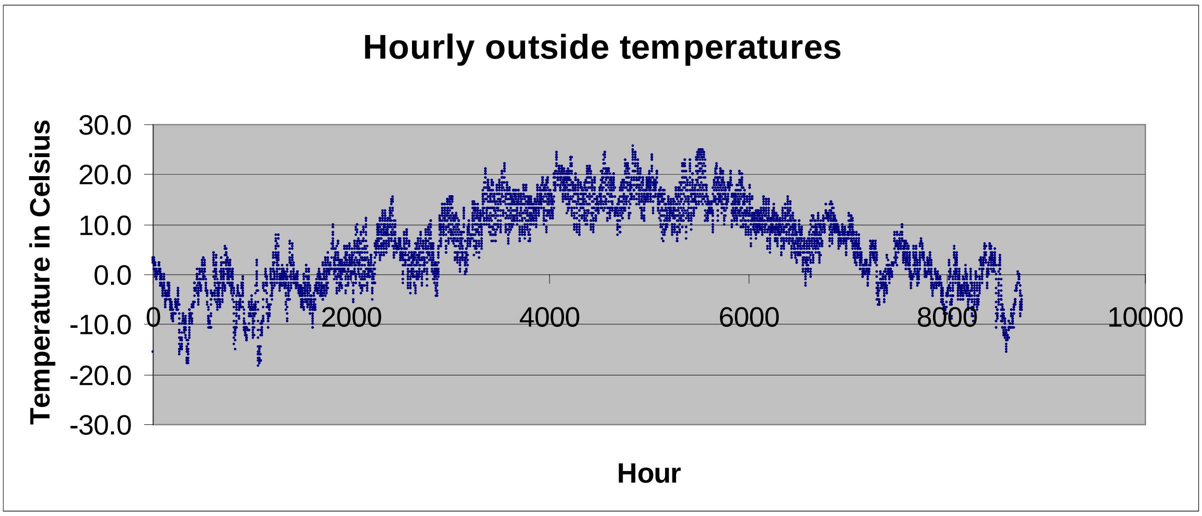


Figure 31. Hourly dry bulb temperatures. From January 1st 2001 through December 31st 2001

A hand calculation of the energy use was performed to verify that the model being used was reasonable. The hand calculation is based on a method from NS3031. NS3031 is a Norwegian standard for calculating the energy and effect needed for heating and ventilation of buildings. It is a fairly simple approach but the results from the calculations give a good indication of the actual demands. The calculations were performed for the month of January and suggested an energy demand of 2817.9 kWh for heating and ventilation. [Appendix D] [15]

Case 2 simulated for the month of January showed a hot water demand of 2758.8 kWh. Total electric power used in the same month was 1153.3kWh. The SS-M report from the DOE output file shows that 52.2 kWh of the electric demand is used by the fan. [20] The energy to operate the fans are only partially considers in the hand calculations. The practice of considering fan energy separately has become more of a focus in recent times and the unpublished and updated version of NS3031 will have a separate calculation of fan energy. [28]

Case 1 has a much higher energy demand. January hot water demand is 4722.7 kWh and an electric use of 1791.0 kWh where 689.9 kWh constitute fan power. [19] The much energy demand in Case 1 compared to Case 2 may be explained by the large amounts of cold air that the system has to heat. Still the difference is very large. The hand calculations do not consider what kind of system the building has and that makes it harder to truly verify the model.

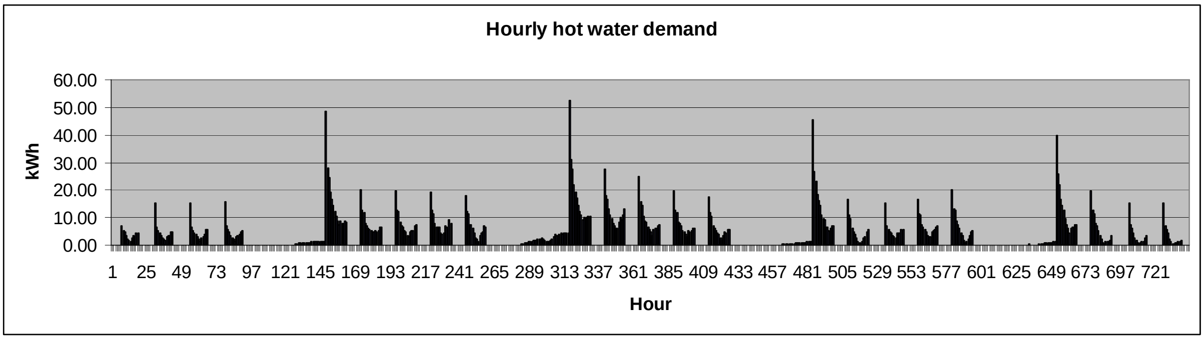


Figure 32. Case 2; hourly hot water demand in January. The graph shows how very high demands for heating occur early in the morning. Total hot water supply for January is 2758.8 kWh.

The high demand for heating in the morning is a result of the heating schedule changing from 12 degrees Celsius to 20 degrees Celsius. Because the simulated baseboard effect is set very high the building is able to heat up very quickly. Realistically less baseboard effect is installed. This might require the system to start heating the building earlier to achieve the desired temperature before workers arrive. Each zone in Case 1 and Case 2 are fitted with 23.4 kW of baseboard heating.

The main findings in this section are that the energy demand simulated with the Case1 DOE2 model corresponds very well with the hand calculations. The hand calculations are not able to distinguish between system types like VAV or CAV. This makes it difficult to truly verify the model versus the hand calculations. The VAV system in Case 1 uses approximately half the energy of the Case 1 CAV system.

3.2 The simulated results

The simulated results presented here are hourly hot and cold water demand vs. hourly outside temperature. This way of presenting the energy use has been chosen because it presents the energy demands very clearly. For Case 2 a scatter plot of the hot and cold water demand versus outside temperature was developed. The scatter plot shows how the building performs at different temperatures and can also indicate changes that should be made. The DOE2 systems report SS-J will also be presented to show the system peak heating and cooling days. Simulated results for Case 1 and Case 2 are presented separately in the subsequent sections. A summary where the two Cases are compared is presented in Section

The energy demand that is considered is the hot-water, cold-water and electric power. These demands do not consider how the hot and cold water is made, like furnaces and chillers. The demands considered are only those delivered to the system. DOE2 is able to add chillers, furnaces or other types of equipment to a simulation. This is not considered in this thesis.

The energy demands are presented as 3-D graphs. The program used to create the 3-D graphs is called LOOK3D. It was found that this version of the program was unable to show all days of the simulated year in one graph. They are therefore split into two separate graphs. One for the first six months of the year (day 1-181) and one for the six last months (day 182-365). The 3-D graphs give a good graphic visualization of how the demands are distributed over the course of a day and year. It also makes it easier to evaluate changes that should be done to the system or discover abnormalities.

DOE2 has an option to view hourly energy demand for each zone separately, however, this is not done in this thesis.

3.2.1 Case 1 – CAV system

The energy demand considered in the CAV system is the total for all the 6 zones in the office. In this section the whole building demand for hot water will be presented. After that follows the demand for cold water and lastly electricity. The days of peak cooling and heating loads are presented. Comments about the validity of the simulated results are given. Hot and cold water 3D graphs have been enlarged and added to the appendix. [Appendix E][Appendix F]

Hot water;

Generally, the graphs below show how the demands for heating tend to be highest in the morning from 5 AM to 7 AM. This can partially be explained by the night set back temperatures and the system trying to heat the zones from a low set back temperature of 12 degrees Celsius to 20 degrees Celsius. Another explanation for the peak at 5 AM is that the system starts to take in air at this time. Large amounts of cold outside air need to be heated combined with low internal loads. Low internal loads simply mean that no equipment, lighting or people are present contribute to heating during these early hours. Even during hours with set back temperatures there is some demand for heating during the cold months. This is however very low compared to the demand during normal operating hours which are between 7 AM and 8 PM. Figure 33 shows the dramatic drop in hot water demand when set back temperatures are used.

The total amount of hot water demand for one year is 22082.5 kWh. From Figure 33 one can observe that the hot water demands are very low during summer months. The daily average demands for hot water drops from 30 kW to 13.2 kW from April to May. The daily average demand for hot water then rises again from 9.2 kW to 41.3 kW from September to October.

The sensible heating capacity of the HVAC system in Case 1 is 9.7 kW. The heating capacity of the system is probably determined based on the OA intake, minimum outside temperatures and the size of the preheat coil. As mentioned the supply air temperature is never higher than 20°C which is the same as the desired room temperatures for the heating season.

