Mathias Metlid

Simulation-based building integration of a multifunctional heat pump system

Case of Otto Nielsens vei 12E

Master's thesis in Energy Use and Energy Planning
Supervisor: Laurent Georges
June 2019

Master's thesis

NTNU
Norwegian University of Science and Technology
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Department of Energy and Process Engineering

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Background and objective

In Norway, heat pump systems become a standard solution in highly energy-efficient office buildings, such as passive house standard or (n)ZEB. Such buildings are equipped with highly-insulated building envelopes, limiting net space-heating needs significantly. In passive office buildings, net mechanical cooling needs are relatively small but not negligible. Even though these thermal needs have been reduced, the heat pump system should still be highly energy efficient to keep to electricity delivered to the building at a very-low level. The design of such heat pump system is central to reach this objective. Nevertheless, high level of insulation makes the evaluation of space-heating and cooling needs more complicated while these are important boundary conditions for the design of the heat pump system. The master thesis aims at investigating the impact of the simulation model quality on the key physical quantities influencing the design of the heat pump system.

Otto Nielsens vei 12E is an office building complying with the Norwegian passive house standard and BREEM Excellent. It is equipped with a 290 kW ground source heat pump for heating and cooling. It also has a need for process cooling. During the project, a detailed IDA-ICE model of the building will be further developed. Detailed measurements of the monitoring system will also be used to tune/calibrate the model. The final aim is to determine the level of accuracy required by the building simulation to come to a reasonable estimate of the key physical quantities for the heat pump design (i.e. energy and power use).

The following tasks are to be considered:

1. Literature review on model calibration and design procedure for heat pumps. Short summary of the master theses done on similar subject.
2. Improvement of IDA-ICE model by including measurement data.
3. Discuss how simulations is able to reproduce reality and support design.
4. Propose ideas for further work in a continuation work.

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Laurent Georges, Associate Professor, NTNU
Supervisor

Co-Supervisor(s):
Thomas Haavi, Associate Professor, NTNU
Maria Justo Alonso, PhD student at NTNU and research scientist at SINTEF Byggforsk

Sammendrag

Masteroppgaven ”Simulation-based building integration of a multifunctional heat pump system: Case of Otto Nielsens vei 12E” har som formål å identifisere hvordan IDA-ICE som et bygningssimuleringsverktøy kan simulere det multifunksjonelle varmepumpesystemet ved Otto Nielsens vei 12E med høyest mulig grad av nøyaktighet ved bruk av målinger i stedet for bruken av standarder.
Ved hjelp av en IDA-ICE-modell fra masteravhandlingen til Florent Dulac våren 2018 [1], er tanken å oppnå simuleringsresultater som har en høyere grad av nøyaktighet med hensyn til energiforbruket i kontorbygget. Modelleringen har blitt gjennomført gjennom bruk av målinger, for å kunne se hvordan bruken av disse som inputparametre kan påvirke simuleringsresultatene.

Formålet med masteroppgaven er å muliggjøre nøyaktige estimat av energibehov ved hjelp av målinger innhentet fra byggets overvåknings- og målesystem. Målinger som skal inkluderes er eksempelvis luftstrømningshastighet, temperatur-settpunkt, interne varmetilskudd, lokal værdata og det termiske energisystemet.
Resultatene blir analysert og sammenlignet med målinger innhentet fra byggets sentraldriftsanlegg (SD) [2], Simien-simuleringer [3], masteroppgaven til Marie Sveen Olsen om topplaster [4] og Linn Charlotte Melvik Alfstad sin masteroppgave om det termiske energisystemet ved Otto Nielsens vei 12E [5].
Hovedintensjonen til masteroppgaven er å analysere og vurdere hvordan det simulerte miljøet kan representere kontorbyggets energiforbruk ved hjelp av målinger i stedet for bruken av standarder.

Innledningsvis belyser prosjektrapporten formål, motiv, rammeverk og viktige emner som omhandler prosessen med å vise arbeidet med masteroppgaven.
Hovedtyngden i oppgaven består av CO_2 - målinger, strømmålere og luftstrømningshastigheten til ventilasjonsaggregatene, for å kunne oppnå mer nøyaktig modellering av tilstedeværelse for personer og varmetilskudd fra utstyr og lys.
Forarbeidet til masteroppgaven, som ble gjennomført høsten 2018 [6], er oppsummert i masteroppgaven for å gi en bedre forståelse av grunnlaget masteravhandlingens arbeid er bygget på. Oppsummeringen består av oppstartsfasen for modelleringen ved bruk av målinger. Prosjektarbeidet fra høsten 2018 presenterer kort resultatene og konklusjonene med formål å avdekke mulige forbedringer, i tillegg til å danne et startpunkt for masteroppgavens gjennomføring.
Metoden for arbeidet er utledet med hovedfokus på modellering av ventilasjonsaggregatene for å redusere ventilasjonsoppvarmingen og øke ventilasjonskjølingen. Videre har modelleringen av interne varmetilskudd fra lys, utstyr og personer blitt implementert ved å utforske strømmålerne i kontorbygget for belysning og stikkontakter. Tilstedeværelsen av personer er modellert ved hjelp av luftstrømningshastighet fra ventilasjonsaggregatene i tilluftskanalene til hver sone, og ved hjelp av CO_2-målinger fra SD-anlegget.
Det er gjennomført sensitivitetsanalyser av simuleringsresultatene ved å sammenligne IDA-ICE-simuleringene med Simien-simuleringene gjennomført av COWI [3]. Resultatet fra IDA-ICE-modellen sees i sammenheng med byggets energimålinger for å kunne si noe om nøyaktigheten på simuleringene som er gjort. Interne varmetilskudd, radiatoroppvarming, topplaster og luftaggregat er noen av hovedbestanddelene som blir analysert i resultatkapitelet.

Simuleringsresultatene fra den detaljerte modellen viste at ventilasjonsoppvarmingen har blitt redusert sammenlignet med tidligere tester fra fordypningsprosjektet [6]. Dette resultatet er tilnærmet lik det samme nivået som målingene fra byggets SD-anlegg [5]. Samtidig viste en sammenligning mellom fordypningsprosjektet [6] og masteroppgaven at ventilasjonsoppvarmingsbehovet har blitt redusert fra et avvik på målingene på 289%, til et avvik på 8%. Det totale varmebehovet hadde et avvik på cirka 50 000

kWh, som kan avhenge av varierende værforhold fra år til år. Ved å øke det interne varmetilskuddet fra mennesker, lys og utstyr, økte kjølebehovet i resultatet fra de detaljerte simuleringene. Dette førte til at prosesskjølebehovet i større grad ble gjenskapt i modellen.

Ved å sammenligne IDA-ICE-modellen med Simien-simuleringene [3], var varmebehovet mer nøyaktig i IDA-ICE-modellen, mens Simien-simuleringene viste et høyere prosjektert kjølebehov.

Det ble samtidig funnet ut at en forenklet modell av bygget vil føre til en høyere grad av unøyaktighet når det kommer til å estimere energiforbruket både med tanke på kjølebehov og oppvarmingsbehov. Avslutningsvis vil det anbefales å bruke målinger i stedet for standarder, når det er ønskelig å få et mest mulig nøyaktig estimat av byggets energiforbruk.

Abstract

The master thesis ”Simulation-based building integration of a multifunctional heat pump system: Case of Otto Nielsens vei 12E” has a goal to identify how IDA-ICE as a BPS tool can simulate the multifunctional heat pump system of Otto Nielsens vei 12E with the best accuracy possible, by applying measurements instead of the use of standards.
With the utilization of an IDA-ICE model from the master report of Florent Dulac in the spring of 2018 [1], it is intended to obtain simulations and results that give a more precise description of the energy usage of the office building. The modeling has been completed through measurements in order to see how using different measurement parameters solely can influence the simulation results.

The objective of the dissertation is to enable accurate energy demand estimations through measurements from the building operation system with air flow rates, temperature set points, internal gains from equipment, lighting and occupants, local weather data, and the thermal supply system at Otto Nielsens vei 12E.
The results are analyzed and compared with the energy data of the building operation system [2], the master thesis of Marie Sveen Olsen [4], measurements from Linn Charlotte Melvik Alfstad [5] and the As-built report from the Simien simulation [3]. The main intention is to evaluate how the simulated environment is able to represent the actual building with the help and benefit of using measurement data instead of standards.

To begin with, the report elucidates the purpose, incentive, framework and essential topics of the hypothesis and work process, with the goal to clarify how the master thesis will be executed.
The main emphasis of the outline of the report is the use of CO_2 measurements, electrical meters and ventilation air flow rates to enable more accurate modeling of occupancy, internal heat gain from equipment and lighting.
The previous work of the specialization project on the autumn of 2018 [6] is summarized in the master thesis report in order to give a better understanding of the platform that the dissertation research is built on.
The summarizing consists of the initial modeling process with the use of measurements. It is further elaborated how the ventilation strategy of the office building functions. The heat pump model and infrastructure is explained in terms of heat pump unit, liquid chiller and ground source boreholes. The previous work shortly present the previous results and conclusions made, and are shown in the master thesis to identify what needs to be improved as well as creating a starting point for the master thesis execution.
The methodology of the dissertation work is elaborated with the focus on modeling the air handling units to enable the ventilative heating to be reduced, and the ventilation cooling to be increased. It is further shown how the modeling of internal gains have been implemented by looking into electrical meters, for equipment and lighting. The modeling of occupancy is established by using ventilation air flow rates and CO_2 measurements from the building operation system at Otto Nielsens vei 12E.
A sensitivity analysis of the simulation results is done through comparing the IDA-ICE simulation with the Simien As-built report [3]. The modeling outcome in regards of simulations, is compared with measurements done in the building operation system to evaluate the accuracy. Both internal gains, local heating and cooling, peak demands and air handling units energy consumption is some of the main parts investigated and analyzed in the results.