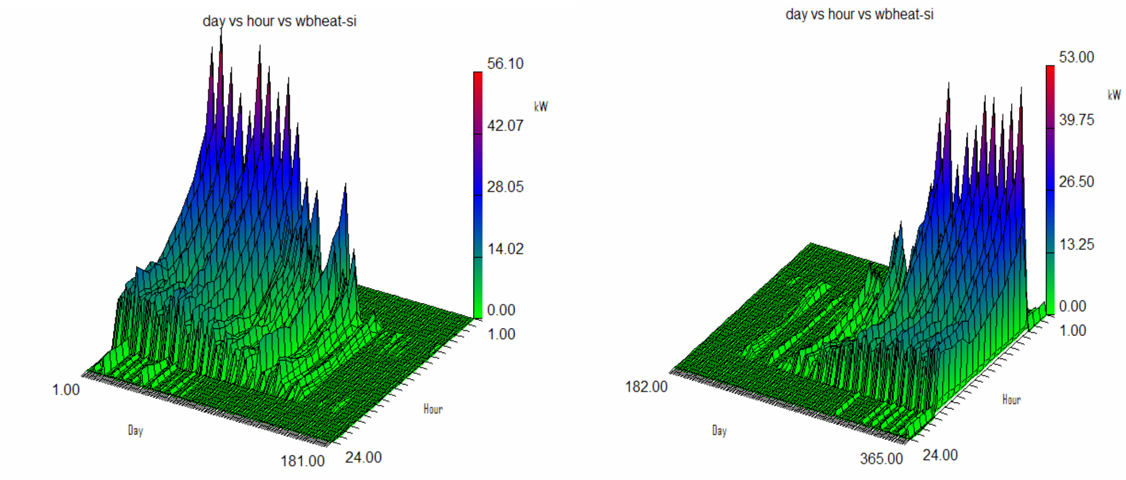


Figure 33. Case 1. Hot water demand for an entire year. Day vs. Hour vs. whole building heating in SI-units. [Appendix E]

By looking at the graph in Figure 33, one might argue that it would be reasonable to have a heat-up period in the morning during the cold months. This would smooth out the spikes that can be observed at 5 AM. For a real system this would dramatically decrease the installed capacity for heating. Decreasing installed capacity is desirable because it decreases the size of pipes and equipment for delivering and producing the hot water. Equipment also works at a lower degree of efficiency at part load. It is therefore desirable to avoid spikes like those on Figure 33.

The maximum demand for hot water is 56.1 kW. This occurs at 5 AM on January 14th. Average outside dry bulb temperature on January 14th is -10.1°C with a standard deviation of ± 0.9°C. This was calculated with the STDEV() function in Excel.

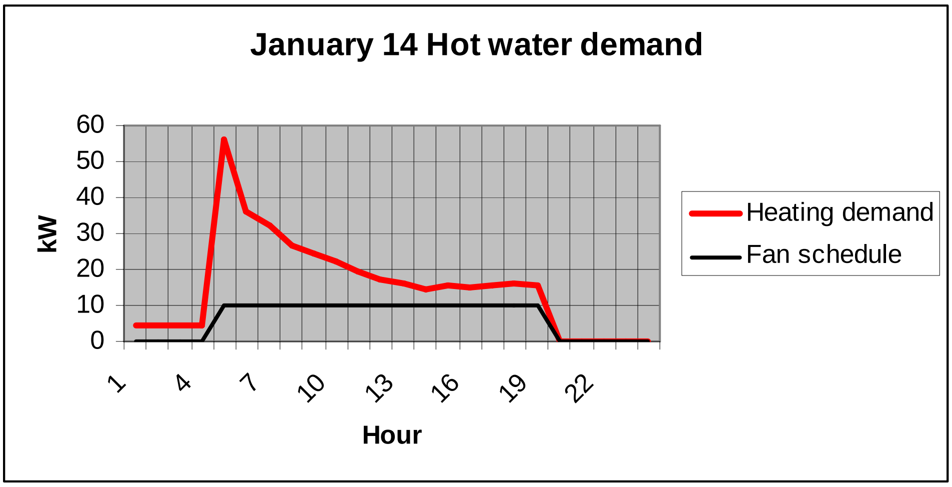


Figure 34. Hot water demand on January 14th, peak heating day. Fan schedule is on from 5 AM.

Cold water;

The total demand for cold water is 4306.0 kWh for the entire year, (i.e approximately 1/5 of the hot water demand). Note that the loads were not met so it is realistic that more cooling is needed in this building.

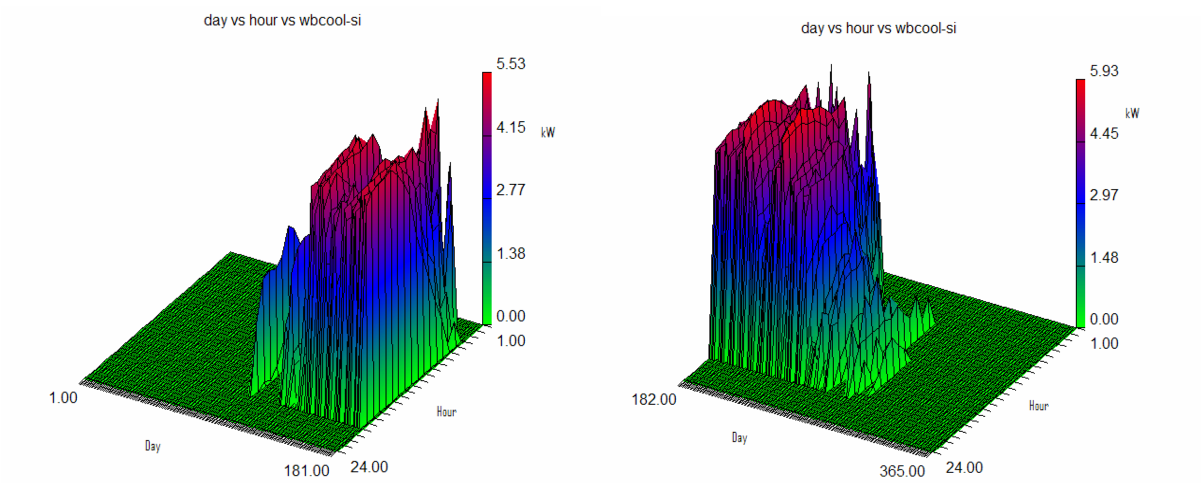


Figure 35. Case 1. Cold water demand for an entire year. Case 1. Day vs. Hour vs. whole building cooling in SI-units. [Appendix F]

Zone 6 (offices facing north-east) was found to have the most hours of being "under cooled" during the month of July. This is the same as days 182 to 212. This section has been cut out and enlarged for a closer look, see Figure 36. From Figure 36 we can observe that the demand for cold water in periods is close to the maximum, with some variation. This indicates that maximum cooling demands for each zone are not coinciding. Some zones are therefore within desired temperatures even though zone 6 might be too hot. An attempt to extract the hourly temperature data in DOE2 for zone 6 was made, to see the variation during July. It is possible to access this data, however, the attempt failed. Instead the SS-O report from the DOE2 output was used. This is presented in Figure 38

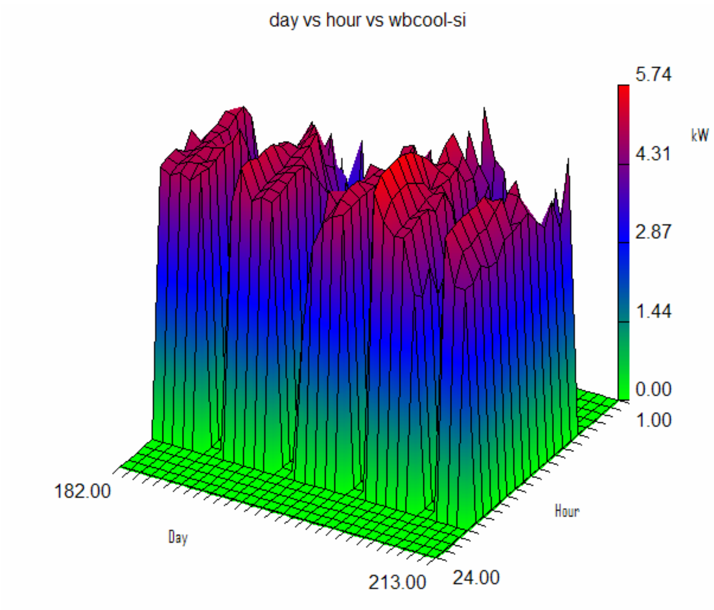


Figure 36. Case 1. Cold water demand for entire building in July.

The day with peak demand for cooling was August 19th. The maximum cooling air capacity is 6.2 kW. Still the highest hourly cooling load was 5.9 kW. This may also suggests that some zones are within desired temperatures while others are not. The average outside dry bulb temperature on August 19th was 20.6°C with a standard deviation of ± 3.5°C

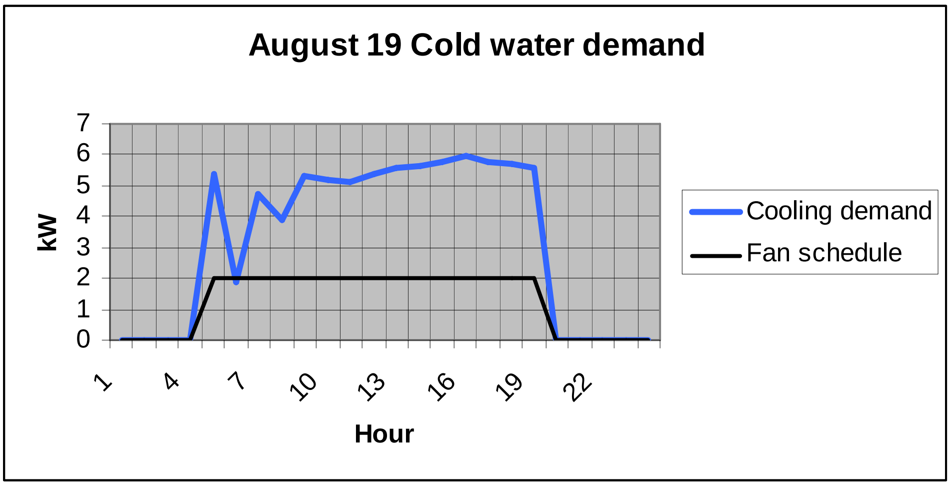


Figure 37. Case 1. Cold water demand on August 19th, peak cooling day. Fan schedule is on from 5 AM.

The SS-J report from the DOE2 output file for the simulation gives the days of peak heating and cooling for the system that was presented in Figure 37. It can be noted that hours where the loads are not met should be marked with an asterisk (*). [19] According to this report the day of peak cooling had no hours where loads were not met, i.e., no hours were marked with an asterisks. In Figure 38 we can see that about 50 cases of temperatures above 29.4 °C are simulated for zone 6. Therefore it seems unreasonable that the day of peak cooling have no hours where system loads are not met. No reasonable explanation for this event can be found since all hours during peak cooling for Case 2 are marked with asterisk.

From the SS-O report in the DOE2 output file for the simulation we find the total hours at a temperature level plotted versus time of day. [19] This is on a zone by zone basis. The plot for

SS-O report for Zone 6 is shown below. Only hours between 7 AM and 8 PM are shown. All other hours had zero occurrences. From the manual it states that this scatter plot only account for the hours where the fans are completely on. The start up period is therefore not included. Each pole in Figure 38 represents the number of hours for an entire year where zone 6 is within the specific temperature level. The x-axis states the operational hours, time of day. Colors pink and dark blue are not found because no hours within operational hours had this temperature level.

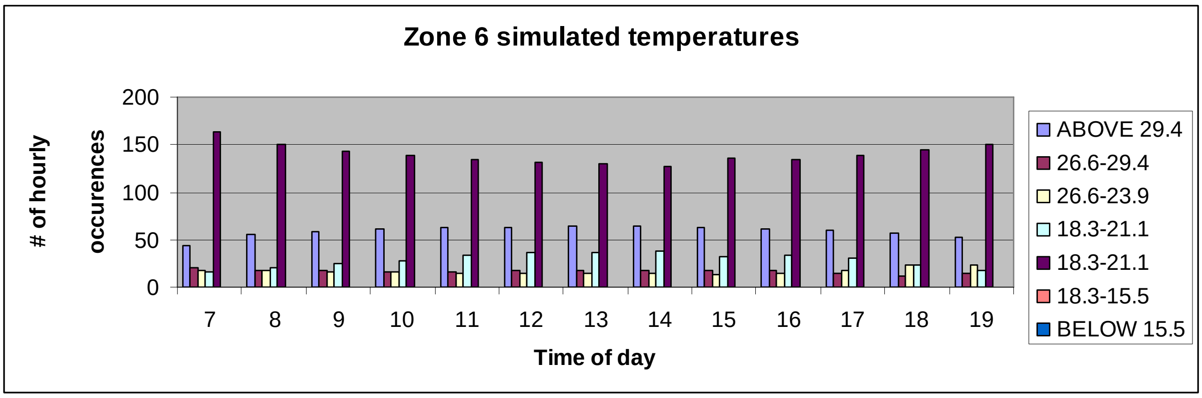


Figure 38. Case1. Zone 6 SS-O report. Total hours at a temperature level accumulated over a one year simulation. All temperatures are in Celsius.

A quote from [22] (i.e. the DOE manual about the SS-F report) says: “If the capacity of the HVAC system is less than the hourly heat extraction or heat addition load for this zone, a load-not-met is recorded as either an under heated or under cooled hour. The number of hours reported as under heated or under cooled may be startups after a night shutdown of the HVAC system.” The SS-F report gives the monthly maximum and minimum temperatures for each zone. A summary of the SS-F report for all zones in the month of July is given in Table 9. There are many hours where the zones are too hot. Especially for zones 4, 5 and 6. The office zones are particularly hot with minimum temperature over two degrees Celsius higher than the desired temperature.

ZONE	MONTH	HEAT EXTRACTION ENERGY (KWH)	HEAT ADDITION ENERGY (KWH)	HEAT BASEBOARD ENERGY (KWH)	MAXIMUM BASEBOARD LOAD (KW)	MAXIMUM ZONE TEMP (C)	MINIMUM ZONE TEMP (C)	LOADS NOT MET HOURS UNDER HEATED	LOADS NOT MET HOURS UNDER COOLED
SPACE1-1	JULY	544.4	0.0	0.0	0.0	33.1	23.4	0	33
SPACE2-1	JULY	285.5	0.0	0.0	0.0	32.7	23.4	0	30
SPACE3-1	JULY	403.7	0.0	0.0	0.0	31.8	24.2	0	111
SPACE4-1	JULY	128.1	0.0	0.0	0.0	31.9	26.4	0	340
SPACE5-1	JULY	560.0	0.0	0.0	0.0	32.6	26.4	0	356
SPACE6-1	JULY	913.4	0.0	0.0	0.0	39.3	27.7	0	593

Table 9. Case 1. SS-F report for July, Very high temperatures and many hours under cooled. Zone 1 = Space1-1, Zone 2 = Space2-1, etc.

Electric load;

To get a well calibrated model, the electric loads should be compared to readings from the actual building. No baseline of the actual electric load has been used in this simulation, only preferred numbers of the electric load from NS3031. In the CAV system the fans run constantly during hours of operation. Since all other electric loads in the simulation are constant one should expect the electric demand to be the same for all operating days. This is not the case for a real system where electric loads will vary on a daily basis. The simulation yielded the repetitive electricity pattern that was expected. Each "slice" of the graphs in Figure 39 indicate five weekdays while the spaces in between are the two days during weekends. The total electric demand for one year was simulated to be 19364 kWh.

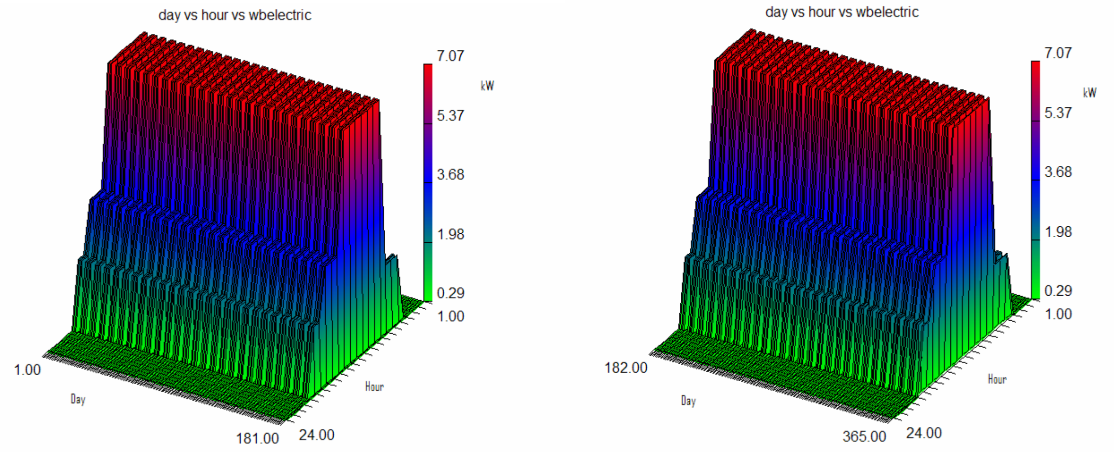


Figure 39. Case 1. Electric demand for an entire year. Day vs. Hour vs. whole building electric in SI-units. Note the repetitive pattern.

3.2.2 Case 2 – VAV system

This section describes how a VAV system will perform in the same building. It is expected that the VAV system will perform with lower hot water demand and lower electric load. The cold water demand was originally not expected to be significantly lower than the CAV system because the ventilation rate of the systems was already proven to be too small to provide sufficient cooling. This theory was disproved by the cooling demand that is presented here and is discussed further in Section 3.2.3.