The simulation results designated that the ventilation heating has been reduced to be equal with the measurements of the building operation system [2]. Consequently the simulated ventilative heating has been improved in the detailed model from a deviation of 289% in the specialization project to a deviation of 8% [6]. The over-all heating demand were differing from the measurements by approximately 50 000 kWh, which could depend on alternating weather conditions. Moreover, by amplifying the internal gains from

equipment, lighting and occupants, the cooling demand were increased for the model results.
Comparing the IDA-ICE model with the As-built Simien report [3], the heating demand were more accurate in the IDA-ICE representation, while the As-built simulation indicated a higher projected cooling demand.
Comparing the simplified model with the detailed model, showed that the detailed model represented reality in a much more accurate manner than what the simplified model was capable of.
Conclusively, it is recommended to use measurements in favor of standards when it is possible and when the accuracy of the energy performance is the main target. The measurement based modeling is difficult to complete during a design phase of a building, and it is generally complex to predict the energy performance and need of the building based only on standards.

Preface

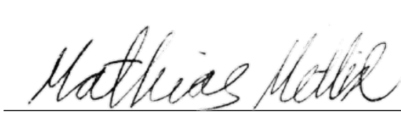
The master thesis report is written as part of the work for the course TEP4920 Energibruk og energiplanlegging - Varmeenergi, masteroppgave. The thesis work has been carried out during the spring of 2019.

First of all I want to thank Associate Professor at NTNU Laurent Georges for his guidance, consultations and helpful advice during the development of my work.

I would like to thank Research Scientist at SINTEF Byggforsk Maria Justo Alonso for her advice and help. I would also thank Associate Professor at NTNU Thomas Haavi for his input on the measurements and works of the multifunctional heat pump system at Otto Nielsens vei 12E.

A thanks to Engineer at Schneider Electric Ole Morten Småøien for helping me with the building operation system at Otto Nielsens vei 12E as well as answering all my technical questions about the office building.

Trondheim, June 5, 2019



Mathias Metlid

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Abbreviations

- **AHU** Air Handling Unit
- **AMI** Advanced Metering Infrastructure
- **BOS** Building Operation System
- **BPS** Building Performance Simulation
- **BREEAM** Building Research Establishment Environment Assessment Method
- **CAV** Constant Air Volume
- **COP** Coefficient Of Performance
- **CO_2** Carbon Dioxide
- **DCV** Demand Controlled Ventilation
- **DHW** Domestic Hot Water
- **dT** delta Temperature
- **ESBO** Early Stage Building Operation
- **g** gram
- **h** hour
- **hh:mm** 24 hour based time system hh are hours and mm are minutes
- **HVAC** Heating Ventilation and Air Conditioning
- **IAQ** Indoor Air Quality
- **IDA-ICE** IDA Indoor Climate and Energy
- **IEA** International Energy Agency
- **ISO** International Organization for Standardization
- **IWEC** International Weather files for Energy Calculations
- **J** Joule
- **K** Kelvin
- **k** kilo
- **LED** Light Emitting Diode
- **m** meter
- **Matlab** MATrix LABoratory
- **max** maximum
- **mm** millimeter
- **m^2** meter squared
- **m^3** cubic meter
- **NaN** Not a Number
- **NS** Norwegian Standard
- **ONV12E** Otto Nielsens Vei 12E
- **Pa** Pascal
- **PI** Proportional Integration
- **ppm** parts per million
- **PV** Photo Voltaic
- **T** Temperature
- **TMY** Typical Meteorological Year
- **SCOP** Specific Coefficient Of Performance
- **SD** Sentral Drift-anlegg
- **U-value** Thermal transmittance
- **VAV** Variable Air Volume
- **vs.** versus
- **W** Watt
- **^{o}C** Degree Celsius
- § Section sign
- Δ Delta
- λ Lambda
- **st** First
- **nd** Second
- **rd** Third
- **th** Fourth and Fifth

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1 Introduction

From the specialization project of the Autumn of 2018 [6], the general target was to create an accurate representation of the office building located at Otto Nielsens vei 12E by using the BPS tool IDA-ICE. The office building is located at Otto Nielsens vei 12E in Moholt, Trondheim. It is considered to be a high-performance building [7]. The main goal of the master thesis, after consulting with supervisor Laurent Georges, is to continue this work through examining measurements, such as the electrical meters, ventilation air flow rate measurements and CO_2 level in order to get an improved representation of the office building.

1.1 Intention and motivation

The main purpose of this master thesis is to investigate how internal gains and behaviour of the building occupancy can interact with the simulation results. From examining the energy monitoring system at the office building, it is of interest to further elaborate what impact measurements of electrical consumption and measured air flow rates could have on the net energy demand of the building. Creating a bigger understanding of how the building facility measurements can influence the modeling and simulation process, the results, and eventually improve how the net energy demand sizing of non-residential buildings such as the office building at Otto Nielsens vei 12E can be done.

Furthermore, the motivation of the master thesis is to run simulations and by this improving already existing mathematical models to represent the office building energy demands as accurately as possible. The internal gains and ventilation strategy will be the main motivational source of the master thesis work. These two topics are central when it comes to sizing the energy demand of especially non-residential buildings. It will therefore be of interest to see whether or not measurements of the actual office building can influence the sizing of internal gains and ventilation strategy of that particular building.

1.2 Framework and essential topics

The master thesis contains six main parts.

- **Previous work on the energy model at Otto Nielsens vei 12E**: This part explain the previous work undergone in the specialization project and creates a platform for the further work on this master thesis. The work and methodology elaborated in this section is applicable in the detailed model further development in chapter 3 "Thermal energy system, internal gains and building infrastructure modeling methodology".
  In particular the chapter consist of the multifunctional heat pump system explained with system sketch and modes of temperature control, local weather data implemented into the model, the ventilation strategy, the rooms that were subject for measurement extraction, the heat pump model and the thermal energy supply system modeling and the results and conclusion of the specialization project work.
  This chapter represents the literature review of the previous theses and project work in regards of the thermal supply system and ventilation.
- **Thermal energy system, internal gains and building infrastructure modeling methodology**: This chapter is considered the methodology chapter, and will elaborate on how the internal gains are modeled through measurements from the building, as well as deducing how the ventilative heating is

improved. Further scheduling the occupancy with the consideration of CO_2 measurements and ventilation air flow rates. The last part of the methodology chapter elucidates minor technical improvements of the detailed model such as the floor heating.

- **Results and analysis from the different modeling strategies**: The results will be presented and analyzed here, both from the different testing procedures as well as the final detailed model results from IDA-ICE. The detailed model will be compared with both a simplified model of Otto Nielsens vei 12E and the Simien As-built report as a sensitivity analysis.
  The energy consumption for each floor level from the detailed model will be compared with the electrical meters at the office building in order to verify the simulation results. The final part of this chapter will focus on the air handling units with their energy consumption, the peak demands and the used energy.
- **Discussion**: Uncertainties and possible deviations will be clarified in this section of the report. Evaluating possibilities for improvement and commenting on processes that could have undergone differently.
- **Conclusion**: A unification of the most essential findings of the thesis work will be concluded in this section based on the results and discussion chapter.
- **Further work**: Based on the discoveries from the master thesis work, a recommendation for future reviews within sizing and modeling of non-residential buildings is suggested in this section.

2 Previous work on the energy model of Otto Nielsens vei 12E

In this chapter, the most important findings and sections of the specialization project are presented. The main target of the chapter is to clarify the development of the heat pump model in IDA-ICE from the work undergone in the specialization project [6]. It is intended to define the platform that the master thesis work will originate from, consequently this chapter is considered to be the literature review aspect of the thesis.

The chapter consists of an introduction to the most central building aspects, with the system design, as well as some central building energy specifications. Further on, the modeling process undergone in the specialization project [6], will be summarized by including the most distinctive results.

The specialization project of the autumn 2018 presented the multifunctional heat pump system at Otto Nielsens vei 12E using the BPS-tool IDA-ICE [6]. Some of the key aspects of the project was to implement measurements combined with the previous model of Florent Dulac's master thesis [1]. Through comparing the energy results of Alfstad [5] with simulated results from the specialization project model [6], it would be possible to evaluate to which extent the BPS-tool IDA-ICE would be capable of representing reality.

The following aspects were the most central topics during the specialization project:

- Implementation of zone measurements and central data from the monitoring system
- The heat pump model
- Improved model evaluation
- Energy consumption for each floor level

2.1 The framework for utilizing the multifunctional heat pump system

The building ONV12E is part of five buildings at Otto Nielsens vei [5]. The other buildings consists of the numbers A-D, and are not included in the specialization project, or the master thesis. The central data regarding ONV12E is presented below .

- The building were completed in June 2017 [5]
- The building floor area is 9 100 m^2, although the heated floor area is 8940 m^2 [5]
- Yearly energy consumption of the building is 67.2 kWh/m^2 [3]
- The project of ONV12E is considered the first BREEAM-Excellent project in the Trondheim area [8].
- The BREEAM classification exists with the purpose of classifying and designing sustainable buildings with the classification levels pass, good, very good, excellent and outstanding [9]

A picture of ONV12E is shown in figure 2.1, where the front side of the building is shown with the Atrium glass wall. It is worth to mention that this picture were taken during the specialization project [6], but not shown in the report.