Hot water;

From March to April the daily average demand for hot water dropped from 1.2 kW to 0.2 kW. From September to October the hot water demand rises again from a daily average of 0.01 kW to 2.3 kW. The total hot water demand for one year was 10728.6 kWh. The sensible heating capacity of the HVAC in Case 2 is 0.97 kW.

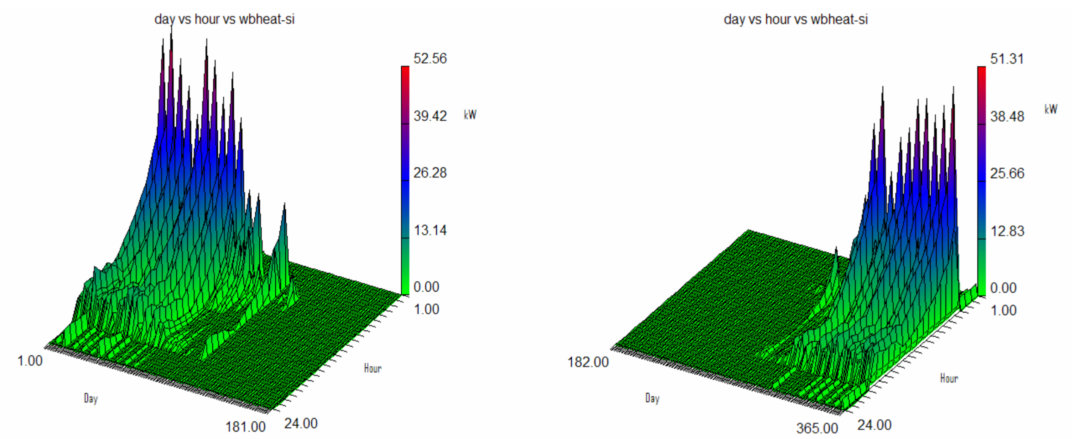


Figure 40. Case 2. Hot water demand for an entire year. Day vs. Hour vs. whole building heating in SI-units.[Appendix G]

The day of peak heating demand is January the 14th. This is the same day as for Case 1. Max demand is 52.1 kW and happens at 5 AM.

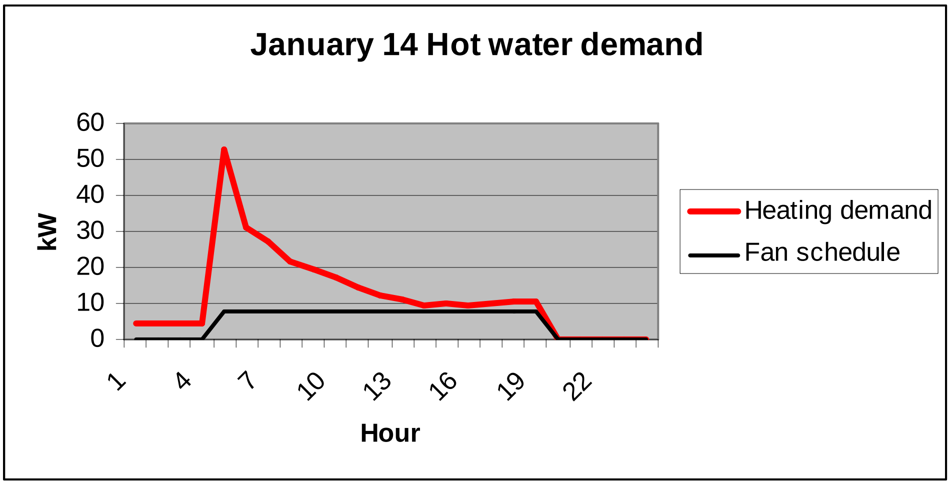


Figure 41. Hot water demand on January 14th, peak heating day. Fan schedule is on from 5 AM.

Cold water;

The total demand for cold water is 2459.5 kWh. The demand for cold water starts some time in April and ends some time in September.

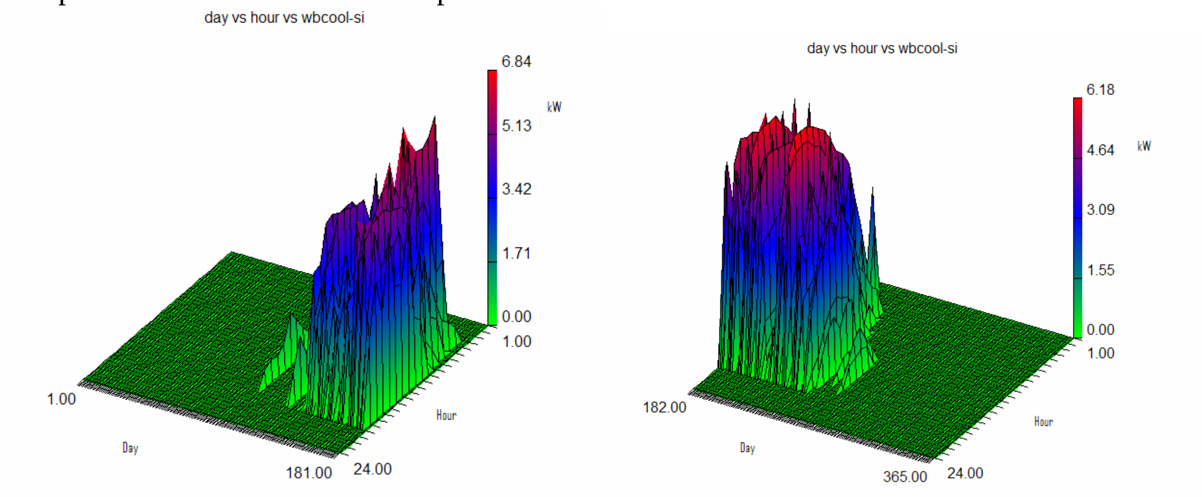


Figure 42. Case 2. Cold water demand for an entire year. Day vs. Hour vs. whole building cooling in SI-units. [Appendix H]

The day with peak demand for cooling was June 20th. The average outside dry bulb temperature on June 20th was 20.1°C with a standard deviation of ± 1.4°C.

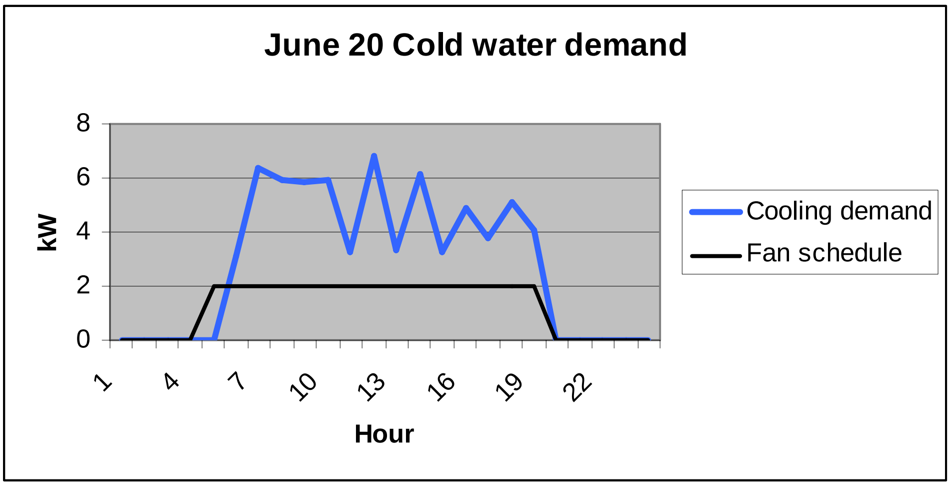


Figure 43. Cold water demand on June 20th, peak cooling day. Fan schedule is on from 5 AM.

The SS-J report from the DOE2 output file for the simulation gives the days of peak heating and cooling for the system. It can be noted that hours where the loads are not met should be marked with an asterisk (*). In Case 2 all hours between 7 AM and 8 PM on June 20th were marked with asterisks. This means that the system was unable to meet the loads for all these hours. This seems reasonable since four out of six zones have minimum temperatures above 24°C the entire month of July as shown in Table 10.

A summary of the SS-F report for all zones in the month of July is given in Table 10. The numbers of hours where the loads are not met are approximately the same.

ZONE	MONTH	HEAT EXTRACTION ENERGY (KWH)	HEAT ADDITION ENERGY (KWH)	HEAT BASEBOARD ENERGY (KWH)	MAXIMUM BASEBOARD LOAD (KW)	MAXIMUM ZONE TEMP (C)	MINIMUM ZONE TEMP (C)	LOADS NOT MET HOURS UNDER HEATED	HOURS UNDER COOLED
SPACE1-1	JULY	544.4	0.0	0.0	0.0	33.1	23.4	0	33
SPACE2-1	JULY	285.5	0.0	0.0	0.0	32.7	23.4	0	30
SPACE3-1	JULY	403.7	0.0	0.0	0.0	31.8	24.2	0	111
SPACE4-1	JULY	128.1	0.0	0.0	0.0	31.9	26.4	0	340
SPACE5-1	JULY	560.0	0.0	0.0	0.0	32.6	26.4	0	356
SPACE6-1	JULY	913.4	0.0	0.0	0.0	39.3	27.7	0	593

Table 10. Case 2. SS-F report for July, Very high temperatures and many hours under cooled. Zone 1 = Space1-1, Zone 2 = Space2-1, etc.

Electric load;

The electric loads in Case 2 vary more than in Case 1. Because we know that all other electric demands except for the fan are constant we can conclude that the variation in electric demand is caused by the fan power. From Figure 44 it is clear how the fan increases the flow rates to meet cooling demands. In the heating season they run on the minimum allowed flow rates which are then governed by the constant occupancy schedule. The total electric demand for the entire year is 14776 kWh.

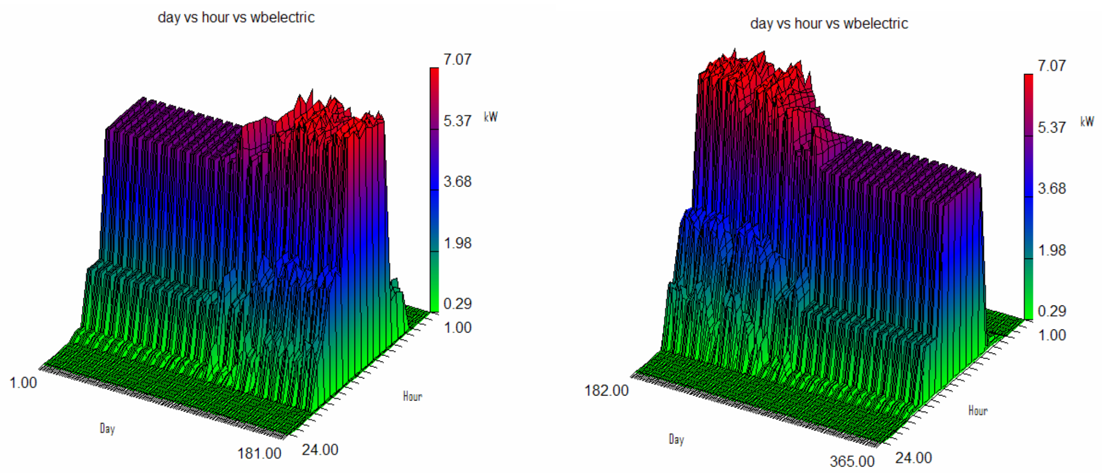


Figure 44. Case 2. Electric demand for an entire year. Day vs. Hour vs. whole building electric in SI-units. Note how the pattern changes for months with cooling demand. [Appendix I]

A monthly presentation of the electric demands shows the months September thru April have the lowest demands for electric power while the months between May and August have the highest demands. This is the same as saying that the fans operate more during the cooling season.

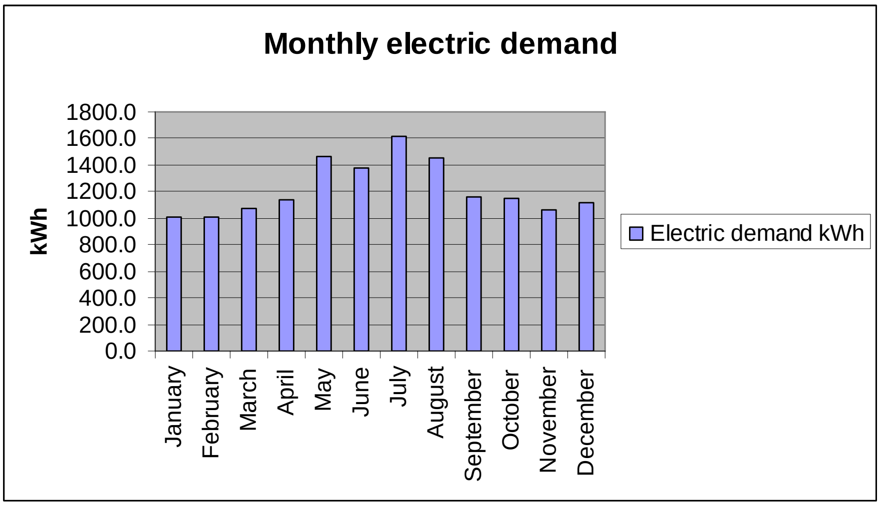


Figure 45. Monthly electric demand. Case 2.

A scatter plot of the systems hot and cold water demand was created to show how the demands for hot and cold water vary according to the outside temperature. We can observe that the hot water scatter plot has less concentrated points than the cold water demand. This is most likely caused by the night set back temperatures. It is a bit unexpected that the hot water demand does not increase more as the temperatures drop. This could be a result of the high efficiency heat exchanger. The cold water demand can be observed to start when outside temperatures reach 12 degrees Celsius. It then increases linearly as the outside temperatures rise.

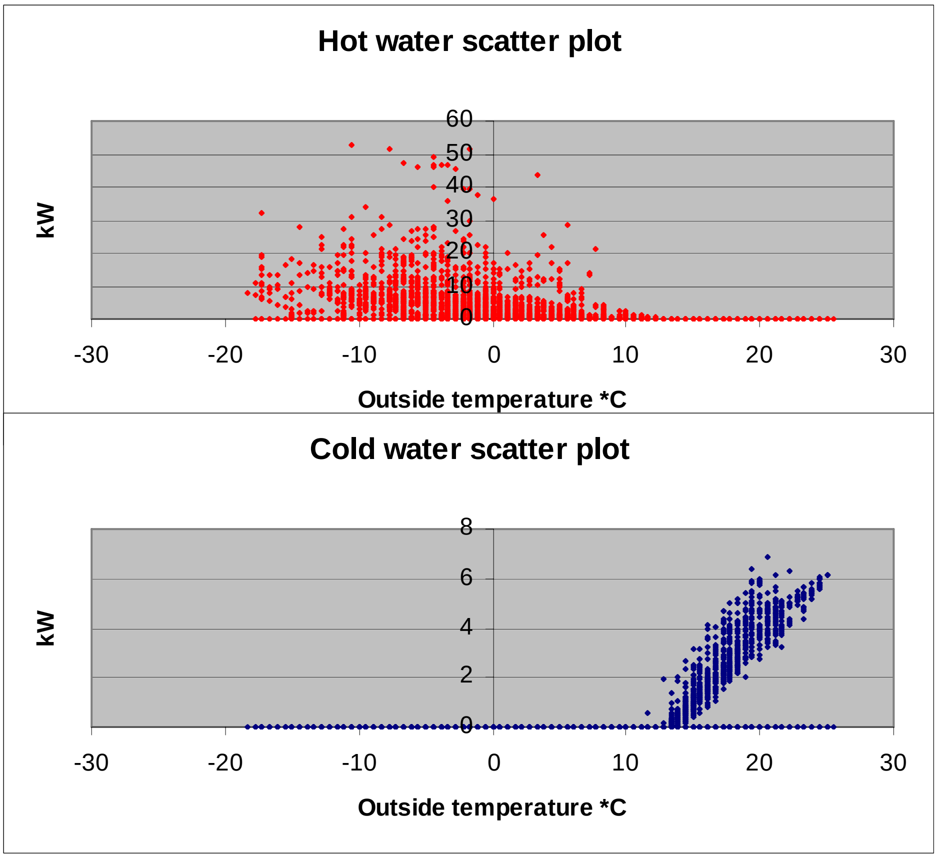


Figure 46. Case 2. Hot and cold water scatter plot.

3.2.3 Case 1 and Case 2 compared

Here we summarize the differences between Case 1 and Case 2.

Demand for cold water decreases by 57.0% from Case 1 to Case 2. This result was not expected since the cooling demand was considered to be to low in both cases. It was believed that the systems in both Cases would use approximately the same amount of cold water. This could be explained by larger quantities OA air being drawn into the system, but no definitive reason for this result could be concluded.

The total hot water demand decreases by 51.4 % from Case 1 to Case 2. Even so, the spikes have very similar max demand. This can also be observed on the day with peak heating as well as the 3D graphs. See Figure 34 and Figure 41.

Total electric demand decreases by 23.4% from Case 1 to Case 2. This includes fan and other electric appliances. The decrease in electric demand for the fan alone is even larger from Case 1 to Case 2. It decreases with 76.2 % from Case 1 to Case 2.

The same kind of spikes in hot water demand found for the CAV system can be found for the VAV system, see Figure 33 and Figure 40. The coldest days tend to have a very high demand for hot water at 5 AM in both Cases. This is a bit unexpected since it is believed that the simulation of Case 2 only starts to take in OA according to the occupancy schedule. The other factor that control OA intake in Case 2 is the temperature which would only allow extra OA when free cooling is available. It was therefore assumed that this should have minimized the heating required to heat OA for Case 2 and reduce the spikes. An expected peak for Case 2 would however be at 7 AM where the heating schedule changes from its night set back temperature to daytime temperatures, thus increasing the baseboard heating. In both Cases there are some days that have their peak at 7 AM while the really cold days have their peak at 5 AM. There was not found any pin point reason why the spikes occur at 5 AM.