Figure 2.1: ONV12E with the Atrium glass wall, picture taken by Mathias Metlid in September 2018

The thermal system of the building consists of a multifunctional heat pump, which means that the heat pump can both cool and heat the building both for space heating and cooling, including heating of domestic hot water [7]. Surplus heat from the building is transferred to buildings A-D. As for peak load heating, district heating is meant to cover heat loads during maintenance of the heat pump unit, included when the heat pump is unable to cover peak demand for heating [7].

The heat pump thermal storage consists of 25 bedrock boreholes with a depth of 250 meters. The boreholes operates as both heat source and heat sink, and will enable free cooling during the summer months [7]. The heat pump has a cooling capacity of 298 kW and a heating capacity of 230 kW, with reciprocating Piston compressors [7]. The working fluid of the heat pump is R134a [7]. Including a sub cooling heat exchanger, a super heating heat exchanger, and with big heat exchanger surfaces for the both of them [7]. This enables temperature delivery up to 65-70^{o}C [7]. The system is designed with a single-stage unit, enabling excellent part load characteristics with high quality [10]. The heat pump compressor consists of three Piston compressors including two variable speed drive controllers, and one on/off control, which operates intermittently [10]. The heat pump unit data is important for accurately modeling the heat pump in the plant of the BPS-tool IDA-ICE.

The thermal system at the office building consist of six central parts [7]:

- Cooling distribution system
- Heat pump/liquid chiller
- Bedrock and brine system
- Heat delivery to the connected buildings
- Heating distribution system
- Heating of domestic hot water

In figure 2.2, the heat pump components are shown in a system sketch, which were drawn by Linn Charlotte Melvik Alfstad [7].

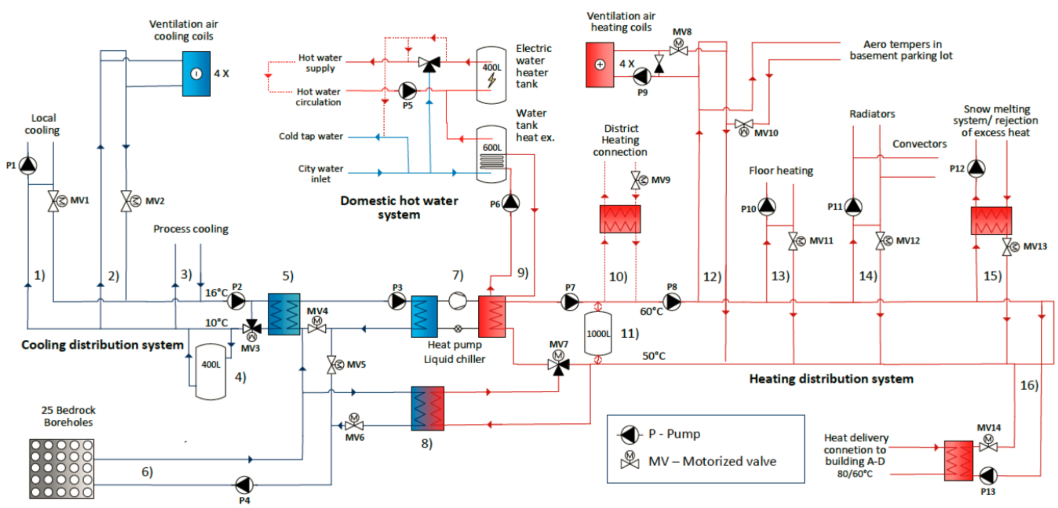


Figure 2.2: System sketch of the multifunctional heat pump system [7]

The monitoring system at ONV12E that was used in the specialization project [6] is also a big part of the master thesis execution. The system is called Building Operation System [2], and enables the user to see temperature set points and measurements, air flow rates, as well as control strategy of the building [6]. In figure 2.3, the control set points for heating and cooling of a selected zone in the building is shown.

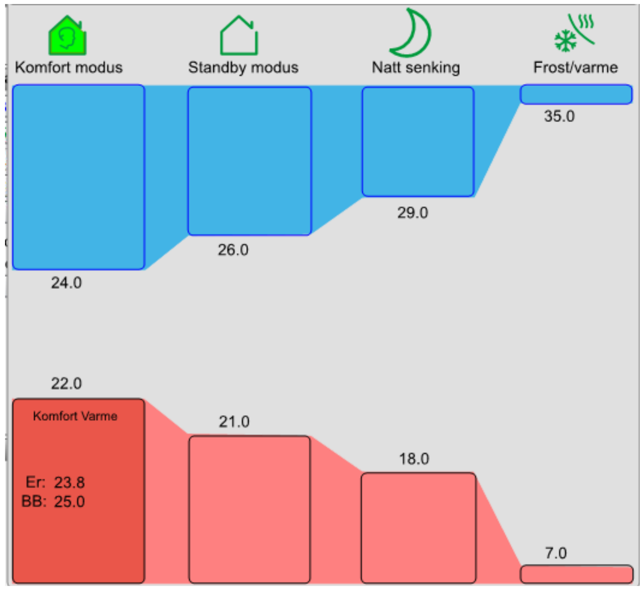
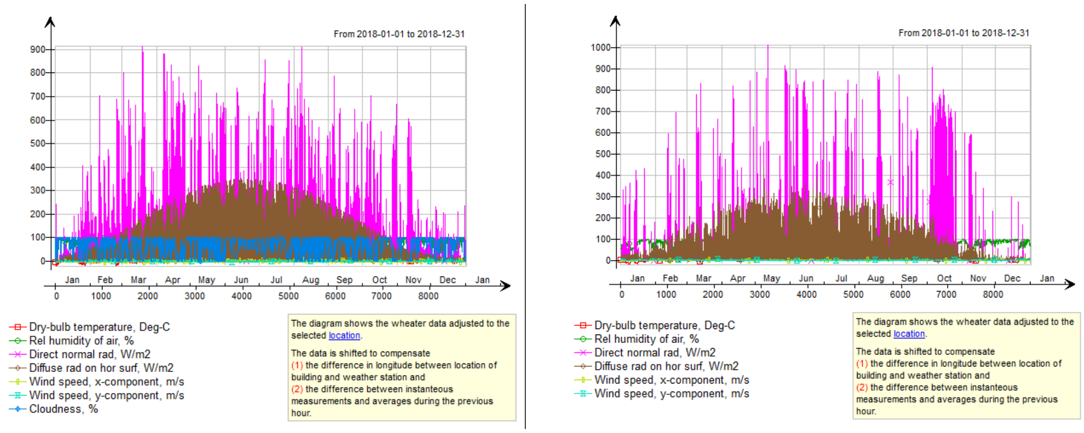


Figure 2.3: The different modes of the temperature control of all the heated zones of the building depending on the usage. Where 24^{o}C is the maximum for cooling, and 22 ^{o}C is the minimum for heating [6]

2.2 Zone measurements and central data from the monitoring system

This part of the previous work chapter explains the measurement data and discoveries that were accomplished during the specialization project.

The weather data were implemented into the IDA-ICE model, as shown in figure 2.4b, where the local weather data was implemented in order to better match with the building location. The figure 2.4a shows the typical meteorological year that was originally used in the model of Florent Dulac [6] & [1].



(a) TMY - from the standard IWEC files in IDA-ICE [11]

(b) Weather data from Shiny weather data [12]

Figure 2.4: Comparison between the different weather data types used in the detailed model

The temperature set point for normal zones are set to 20^{o}C with a 2^{o}C drift range for the daily use of ONV12E [1]. The zones have different operation strategies depending on working hours, non-working hours, and when the building is not being in use. This can be seen in figure 2.3. As seen from figure 2.5, the temperatures in the occupied rooms are more or less constant and possible to control with the heating and cooling strategy of the real system.

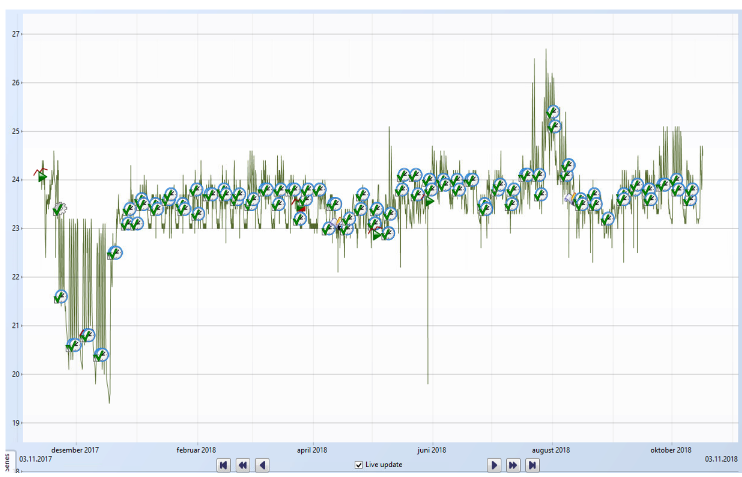


Figure 2.5: Exported measurements of the temperatures for example-office 102 at Otto Nielsens vei 12E

The detailed model in IDA-ICE from the specialization project were containing data extracted from the rooms shown in table 2.1 [6]. Both air flow rates and temperature set points were derived from these rooms, and used in the model as schedules for operation. The rooms were during the specialization project divided into three different room types for simplification purposes [6]. Corridors, elevators and laboratories were for instance not a part of this evaluation. The three room types were offices, meeting rooms and co-working spaces.