SS-F reports in Table 9 and Table 10 for Case 1 and Case 2, respectively, are both very similar. This proves that the system is unable to meet minimum cooling demands in many zones during cooling season.

The cooling air capacity increased from Case 1 to Case 2 by 22.5%. The cooling air capacity in Case 2 was 7.6 kW and 6.2 kW in Case 1. Factors that might have caused this increase are unclear. The highest hourly cooling load in Case 2 is 6.8 kW. This may again suggests that some zones are within desired temperatures while others are not.

Sensible heating capacity of the system decreases from Case 1 to Case 2. In Case 1 it is 9.7 kW and in Case 2 it is 0.97 kW. This strengthens the theory that the size of the HVAC heating capacity is determined based on the OA intake, minimum OA temperature and the size of the preheat coil. Remember that minimum airflow rates drop from 100% to 10% and it is likely that we find minimum OA intake during heating season.

A disturbing error was discovered with the Case 1 and Case 2 input files. The actual ventilation capacity from building HVAC plans shows 3029.1 m^3/h instead of the simulated 2286.6 m^3/h. This error was corrected and a simulation with the correct ventilation capacity was performed. Minimum temperature in zone 6 during July is still 27 degrees and the system is still too small to meet cooling loads. Because of the time it would take to reprocess the data and the fact that this would not change the overall findings from chapter 3.2.1 and chapter 3.2.2 this error was not corrected. The ventilation rate of 2286.6 m^3/h is the one used in chapter 3.2.1 and chapter 3.2.2. Hot water supply in January in the current Case 2 model is 2758.8 kWh and fan energy is 52.2 kWh. With corrected ventilation capacity this changes the hot water supply to 2742.2 kWh and fan energy to 69.1 kWh.

The main findings are that VAV systems are more energy efficient than CAV systems. They save heating energy, cooling energy and fan electric energy. Savings can be as high as 57% for cooling demand, 51.4% for heating demands and 76.2% for fan energy. The system in Case 1 and Case 2 does not met cooling demands.

3.3 DOE2 parameters and alternative systems

The first subsection considers the simulations of maximum and minimum occupancy in Case 2. This will show how much effect the occupancy has on the energy demand. The occupancy schedules used in Case 1 and Case 2 were the average occupancy found in Chapter 1.2, see Figure 9. Now we will investigate how the extreme values of the occupancy level from Figure 9 will affect the energy demand of Case 2.

The second part of this section presents results of a system that is sized by DOE2. This system is able to meet the cooling loads for the building. This system forms the foundation for two new cases called Case 3 and Case 4. Some important factors as minimum outside air and heat recovery efficiency will be looked into.

3.3.1 The occupancy effect on the Case 2 system

Only the Case 2 system is able to adjust to different levels of occupancy. It is expected that cooling and electric loads will increase with an increasing occupancy level, while heating might rise because of the slightly lower internal load. Only hours within fan operating hours are of interest. It was discovered that the occupancy schedule that was used for Case 1 and Case 2 had been offset by one hour. This shouldn’t have affected the results considerably. A new simulation will be done and presented together with the max and min occupancies where this offset has been corrected.

Note that only the effect of outside air controlled by occupancy has been checked. Other factors that can impact the occupancy are individual room temperatures, ventilation rates and internal electric loads from lighting and equipment. These factors have not been simulated.

Figure 47 shows the occupancy schedule found in Chapter 1.2, Figure 9. The lines are much smoother in this version of the same figure as Figure 9 because DOE2 only take 1 hour intervals while Figure 9 has 5 minute intervals. Figure 47 is therefore an average of Figure 9. Figure 47 has the fan normal operational hours added to it. Note that Fan operational hours is not the same as the fan power. 100% fan operational hours on Figure 47 simply means that the fan is “on”, while 0% means that it is “off”.

Table 11 summarizes the three simulations performed for the three different occupancy levels. The corresponding hot water, cold water and total electric demand is shown in the respective rows and columns.

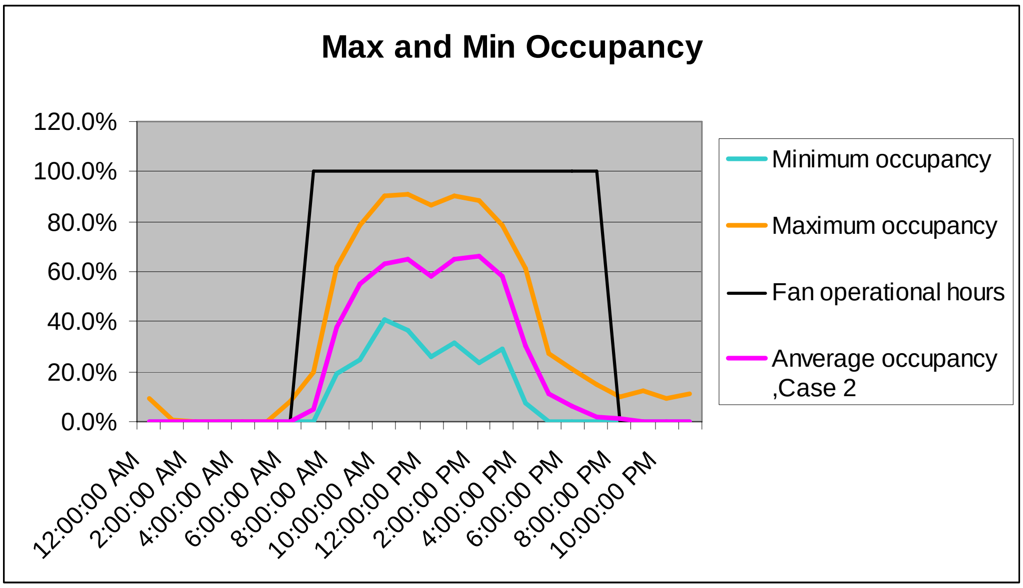


Figure 47. Maximum and minimum occupancy. The values are based on the experiment with infrared motion sensors, average occupancy for all offices. Same values as presented in chapter 1.2.

The simulation showed that controlling the outside air intake for occupancy levels has a minimal effect on the overall energy demand.

	Cold water (kWh)	Hot water (kWh)	Electric power (kWh)
Min	2444.2	11237.9	14735.2
Average	2459.4	10721.2	14775.9
Max	2477.6	10192.1	14815.7

Table 11. Case 2 simulated with min, average and max occupancy.

Very small variations from min to max values are observed from Table 11. The simulations showed that controlling the outside air intake for occupancy levels have a minimal effect on the overall energy demand.

3.3.2 DOE2 sized system, Case 3

A model with ventilation rates for each zone (being sized by DOE2) was used to investigate the relation between OA intake and occupancy levels further. This will ensure that we have a system that is able to cope with the cooling demand. The basis for this system is the Case 2 VAV system. The new system simulation is called Case 3. The specifications of changes made to the system by DOE2 are listed below;

Ventilation capacity 7998.9 m^3/h
Fan effect 5.5 kW
Cooling capacity is 34.1 kW
HVAC heating capacity 2.6 kW

The simulation is run for an entire year and total demands are compared, see Table 12. The table shows an increase of 572 kWh of cold water demand from minimum to maximum level of occupancy. Hot water demand decreases by 2134 kWh from minimum to maximum level of occupancy. Less hot water is needed at high levels of occupancy while the need for more cold water increases with increasing occupancy levels. This can be explained by internal loads getting higher as the occupancy level get higher. Higher levels of occupancy also require larger amounts of OA to be heated or cooled.

	Cold water (kWh)	Hot water (kWh)	Electric power (kWh)
Min	3935.5	13706.9	15251.4
Average	4171.1	12714.3	15403.7
Max	4507.6	11573.3	15619.3

Table 12. Case 3 min, average and max occupancy.

This new system does not consume a lot more energy than Case 2. The new system manages to hold the temperatures within desired range. As expected a lot more cooling was needed for this building than the Case 2 ventilation capacity could handle. Case 3 run with average occupancy uses 1711 kWh more cold water, 1993 kWh more hot water and 628 kWh more electric power than Case 2. The increase in hot water demand and fan power can be explained by the “MIN-CFM-RATIO” function which is used in the simulation model. This function states how many percent open the terminal VAV boxes are allowed to be at minimum supply air requirements. For both simulations this value was set to 10%. This means that the Case 2 system would move 228.6 m^3/h at minimum airflow requirement while the Case 3 system would move 799.9 m^3/h at minimum airflow requirement. This can explain the increased energy demands. Allowing lower fraction for the minimum supply air is however very unrealistic. Fans and system equipment are not able to operate below a certain capacity and usually do so with low efficiency. A over sized system would therefore operate with low efficiency for a large portion of the year. Larger systems are also more expensive to purchase.

The ventilation rate in Case 3 is determined by the zone loads. It is therefore possible to decrease the ventilation capacity and demand for cold water by decreasing the loads on the building. This can be achieved with better glazed windows, shading devices, walls and roof with bright/reflective colors and better insulation properties.

Case 3 still allows return air and the minimum outside-air fraction is 0%. We will now investigate how increasing the minimum outside-air fraction affects the energy use. Four simulations are considered, i.e. 0%, 25%, 50% and 100%. The heat recovery unit efficiency is 70%. Note that 0% minimum outside air does not mean that the system takes in 0% outside air. It simply states that the system is allowed to run with 0% outside air if temperatures and the outside air per person criteria are fulfilled.

Minimum OA frac.	Cold water (kWh)	Hot water (kWh)	Electric power (kWh)
0%	4171.1	12714.3	15403.7
25%	4170.9	12714.6	15402.8
50%	4170.7	12714.7	15402.3
100%	4170.2	12714.9	15400.3

Table 13. Changes to minimum allowed outside air intake.

Close to no change in energy demands is observed from Table 13.

We will now consider the affects of changing the heat recovery unit efficiency at 0% minimum outside air and 100% minimum outside air. The heat recovery unit efficiency will vary from 0%, 50% and 70%. It becomes apparent from these simulations that a high efficiency heat recovery unit is important for this building in order to conserve energy needed for heating. Allowing return air is however not important according to these runs. 100% outside air is the same as not allowing return air.

Min-OA	Heat rec. eff.	Cold water (kWh)	Hot water (kWh)	Electric power (kWh)
0%	0%	4168.2	21501.0	15394.1
0%	50%	4171.1	14660.8	15403.7
0%	70%	4171.1	12714.3	15403.7
100%	0%	4167.0	21744.2	15388.3
100%	50%	4170.2	14662.2	15400.3
100%	70%	4170.2	12714.9	15400.3

Table 14. Case 3. Changing minimum allowed outside air intake and heat recovery efficiency.

Lastly we will make the Case 3 VAV system a CAV system by setting the "MIN-CFM-RATIO" for the terminal boxes to 1. This simulation will be called Case 4. The heat recovery efficiency is kept at 70%, see Table 15.

Min-OA	Heat rec. eff.	Cold water	Hot water	Electric power
0%	70%	9186.0	48199.9	32015.8
100%	70%	9195.4	48193.5	32015.8

Table 15. Case 4. Case 3 simulated as a CAV system with 0% and 100% minimum outside air fraction.

For Case 4 we find the highest demands for energy. Allowing 0% outside air doesn't change the energy demands much. This supports the findings in Table 14 that allowing return air in DOE2 simulations in addition to a heat recovery unit of high efficiency does not reduce the energy demands. This theory might only be applicable to the DOE2 VAVS which was simulated. No significant increase in hot water demand between row 1 0%,0% and row 4 100%, 0% in Table 14.

The main finding in this chapter is that the difference between maximum and minimum occupancy levels does not change the energy demands significantly. Further, allowing return air for VAVS systems in DOE2 simulations seem to have no or little effect on the energy use.

3.4 Summary of the simulations

What conclusions can be drawn?
What are the causes of the differences?
How can we improve the model?
Why should we control the system according to the occupancy level?

These questions are answered in the subsequent subchapters.

3.4.1 Chapter conclusions

The conclusions in this chapter are as follows;

- A VAV system shows a much better performance over a CAV system. This applies to both Case 2 over Case 1 and Case 3 over Case 4.
- For this particular climate it can be concluded that the discrepancy in performance between a VAV system and a CAV system is most prominent when systems are in heating mode.
- Changing occupancy schedules from a predicted maximum occupancy to a predicted minimum occupancy showed small changes in the energy demands to the building.
- The VAVS model in DOE2 can run with 100% OA (i.e. not allow return air) without significantly increasing energy demands.
- The main parameter that determines how much more efficient a VAV system is over a CAV is the VAVs ability to run at reduced airflow. Less airflow --> less energy consumption. See 3.4.4 for more details.
- Controlling the system according to occupancy levels has very limited effect on the overall energy consumption. Scheduled minimum air flow requirements during heating season might be just as good as real time occupancy data. Further work should be carried out to study this theory closer.
- The systems ability to run efficiently at minimum airflow is vital to the energy savings that can be obtained.

3.4.2 Why is VAV and CAV different

Here we will compare the differences of the Case 1 CAV system with the Case 2 VAV system and comment on factors that cause differences in energy consumption.

A VAV system allows the airflow to be reduced when temperatures and OA requirements are met. In CAV system the airflow is always constant when the system is turned on. This is the main difference between a VAV and a CAV.

If we compare the equipment sizes from Case 1 and Case 2 we find that many equipment sizes are not the same even though ventilation capacity is the same. Note that ventilation capacity is fixed for Case 1 and Case 2.

Fans will always run on maximum speed in a CAV. In a VAV the fans will reduce their speed with the help of a variable speed drive. This allows the VAV to consume less electric power than the CAV. It also means that a larger quantity of OA is pulled in by the CAV causing increased hot and cold water demand.

Heating capacity of the air is determined by the minimum OA and OA temperatures for both Case 1 and Case 2. This means that the preheat coil is much larger in Case 1 because minimum OA is larger. This increases the hot water demand in Case 1.

Cooling capacity is 20% larger in Case 2. The increased cooling capacity could not be explained. However, cold water demand is much lower in Case 2. This is probably due to the reduced airflow which causes the fans in Case 2 to produce less heat for the system to remove.

3.4.3 Improving the model

Here we present some possible improvements of DOE2 model.

Some of the simplifications that are made in the models are worth mentioning again. The models that have been simulated in Case 1 thru Case 4 are all very simplified models. Insulation is based on U-values. [14]

A more advanced way of simulating walls in DOE2 is to use layers. This causes a more dynamic heat transfer through the walls and is considered to be a more accurate approach. The negative thing about layers is that it requires more knowledge about the building materials used because the use has to specify what materials and in what order they are placed in the walls/roof. This might have changed energy demands and equipment. This approach should be used when testing the effects of extra insulation.

For infiltration it would have been more accurate to use a measured value instead of preferred values from NS3031. This might have changed energy demands and equipment.

The electric loads have not been compared to any measured data from the building that was simulated. This might have changed energy demands and equipment. The current model was compared to a hand calculation of the energy demands based on a method from NS3031. The hand calculation was performed for the month of January. It indicated a total energy demand of 2817 kWh to cover heating and ventilation. The results from Case 2 are close to this value with a hot water demand of 2759 kWh and 52.2 kWh to power the fan. Case 1 showed a hot water demand of 4557 kWh and 623.2 kWh to power the fan. This shows that the hand calculation of NS3031 is a poor way of calibrating a model. Changing the system from a VAV to a CAV changes the discrepancy between the hand calculations and the simulated results from (|2759 +52.2 – 2817|) 5.8 kWh to (|4557+623.2-2817|) 2363.2 kWh.

Ideally the model should be divided into more zones with one zone per room. Each model could then be given its own schedules. This was not done because a model with one zone per room would become very large and the possibility of programming errors would increase dramatically. It was therefore chosen to keep the model as simple as possible without simplifying it too much.

3.4.4 System control and occupancy

The objective here is to present some important observations that were made in this thesis in regards to controlling the system in accordance to occupancy. We will also present the parameter that decides how well a VAV system performs over a CAV.

The ventilation rate to the zone would be the ideal parameter to control. The control should be a function of temperature and presence or a pre-scheduled value based on simulations. There are two reasons why this has not been done. DOE is not able to control the ventilation rate to the zone based on occupancy level. It can however control the minimum outside air to the zone based on occupancy. When the system is running with 100% outside air and is in heating mode the ventilation rate is most likely to be controlled by the occupancy level. In cooling mode the picture is not so clear. The cooling loads in the zones, the outside air temperature and occupancy levels are all likely to be governing parameters for the ventilation rate when the system is in cooling mode.

An important observation from the simulation is that a VAV system controlled by temperature alone can't ensure that enough air is supplied to the zones. A second parameter for controlling the air flow is needed. This could be a pre scheduled value or occupancy sensors. Occupancy sensors that are best suited for this task are infrared motion sensors or CO_2 sensors depending on room size, number of occupants and utility patent. [27]

A precise estimate of the savings that can be achieved by using occupancy sensors to determine the ventilation rates as opposed to the alternative have not been found. There is simply nothing to compare it to. With occupancy sensors one can precisely predict the demand for minimum ventilation ratio thus providing an ideal indoor environment at the lowest energy cost. Using a predetermined schedule for the minimum ventilation ratio might yield lower energy costs, but can not guarantee that the indoor environment is ideal. Heating season is the time where the system is required will adjust to its minimum ventilation requirements according to occupancy. During cooling season the ventilation rate is more likely to be determined by the loads and not the occupancy. A comparison of the minimum ventilation requirements based on occupancy and the actual ventilation rate should be compared in a future study to confirm or disprove this theory.