Table 2.1: Rooms that temperature measurements and airflow rate set points are extracted from

Description	*Room number*
Meeting room	101
Meeting room	267
Meeting room	364
Meeting room	467
Co-working space	106-107
Co-working space	246-247
Co-working space	372
Co-working space	414-415
Office cell	143
Office cell	262
Office cell	310
Office cell	463

The air handling units are a central part of the specialization project, and are important for the master thesis work as well [6]. In order to get the most accurate results, it is hereby necessary to model the ventilation strategy as precisely as possible. The air handling units were in Florent Dulac's model [1] modeled quite accurately, but from the model it was not possible to implement the by-passing design that the real air handling units contain. The main focus was to enable ventilation strategies for the three room types mentioned in table 2.1.
One of the major problems with the IDA-ICE model has been the ventilative space heating being unrealistically high, and therefore reducing it will be of high priority during the master thesis work. In table 2.2, the ventilation strategies are shown for each of the three room types. The ventilation strategies were found through investigating the BOS [2], as well as consulting with Ole Morten Smaaoien [6].

Table 2.2: Control mechanism for the ventilation system at the different zones

Zone	*IAQ*	*Space cooling*	*Space heating*
Cell office	VAV + Motion	Ventilative cooling	T. sensor - radiator valve
Co-working spaces	VAV + Motion	Ventilative cooling	T sensor - radiator valve
Meeting rooms	VAV + CO_2 + Motion	T sensor - cooling valve + Ventilative cooling	T sensor - radiator valve

In order to control the ventilation of each zone, the ventilation schedule is implemented into the model as seen in figure 2.6. The figure show the specialization project initial schedule, which has been altered in the master thesis, because of an error in the extraction process. The schedule changes are shown in chapter 3. The control strategy is made based on the BOS set point data, and further averaging the values of the measurements for a 24 hour period [2]. In addition to a control for each rooms supply of ventilation air, the operation of the AHU is controlled by an on/off controller in the BOS [2]. As seen from figure 2.7, the air handling units are turned off during weekends and outside of working hours, which is estimated in the BOS to normally be between 06:00 - 19:00 [6].

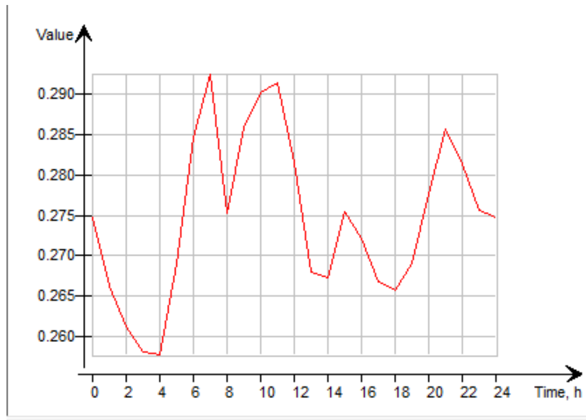


Figure 2.6: Air flow rate set points, scheduled for the meeting room [6]

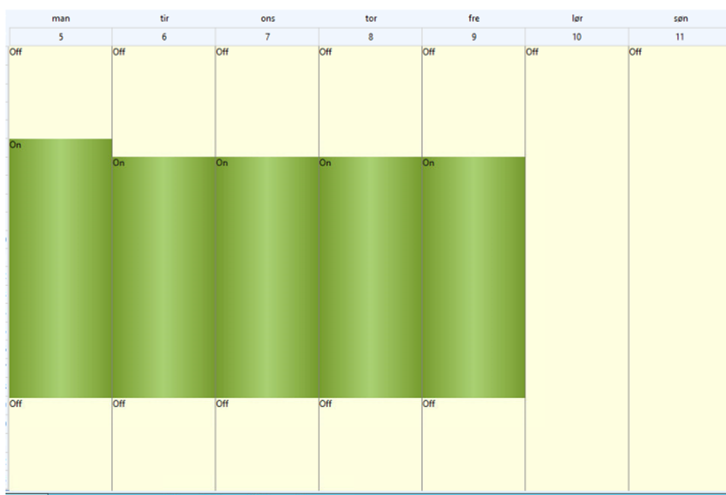


Figure 2.7: Administrative operation control of the office building [6]

2.3 Heat pump model and early thermal supply system modeling

In this part of the specialization project summary, the heat pump modeling process, and the thermal supply system modeling are elaborated. The chapter aim to explain why the different parameter choices were done during the modeling process of both the heat pump, the district heating and the top up boiler heater for domestic hot water.

2.3.1 Heat pump model

The heat pump at Otto Nielsens vei 12E is operating with varying COP depending on the necessary temperature lift [5]. In the model the SCOP is set to 2.6 for heating, and 4.6 for cooling for the heat pump unit based on the measurement results of Alfstad's master thesis [5]. The heat pump at ONV12E is shown in figure 2.8.

Figure 2.8: Picture taken by Mathias Metlid in September 2018 of the heat pump unit

The first outline of the heat pump model in IDA-ICE for ONV12E is shown in figure 2.9. This model will be attempted to get running for the further analysis of the office building. As the model of the heat pump had troubles with working for the mathematical model in IDA-ICE, there will be necessary to find the correct input parameters and connections between components to make the model work in simulations during the master thesis execution [6].

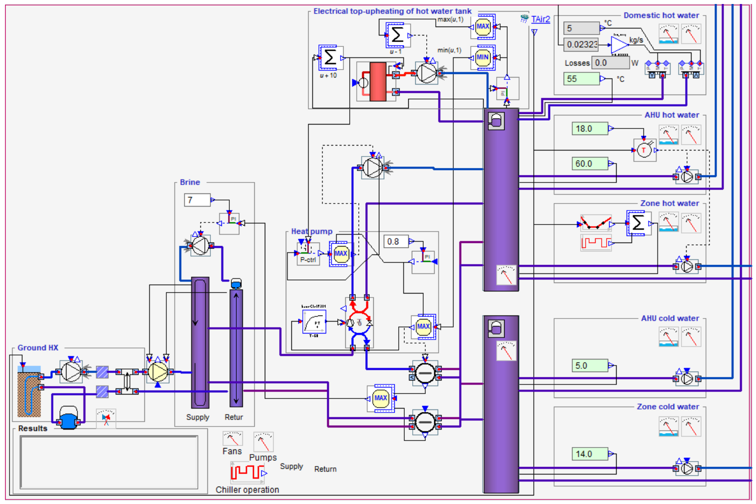


Figure 2.9: Model made in IDA-ICE with ground source heat pump, hot water tank, cold water tank and an electrical boiler for additional heating of hot water [6]

2.3.2 Bedrock boreholes

The heat pump boreholes is 260 meters deep [7]. In IDA-ICE it is possible to define ground properties such as the ground temperature. Based on the thermal response testing of the system and general data about the boreholes, the following parameters were defined in the IDA-ICE model [13]:

- 25 boreholes, 7.5 meters between each well
- Efficient thermal conductivity of bedrock, λ_{eff} = 4.0 w/mK
- Cooling medium in wells: Ethanol-water mixture (25%) and flammable liquid with a maximum temperature of 33^{o}C, freezing point = -12^{o}C
- Borehole diameter = 140 mm
- Thermal resistance of boreholes during heat extraction = 0.12 W/mK

In figure 2.10, the borehole parameters that are inserted into the IDA-ICE model are displayed.

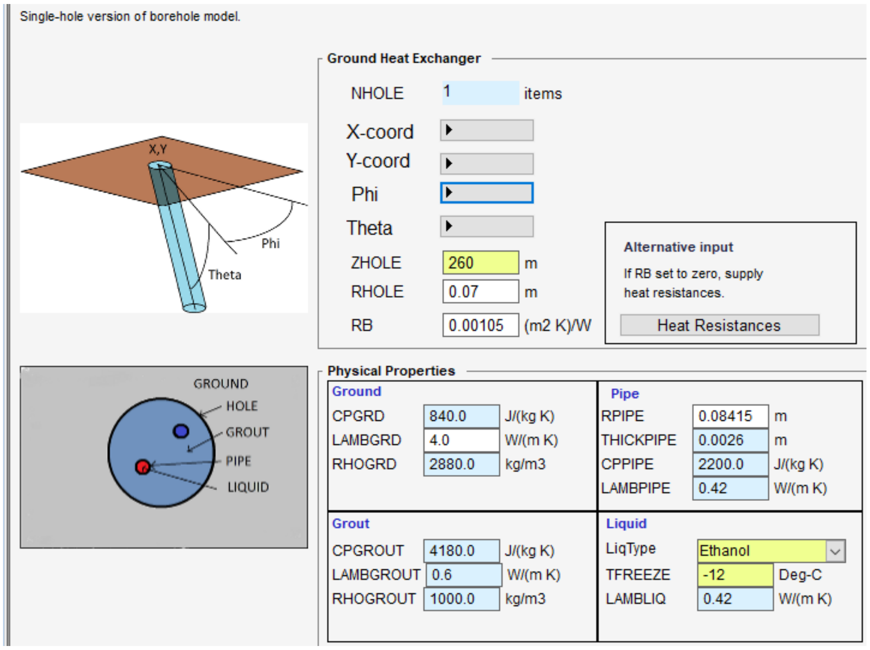


Figure 2.10: The borehole parameters in IDA-ICE, defining angle, heat resistance and depth [6]

2.4 Summary of simulation results and analysis

The following tables 2.3 to 2.6 renders the results from simulating the heat pump system of ONV12E in the specialization project [6].

Table 2.3: Comparison between the measured data from ONV12E and the simulated energy consumption from implementing measured data in the improved model, [5]

Description	*Measurement [kWh/year]*	*Simulation [kWh/year]*
Local cooling	5 946	6 240
Ventilation cooling	21 290	13 110.5
Process cooling	87 371	81.9
Total cooling	**114 607**	**19 432.4**
District heating	**40 680**	**33 522.1**
Ventilation heating	87 500	339 978
Floor heating	15 825	26 588.2
Radiators & convectors	246 710	222 928.7
Snow melting	66 670	-
Total heating	**416 705**	**589 494.9**
Domestic hot water	**65 485**	**63 301**

Table 2.4: Energy consumption from local heating and cooling units per floor level of the simulated improved model at ONV12E [6]

Floor level	*Local heating unit [kWh/year]*	*Local cooling unit [kWh/year]*
Basement	18698.0	0.0
1st floor	59555.3	30.7
2nd floor	42764.8	29.5
3rd floor	41347.8	21.7
4th floor	47863.2	0.0
5th floor	12699.6	0.0

Table 2.5: Used energy per square meter of the simulated improved model at ONV12E [6]

System	*Used energy [kWh/m^2]*	*Peak demand [kW]*
Lighting, facility	15.7	51.12
Electric cooling	0.1	22.81
HVAC aux	30.4	67.85
Electric heating	35.1	103.4
District heating	3.9	541.5
Equipment, tenant	4.2	21.49
Total	**89.4**	-

Table 2.6: Used energy for the air handling units [6]

AHU	*Heating [kWh]*	*Cooling [kWh]*	*Heat recovery [kWh]*	*Cold recovery [kWh]*	*Fans [kWh]*
360.01	112 021.0	3094.0	262 886.0	288.9	56450.0
360.02	64 733.0	2 877.9	263 053.0	251.2	51 094.0
360.03	65 491.0	3 011.3	261 113.0	261.7	45 523.0
360.04	52 036.0	2 993.2	290 708.0	291.7	60 045.0
360.05	45 699.0	1 133.6	167 205.0	375.8	44 515.0
Total	**339 980.0**	**13 110.0**	**1 244 965.0**	**1 469.3**	**257 627.0**

From the results in tables 2.3 to 2.6, the following conditions were different from the expectations [6]:

- Simulated ventilation heating is 289% higher than the measurements
- Measured ventilative cooling is 62% higher than simulated
- Simulated district heating deviates by 21% from the measurements
- Floor heating is 68% higher for the model compared to the measurements
- Total heating demand were 42% higher for the simulations than the measurements
- Peak heating demand were 541.5 kW, and were for the district heating
- Peak cooling demand were 22.81 kW

Conclusively from the specialization project results and research, the following key aspects were identified as the main objectives for improving the model simulations, based on what the specialization project results indicated [6]:

- Schedules for equipment, occupancy and lighting should be improved based on measurement data, for instance electrical meters, where the main motivation for this is connected to increasing the cooling demand and lowering the heating demand. At the same time the internal gains will most likely be more accurately modeled when they are based on measured data instead of standards
- The complex heat pump model had to be simplified in the specialization project [6], but could be modeled more complex in the master thesis model in order to obtain more accurate results in regards of the heat pump and liquid chiller energy performance
- The boreholes are possible to model quite accurately, as the results indicate a sufficiently accurate representation of the boreholes. Therefore, the implementations of boreholes should be utilized in the master thesis work
- Floor heating and radiators were possible to model precisely enough, but the high ventilative heating demand in the results may indicate that the radiator heating capacity should be further evaluated in order to cover more of the space heating demand. The floor heating had higher heating demand in the simulation than what measurements indicated, and the connection between the different space heating and cooling devices should therefore be further investigated in the master thesis work
- High ventilative heating in the improved model needs to be adjusted for in the further work. The results show a 289% higher ventilative heating demand for the detailed model compared with the measurements, which indicates that there is something wrong with the implementations in the specialization project model. Therefore a reduced ventilative heating demand should be attempted to accomplish in the further work. For example, investigate the AHU operation and scheduling including the fans
- Local cooling were modeled through examining the local cooling units in the BOS, and considering the results show a sufficiently low deviation, the local cooling can be considered accurately modeled.

3 Thermal energy system, internal gains and building infrastructure modeling methodology

Chapter 3 has the goal to determine and elaborate the different parameters implemented into the model that has been undergone during the master thesis work. The earlier model parameters has been defined in the specialization project and can be found there [6]. AHU operation and scheduling, electrical measurements for equipment and lighting, advanced heat pump modeling and general ventilation strategy will be the main focus of this chapter.

3.1 AHU and ventilation strategy modeling

The figure 3.1 shows how the different zones in the model is divided according to strategy of ventilation. Each zone have a schedule for operation of both temperature regulation and air flow rate. In an attempt to reduce the high ventilative heating in the building, the ventilation strategy will undergo a simulation where the ventilation will be regulated based [2].

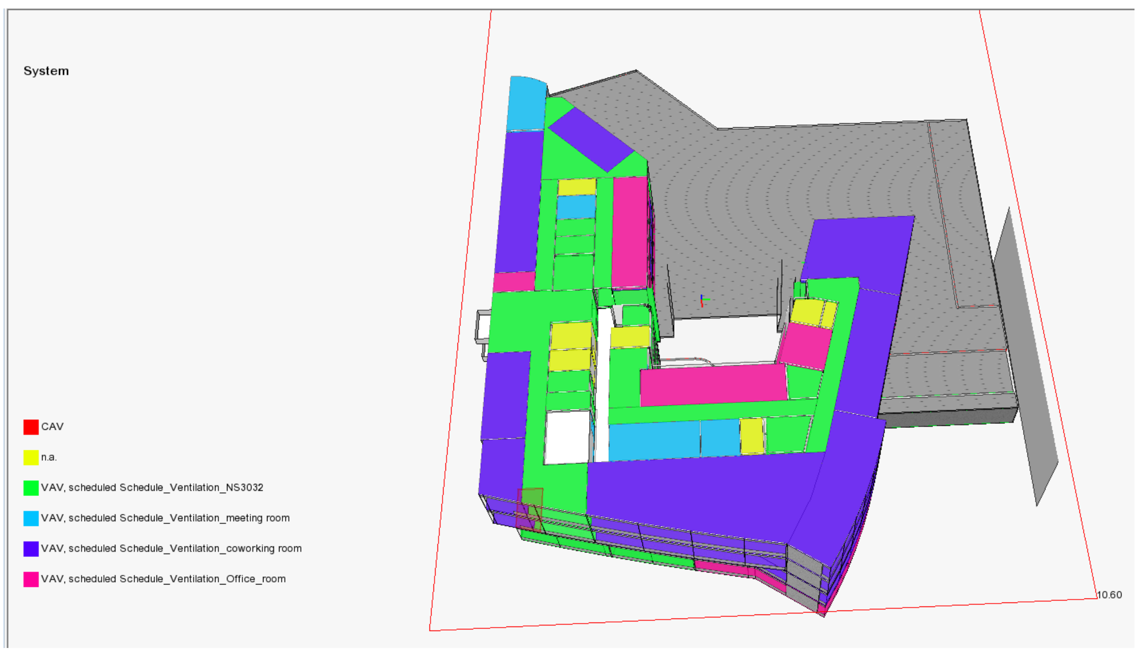


Figure 3.1: The zones divided according to the different ventilation scheduling (IDA-ICE)

However, it is not possible to model the ventilation strategy based on cooling demand of the meeting rooms alone. Therefore, the offices and co-working spaces will also be included in this ventilation strategy. Even if the ventilation control will operate with the CO_2 strategy, the cooling will occur through the ventilation system, but overuse of ventilative heating will ideally be avoided. The desired CO_2 ppm level is between

400 and 800 ppm for all zones, with exception for the parking garage. It is worth to mention that this test is not the final modeling of the building in IDA-ICE, it is done for testing purposes only.

3.1.1 Control strategy of the meeting rooms, office cells and co-working spaces

One of the key aspects for determining the sizing of the building, and in this case the modeling, is to be able to know the strategy of operation for the different room types. Under these conditions it is narrowed down to three different types of rooms that normally occur in any typical office building. The meeting room, office cell and co-working space with their operation status and control for ventilation and temperature, in which are crucial to be able to size and model office buildings. For ONV12E the control strategy of ventilation generally consists of variable air volume, shortened to VAV.

From table 2.2 the control strategy for each room is shown. The major problem area for control, is the co-working spaces. Co-working spaces have multiple occupants within the same zone, and it is complicated to have an overview of the amount of occupants at the different times during the workday. All the three room types operates with VAV and motion sensor. The only room that has CO_2-control, is the meeting room.

Previous simulation results show that the ventilative cooling is high considering the high ventilation rates and that there is a problem with balancing the air flows [6]. The rooms are mainly heated by water radiators in each zone, and are temperature regulated as well. However, the ventilative cooling in each room is regulated by the temperature set point boundary, and is therefore not controlled by presence in the terms of that the ventilative cooling appear when the following two conditions are in order [2]:

- The first condition is that there is someone in the room, the presence detectors
- The second condition is that the temperature is above the maximum set point temperature in the room

These two conditions apply for all co-working spaces, meeting rooms and office cells.

The regulator control in each room adds in this scenario a ventilative cooling signal to the VAV-system. The VAV-system generally operates with 50% throttling of dampers during comfort mode, which is when the occupants are present in the room [2]. This means that in order to set the air flow rates to maximum, it is necessary to have a 50% throttling from the presence detector that states the presence of occupants in the room and therefore it is defined as comfort operating mode. The other 50% are related to obtaining maximum cooling in order to have air flow rates at a maximum level [2].
The heating is regulated by a radiator valve that adjusts depending on the minimum temperature allowed in the room. In the IDA-ICE model, the temperature set points are implemented to regulate the water radiators in the same manner as the BOS. The ventilative cooling will also apply in the same way, however it is overruled by the VAV schedule that has been made from the averaged air flow rates extracted from the BOS [2].