One might argue that infrared motion sensors have no way of telling how many people are in one room. This is of course true and the motion should therefore only be used in areas where the occupancy level is fairly constant when people are present. This includes small offices, small conference room and restrooms. In larger areas a CO_2 sensors should be used.

What is a good way to control the minimum airflow when the system is in heating mode? The results for the sensor experiment showed that the MIM sensor was the most reliable while the SWE came in 2nd. If we use sensors to determine the minimum flow rates it is important to consider whether or no the equipment will be able to follow the minimum flow rates. The system in Case 1 has a max ventilation rate of 2286.6 m^3/h, in Case 3 the max ventilation rate is 7998.9 m^3/h. The maintenance personnel guessed that the current system was approximately 4000 m^3/h after some changes had been made to it. One has to consider that equipment will not run efficiently at part load ratios and it might therefore be understandable if an installed system is not able to meet the peak cooling loads. A system that can handle these peak loads would simply be too large for the majority of the year. Since peak cooling load is the determining factor for the max ventilation rate one might consider alternative ways to reduce the peak cooling load or alternative ways to cool the building to limit these peaks.

This would limit the chance of over sized equipment and ultimately give a more energy efficient system.

Case 1 is run with 100% minimum outside air while Case 2 allows 0% minimum outside air. Note that 0% outside air will only happen if enough outside air per person is provided and the return air temperature and outside temperature allow it, i.e. very seldom. Temperatures are then very high or very low compared to the heating and cooling schedule. It is not clear weather or not DOE will prefer outside air instead of return air when the temperatures are the same or if this scenario can happen.

The decisive factor to the energy demand is whether the system is a CAV or a VAV. The VAV systems in Case 2 and Case 3 run have a considerably lower energy demand than their CAV opposites in Case 1 and Case 4. It's important to remember that the VAV systems terminal boxes were allowed to have a minimum airflow rate of 10% and that creating the CAV system meant locking this parameter at 100%. A parametric run of this parameter reveals how the energy demand increase as the minimum allowed airflow rates increase. Case 3 is used as basis, where the system is sized by DOE. Minimum outside air is set to 100% and recovery efficiency is 70%.

As the minimum allowed airflow rate increases, the system demands more and more energy. This is best shown with separate graphs for cold water, hot water and electric demand. The cold water demand and electric demand has an exponential relation to the minimum cfm ratio while hot water demand has a linear relation. This strengthens the suspicion that hot water demand is linearly dependent on the ventilation rate.

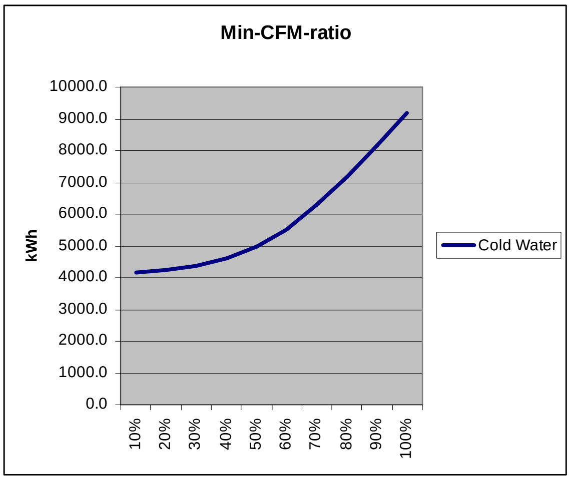


Figure 48. The affect on cold water demand when changing the minimum cfm ratio in the system terminal boxes of Case 3.

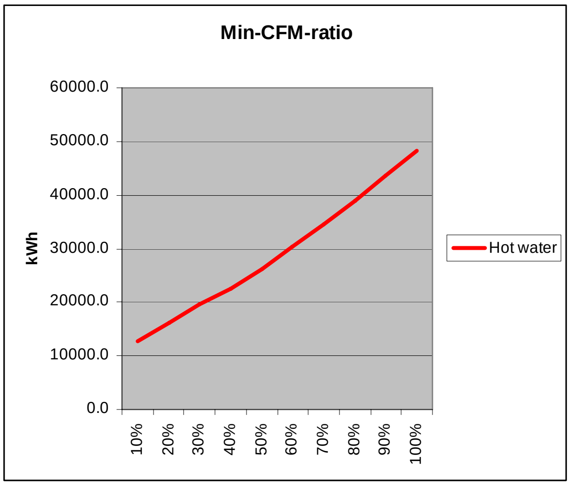


Figure 49. The affect on hot water demand when changing the minimum cfm ratio in the system terminal boxes of Case 3.

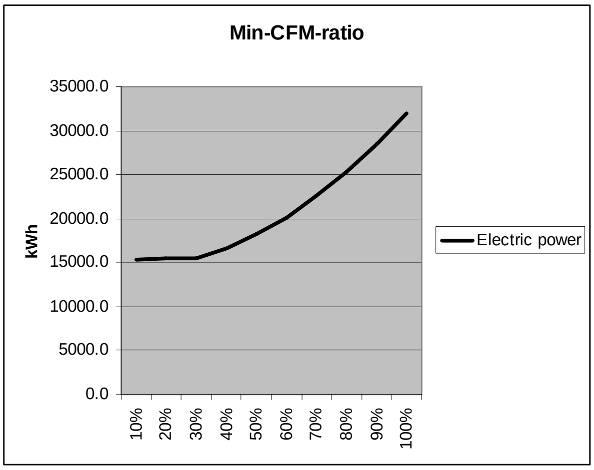


Figure 50 The affect on electric demand when changing the minimum cfm ratio in the system terminal boxes of Case 3.

Min cfm ratio	Cold water	Hot water	Electric power
10%	4170.2	12714.9	15400.3
20%	4255.3	16137.7	15448.9
30%	4378.5	19569.3	15519.8
40%	4600.0	22444.8	16660.8
50%	4970.2	26256.4	18200.2
60%	5519.4	30344.8	20160.9
70%	6268.6	34616.3	22559.7
80%	7170.7	39044.7	25363.8
90%	8164.7	43602.6	28535.0
100%	9195.4	48193.5	32015.8

Table 16. The affect on energy demands when changing the minimum cfm ratio in the system terminal boxes of Case 3. 100% min cfm ratio is the same as Case 4.

Huge savings can be achieved by having a system that is able to have the lowest possible cfm ratio for its terminal boxes. The minimum cfm ratio could be controlled. The minimum cfm ratio is limited by the equipment that is available and its cost. Even though the largest savings can be achieved at a minimum cfm ratio of 10% there are still considerable savings for higher values. Remember that all runs from Table 16 meet peak loads.

Continuation of the thesis work

For the office environment it was likely that a long off-delay resulted in a higher overestimated time and fewer failures to detect presence. The downside of a long off-delay could be fewer savings. This is however not proven since the failure to detect presence may result in more wear and tear on components in the ventilation system. The theory that sensor that frequently turn on an off may cause wear and tear on mechanical components in the ventilation system is not documented in this thesis and can form a basis for a new study.

Further analyzes of the SWE sensor in offices with a different architecture and/or different routines of closing the office doors might reveal that the sensor give considerable amounts of false readings. This can be investigated in a continuation of this thesis.

Certain specifications found in the sensors manuals have not been emphasized. These specifications may affect the accuracy of the sensors. These specifications include detectable speed, price range and what material the sensing material is made of. These specifications may be worth comparing and investigating more thoroughly in a continuation of the thesis.

Manually collected data was only carried out for only two days in this thesis. A future study might consider having more days of manually collected data to give the results better statistical validity. This can be given more emphasis in a continuation of the thesis.

In the simulations it would be desirable to look at an hour by hour discrepancy between the actual ventilation rate and the minimum ventilation requirement. This might confirm or disproof the theory that controlling ventilation rates by occupancy is most important when the system is in heating mode. It would also make it easier to spot when savings can be achieved.

From the simulations of Case 3 there was found little indication that 100% outside air intake would affect the demands for heating or cooling. The demand for cooling decreased by 0.9 kWh, the demand for electric power decreased by 3.4 kWh and a modest increase of 0.6 kWh in heating demand was found when the minimum outside air was changed from 0% to 100%. In Case 4 similar results were observed. Here we find a slight decrease in hot water demand, a slight increase in cold water demand and no changes to electric demand when minimum outside air ratio is changed from 0% to 100%. These results were a bit unexpected. I was expected that allowing return air would reduce the demand for heating in Case 4. Instead the opposite happens. Further investigation of the controls that govern DOE2 systems that incorporate a heat recovery unit and allows return air would be interesting.

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* These files are to large to be added as appendix. They are however available on the CD that is handed in together with the thesis. The name of the files for the respective references are found in the column “Title/ occupation”

List of figures

List of tables

List of pictures