Contrarily, the meeting rooms stands out from the co-working spaces and the office cells in the way of that there are local cooling units in the form of radiators to add additional cooling. This, in order to obtain the desired set point temperatures. For all rooms the temperature set points can be adjusted manually from between 20 and 22 ^{o}C [1].

3.1.2 Fan and heat exchanger operation

To be completely certain that the AHU is not operating during the off work periods, such as nighttime and weekends, the fans and heat exchangers of the five AHU is turned off in the same periods as the ventilation strategy of each zone.
Considering the ventilative heating is too high in the simulated model of the specialization project compared with the measurements of the energy monitoring system, the schedules have been made in order to reduce ventilative heating [6]. In figures 3.2 and 3.3, the implementation process in IDA-ICE has been illustrated.

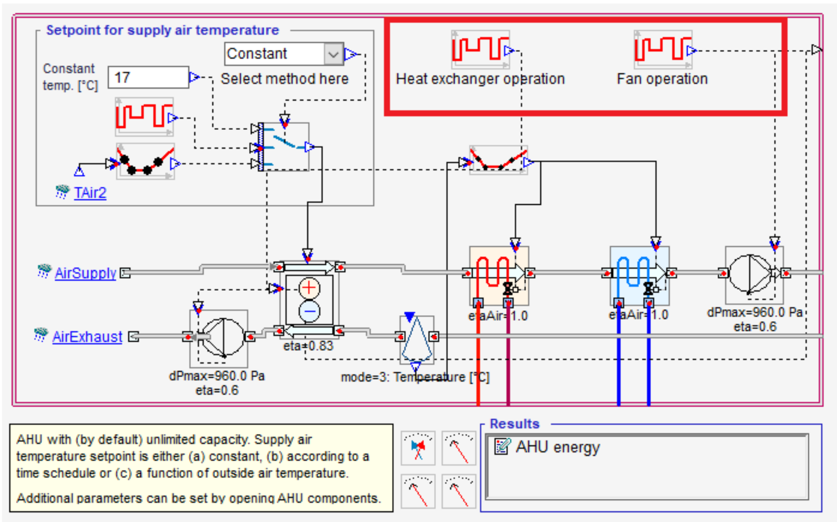


Figure 3.2: Marked in red, the schedule control of the fan operation and the heat exchanger operation (IDA-ICE)

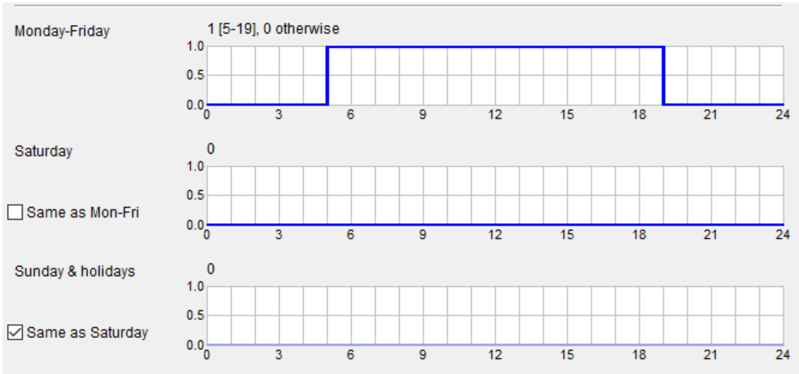
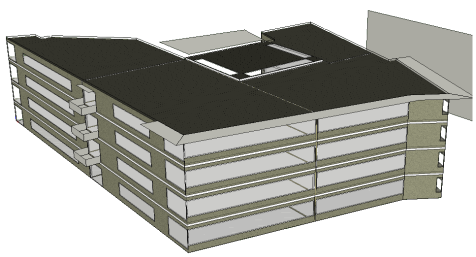


Figure 3.3: The schedule that applies for both heat exchanger and the fan operation (IDA-ICE)

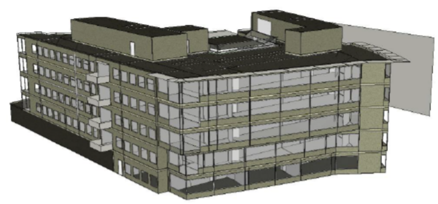
It is important that the heat exchanger operation has the same scheduling as the fan operation, as the heat will be both supplied and extracted from the same zone. If the fan operates without the heat exchanger turned on, the heat losses through ventilation will lead to high ventilative heating of air through the heating coil. This, because the rotary heat exchanger in each air handling unit is recovering 84% of the thermal energy in the extract air [1].

3.1.3 Sensitivity analysis test methods

The background of this section of Chapter 3, is to explain how the high ventilative heating from the results of the specialization project would be addressed [6].
A simplified model was used in order to compare the level of accuracy between the simplified and detailed model. The simplified model is important for determining the complexity of the building and compare differences between simple modeling and complex modeling.
The simplified model has CAV ventilation, same building envelope parameters as the detailed model, but it has no measurements used, only NS3031 standard input data. Additionally, the windows and zones have been merged into larger zones and windows in order to simplify numerical iteration steps in the model [14].
In figure 3.4a and 3.4b the comparison between the building envelope is shown.



(a) The simplified model shown in IDA-ICE [14]



(b) The detailed model from the final simulation in IDA-ICE [1]

Figure 3.4: Comparison between the detailed and simplified model

Additionally three test methods were carried out using different applications such as CO_2-control, balancing air flows, and increasing the radiator net power. The balancing of air flows will be further elaborated in the section 3.1.4, considering this was a valid option in the further modeling process. These tests were undergone to evaluate and improve the high ventilation heating.
The CO_2-controller test did not work out, as the ventilative heating increased as a result from the implementation. The simplified model were made in order to see how important the complex model would be in comparison. Further on, the testing procedure have been executed in the detailed model of the office building at ONV12E. From the tests in the detailed model, it was also attempted to see if an increased radiator net power would reduce the ventilative heating, which turned out to work in the model.
The outcome was the discovery of the low radiator net power in the office building model had to be increased. This will be further elaborated in chapter 3.4. The last test method was the balancing of air flow rates, which turned out successfully on reducing ventilative heating.

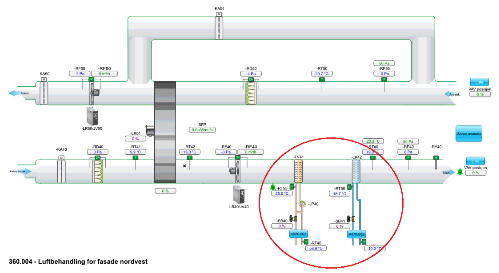
3.1.4 Balancing the air flows

The original detailed model designed by Florent Dulac, was made with cascade ventilation [1]. The cascade ventilation operated with supplied air into the occupied rooms such as offices and meeting rooms, and extracted the air from the corridors and other common areas [1]. This complies well with the ventilation strategy at ONV12E from examining the BOS [2]. The idea of this type of ventilation modeling in the IDA-ICE detailed model, was to set doors to connected zones to be "always open". This would in theory enable the air flows to freely go between the supplied zones and the extracted zones [1].
However, from the results of Dulac it was discovered that the air flows were unbalanced by implementing this ventilation strategy [1]. This led to high air flows going through the external walls. From simulating in the IDA-ICE model, it was detected a warning displaying a leakage through the majority of zones in the model. Most likely the IDA-ICE simulation software is not capable of calculating the air flows between zones, and therefore the zones that receive supply air will experience high pressure, which leads to leaks in those particular zones.

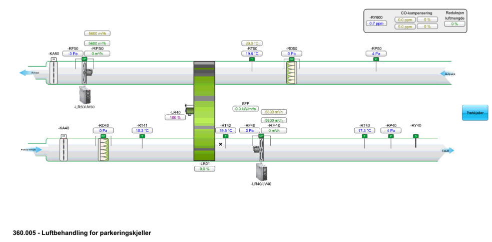
For the purpose of reducing heat loss from air flow leakage, it was decided to balance the air flows for each zone. This means that all zones have both supplied air and extracted air. The air flow rate schedules operate with calculated maximum and minimum air flow rates.
To ensure that this would not interfere with adding different maximum and minimum boundaries to the controller set points - the boundaries were set to the highest value for either supply or extract depending on which values was highest. If the supplied air had the highest maximum rate, the extracted air flow rate would get that value, if the extracted air flow rate maximum were lower than the supplied air flow rate.

3.1.5 Adjustments of air handling unit 360.05

The AHU 360.05 is supplying air to the parking garage and machinery room of floor U1 [1]. However, it was originally modeled in IDA-ICE to have both a heating coil and a cooling coil [1]. After investigating the building operation system of ONV12E, it was discovered that the AHU 360.05 did not have a heating coil and neither a cooling coil. The figures 3.5a and 3.5b show that for another AHU, such as 360.04 there is in fact a heating and a cooling coil. While for figure 3.5b, it does not operate with a heating coil or a cooling coil, because the main task of this air handling unit is to ensure a satisfying level of CO_2 within the parking garage.
The AHU 360.05 is modeled as CAV as the only exception, because VAV with CO_2 control did not function to its purpose in the previous attempts undergone in this master thesis. The AHU 360.05 will therefore be modeled without a heating and cooling coil. Also, the parking garage will not have any set point for minimum or maximum temperature [2].



(a) AHU 360.04 in the building operation system [2]



(b) AHU 360.05 in the building operation system [2]

Figure 3.5: Comparison between the AHU which is serving the parking garage, and an AHU serving an office floor from the BOS [2]

3.1.6 Ventilation strategy for meeting rooms, offices and co-working spaces

The ventilation strategy for the meeting rooms, office cells and co-working spaces will be changed from the schedules that were implemented during the specialization project [6]. The ventilation profiles that were extracted in the master thesis has been taken from the actual measured air flow rate instead of the BOS-calculation of the air flow rate. Hopefully, this will induce more accurate modeling of the ventilation.
From using equation 3.1, the schedules in the meeting rooms, office cells and co-working spaces VAV set points will be calculated. The equation calculates the percentage of maximum air flow for each room type at every hour of the day. The values in IDA-ICE are given in L/(s·m^2), but the schedules are made from measurements in the BOS, which operates with m^3/h. The schedules are generalized from the room types that were extracted from the BOS, and are shown in table 2.1 [2].

Modeling the ventilation strategy is in this case based on the measurements, but occupancy could during a sizing process be used for evaluating the indoor air ventilation such as mentioned in the the article " Occupancy-Based Control of Indoor Air Ventilation: A Theoretical and Experimental Study" [15]. this study could be further useful for both modeling ventilation in meeting rooms and co-working spaces.
The ventilation system is in this thesis modeled through air flow rate measurements which are based on occupancy presence detectors and CO_2 sensors. Demand controlled ventilation was used when testing occupancy-based control of ventilation described in the article [15]. However, the demand controlled ventilation can be based on the same principles as the modeling strategy in IDA-ICE, where the ventilation is controlled by time schedules.

$$Airflow_{throttle}[\%] = \frac{Airflow_{hh:mm}[m^3/h]}{Airflow_{max}[m^3/h]} \cdot 100\% \tag{3.1}$$

- Air flow$_{throttle}$ [%] - Air flow rate throttle for that particular time as a percentage of the maximum air flow rate boundary for that room type
- Air flow$_{hh:mm}$ [m^3/h]- Air flow rate at the given time of the work day
- Air flow$_{max}$ [m^3/h] - Maximum air flow rate set point boundary depending on room type

In table 3.1, the percentage of maximum air flow rate for each room is shown throughout the day. The values are based on the BOS-regulated maximum air flow per room and the air flow rate averages are found through extracting measurements from the rooms in table 2.1 as mentioned earlier [2].
As rendered in the table, the values change on a 24 hour period because of the presence of occupants. There are usually only people present in the building from 07:00 to 16:00, but as seen in the table there are some people in the building during the evenings as well.
The reason for that none of the rooms contains 100% air flow rate at any given time, is connected to that the rooms that were extracted had different maximum air flow rate values. Whether the air flow rate should be 100% or less, will depend on what gets chosen as the maximum air flow rate set point for each room. In the case of ONV12E, this will vary between the same types of rooms as well.
However, the maximum air flow rates that has been chosen, is established based on the most common values for each room type. Hopefully, this will generate and average for the total of all the zones chosen, and thereby make the ventilation strategy work according to what measurements indicate.

Table 3.1: Percentage of maximum air flow rate for each room type at each hour of the day

Time of day [hh:mm]	*Office [%]*	*Meeting room [%]*	*Co-working space [%]*
01:00	0.0	0.1	0.5
02:00	0.6	0.1	0.2
03:00	0.4	1.4	0.1
04:00	0.3	10.4	0.1
05:00	0.1	25.8	0.0
06:00	0.1	34.1	0.0
07:00	2.0	37.5	0.6
08:00	14.6	38.3	6.0
09:00	33.7	37.5	16.7
10:00	41.3	37.9	21.9
11:00	42.1	38.9	23.1
12:00	41.8	38.0	23.2
13:00	41.2	36.7	23.2
14:00	41.3	34.3	23.1
15:00	41.8	30.7	23.3
16:00	41.7	20.2	23.2
17:00	41.2	6.9	23.2
18:00	39.3	3.0	21.4
19:00	35.3	2.0	16.9
20:00	20.1	1.5	10.4
21:00	9.6	0.9	4.1
22:00	5.1	0.4	2.0
23:00	3.2	0.3	1.2
00:00	2.1	0.3	0.9

As an example, in figure 3.6 the ventilation schedule for the meeting room is shown in IDA-ICE. The schedule shows the 24-hour period of an averaged working day. This profile gives a better result that complies with what is expected than the specialization project profile shown in figure 2.6.

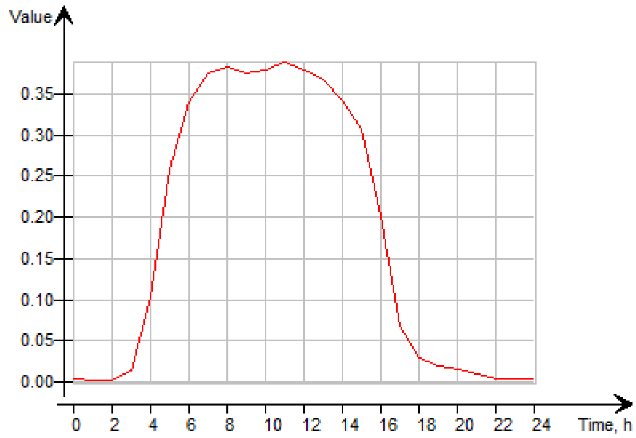


Figure 3.6: Ventilation schedule created based on air flow rates in the meeting room (IDA-ICE)

3.1.7 Ventilation strategy for the laboratories

Temperature and air flow rate set points in laboratories are most likely different than the rest of the zones at ONV12E. It is therefore of interest to investigate if there is any difference in temperature set points and ventilation strategy for these zones in the BOS [2]. This section aims to elaborate why the ventilative cooling should be increased, and the hypothesis concerns that the ventilative cooling demand has its roots in the laboratories and the high internal gains from the computers.

In figures 3.7 and 3.8, the location of the laboratories that the ventilation air flow rates were extracted from. The laboratories examined was the application lab, the prototype lab and the support lab. The code that was used to calculate the averaged air flow rates for each hour is the same as the Matlab code shown in appendix D. The laboratory storage room was not included in the calculations, considering the main processes that demands ventilation is in the ”active” parts of the lab. This was found through examining the BOS [2].

Figure 3.7: Application laboratory and support laboratory that the ventilation air flow rates are extracted from in the BOS [2]

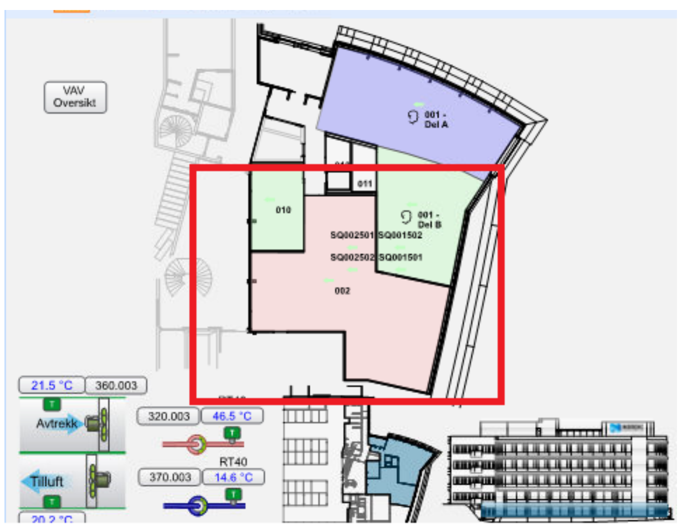


Figure 3.8: Prototype laboratory that the ventilation air flow rates are extracted from in the BOS [2]

The laboratories ventilation strategy was determined based on the averaged ventilation air flow rates shown in table 3.2. The table displays both the averaged hourly air flow rates on the weekdays from November 2017 to January 2019. There were some problems with defining a precise strategy for the lab as well, considering one of the laboratories contained higher maximum air flow rates than the two other laboratories. Through simulations, it will be further evaluated if it is necessary to increase the ventilation for that particular room. Moreover, the internal gains in the model have been implemented such that the heat is distributed between the laboratories, which hopefully will cancel out the different ventilation strategic choice made in the model.

Table 3.2: Percentage of maximum air flow rate for the laboratory, including the averaged air flow rates per hour calculated from the Matlab code in appendix D

Time of day[hh:mm]	*Percentage of max[%]*	*Averaged air flow rate[m^3/h]*
01:00	3.8	20.3
02:00	1.4	7.6
03:00	0.7	3.7
04:00	0.4	2.1
05:00	0.2	0.8
06:00	0.2	0.8
07:00	4.3	22.8
08:00	28.9	153.6
09:00	59.8	317.6
10:00	67.6	358.8
11:00	70.2	373.0
12:00	70.7	375.5
13:00	70.7	375.4
14:00	70.2	383.6
15:00	72.4	384.5
16:00	71.7	380.8
17:00	70.3	373.4
18:00	68.6	364.5
19:00	64.5	342.7
20:00	42.0	223.1
21:00	21.9	116.5
22:00	11.7	62.2
23:00	7.1	37.8
00:00	5.3	28.0

3.2 Electrical usage of equipment and lighting for each floor level

This section generally explains how the electrical meters in the BOS will enable to more accurately model the internal gains of the office building. Hopefully the already implemented internal gains based on NS3031 have been underestimated. Ideally, the cooling demand will increase, the heating demand will decrease, and furthermore result in a more precise representation of ONV12E [2].

3.2.1 Extraction of measurement data from the Building Operation System

To get the most exact results in the simulation for heating and cooling, it has been chosen to look into the internal gains of the building. Previously, in the specialization project, the internal gains were set with the

NS3031 into consideration [16] & [6]. Contrariwise, the more accurate approach will be to investigate the BOS to find the electrical usage for lighting and technical equipment for each floor [2].

From the building operation system, the electrical usage is divided by floor level and orientation north and south. The system logs the energy usage on an hourly basis, and the electricity usage will be extracted for all floors for the same time span and period as for the temperature and air flow rate measurements used in the specialization project [6]. The intention of examining these values in the BOS, is that the general thought concerns that internal gains from NS3031 is underestimated. It will therefore be of importance to increase the internal gains to reduce both space heating and ventilative heating [2].

In table 3.3, the electricity in kWh per year is shown [2]. From the measurements, the energy usage has to be converted into power [W]. The power has been calculated based on that the power is on 8760 hours per year, and by this it is an averaged value. Considering the office equipment and lighting are turned on during working hours, usually from 06:00 to 19:00, the internal gains should be turned on in the model during these hours. The hours of usage would in this case roughly amount to 2871 hours per year.

Table 3.3: Electricity measured in the office building

Sensor ID	*Description*	*Energy [kWh/year]*	*Power [kW]*	*Power$_w$ [kW]*
433.009_RE001_E	Lighting U1 north	3 993	0.46	1.39
433.009_RE002_E	Technical U1 north	91 542	10.45	31.89
433.010_RE001_E	Lighting parking	12 203	1.39	4.25
433.010_RE002_E	Lighting U1 south	2 126	0.24	0.74
433.010_RE003_E	Technical parking/U1 south	17 978	2.05	6.26
433.010_RE004_E	Technical parking	734	0.08	0.26
433.017_RE001_E	Lighting 1st floor north	3 651	0.42	1.27
433.017_RE002_E	Technical 1st floor north	11 946	1.36	4.16
433.018_RE001_E	Lighting 1st floor south	5 382	0.61	1.87
433.018_RE002_E	Technical 1st floor south	12 903	1.47	4.49
433.027_RE001_E	Lighting 2nd floor north	3 547	0.40	1.24
433.027_RE002_E	Technical 2nd floor north	13 222	1.51	4.61
433.028_RE001_E	Lighting 2nd floor south	4 172	0.48	1.45
433.028_RE002_E	Technical 2nd floor south	16 728	1.91	5.83
433.037_RE001_E	Lighting 3rd floor north	3 880	0.44	1.35
433.037_RE002_E	Technical 3rd floor north	13 283	1.52	4.63
433.038_RE001_E	Lighting 3rd floor south	3 446	0.39	1.20
433.038_RE002_E	Technical 3rd floor south	16 044	1.83	5.59
433.047_RE001_E	Lighting 4th floor north	4 411	0.50	1.54
433.047_RE002_E	Technical 4th floor north	11 750	1.34	4.09
433.048_RE001_E	Lighting 4th floor south	4 302	0.49	1.50
433.048_RE002_E	Technical 4th floor south	34 617	3.95	12.06

From the table, the parking garage has lower electricity usage for technical equipment. The lighting in the parking garage remains close to what the other parts of the building uses of electricity. Electricity usage for both the technical and lighting of U1 north seems to be higher than for the rest of the building.
The main reason for the higher energy consumption in this part of the office building, is connected to the location of laboratories at this floor level. The laboratories have a higher power demand than the rest of the

building, considering a lot of computer processes is taking place there. This will also most likely induce in a higher demand for cooling. Power$_w$ describes the power that is used during occupancy of the building.

From the specialization project simulations, the equipment and lighting has been modeled according to NS3031 on the basis of the master thesis work of Florent Dulac [1] & [6]. The lighting has been modeled as 6 W/m^2 maximum heat gains for all zones, and 30 W/m^2 for the equipment [1]. The 30 W/m^2 heat gains were deduced from information about the computers in the office building [1]. When implementing the equipment in the current model, the heat gains will be modeled based on the electricity consumption that has been measured in the BOS.
One valid reason for doing this, is that there could be several types of equipment in the building that has not been accounted for. One example of this could be different kitchen items in the local common rooms of each floor [2].

In figure 3.9, the electricity usage accumulates during each month. As seen from the figure, the electricity consumption leaps in early July. This phenomenon occur for all lighting and technical equipment at that particular time [2]. For calculating the electricity consumption for the different appliances, it is chosen to neglect the leap and use monthly values after the leap took place.
One plausible explanation for the leap in electricity consumption might be connected to a change in electricity meter. For instance, a change from the old electric meter to the AMI measuring device. The AMI is a smart metering device that reports the electricity consumption to the user frequently [17].

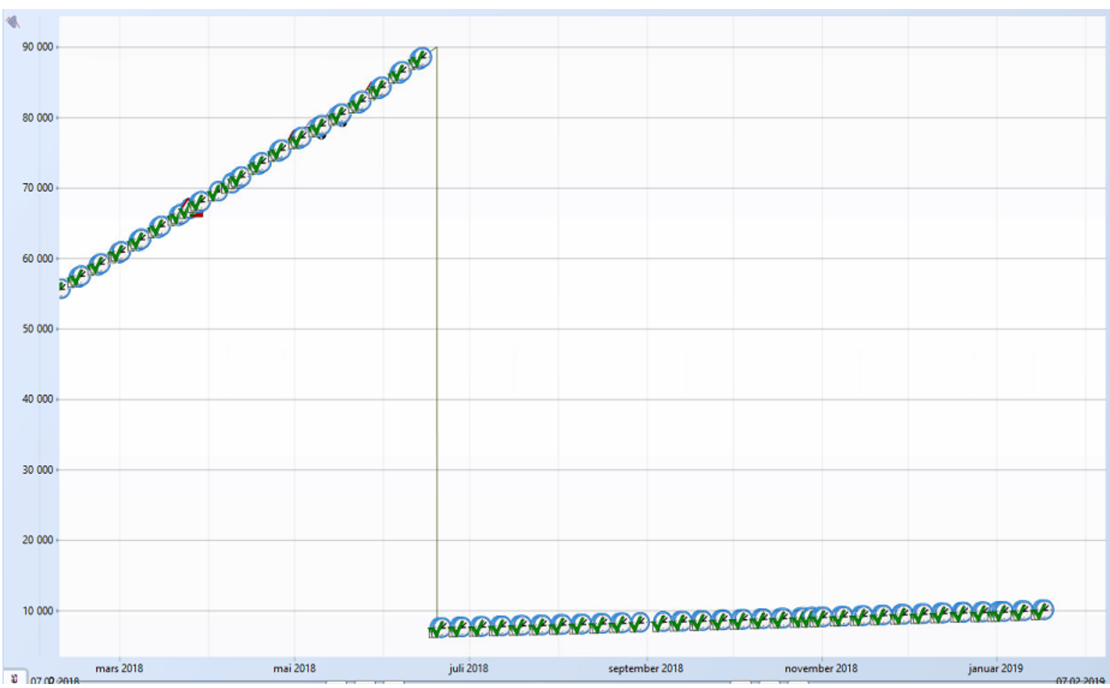


Figure 3.9: Hourly measurements from the BOS throughout a year, showing the different electricity consumption [2]

After communicating with Engineer at Schneider Electric, Ole Morten Smaaoien, it was considered that some of the circuits for equipment and lighting had incorrect wiring in the system [18]. The deviations were corrected in the circuit boards as well as in the BOS during June [18]. The historical data were decided to remain unchanged in the BOS. Because of this, the energy consumption in table 3.3 shows values from after June 2018 to avoid incorrect modeling implementations [2].

3.2.2 The Implementation process of internal gains

The internal gains from equipment will mainly concern the laboratories and the high cooling demand that were estimated for these zones. The other rooms, such as meeting rooms, offices and co-working spaces, will be evaluated between the estimation of Florent and what the extracted electricity consumption for each zone implies.
Regardless, the internal gains will be modeled based on the measurements from the BOS [2]. Although one good argument for using Florent's estimations based on "Klima og kjøleytelser" by Brueng for COWI, is that it is sized for that particular building [19].

From implementing the internal gains for equipment, it is discovered that the meeting rooms, office cells and co-working spaces have higher internal gains from the master thesis of Florent, than for the extracted measurement data [1]. This might be caused by that the electricity consumption were higher during the period before the incorrect wiring were corrected, or that the estimation were too high [2].
The laboratories seems to be underestimated in the earlier thesis of Florent, considering that the electricity meter show a quite high consumption for this particular area of the building. They will be changed in the model with the intention of increasing the cooling demand, so that the results are closer to what the energy monitoring system indicates.

The laboratories have the highest demand for cooling in the office building. The area of the laboratories where the electrical meter applies, is considered to be as shown in figure 3.10 within the red square. The total area of the laboratory where equipment is used is 444 m^2, found in the IDA-ICE floor plan for the model. The figure shows that the laboratories are facing south, meaning that the internal gains from equipment will be calculated based on sensor 433.009_RE003_E Technical parking/U1 south.
However, it looks like the parking lot technical equipment then will be high based on Technical U1 north, even though the sensor 433.009_RE003_E states that this is the parking lot. Since it is challenging to predict what electric meter that applies to where, the model will get internal gains for equipment based on floor level W/m^2 - totals.
The parking garage will not be modeled with internal gains, as temperature demands for cooling are not regulated by the AHU, only ppm level of CO_2. The area of the other floor of the building consist of the same size in surface area, which is 1014.3 m^2, as measured from the floor plan in the IDA-ICE model.
Additionally, the Atrium floor area is 169.1 m^2. Areas such as parking space, wardrobe, corridors, kitchen, elevators and toilets, are not part of the internal gains from equipment - evaluation, and will therefore be neglected.

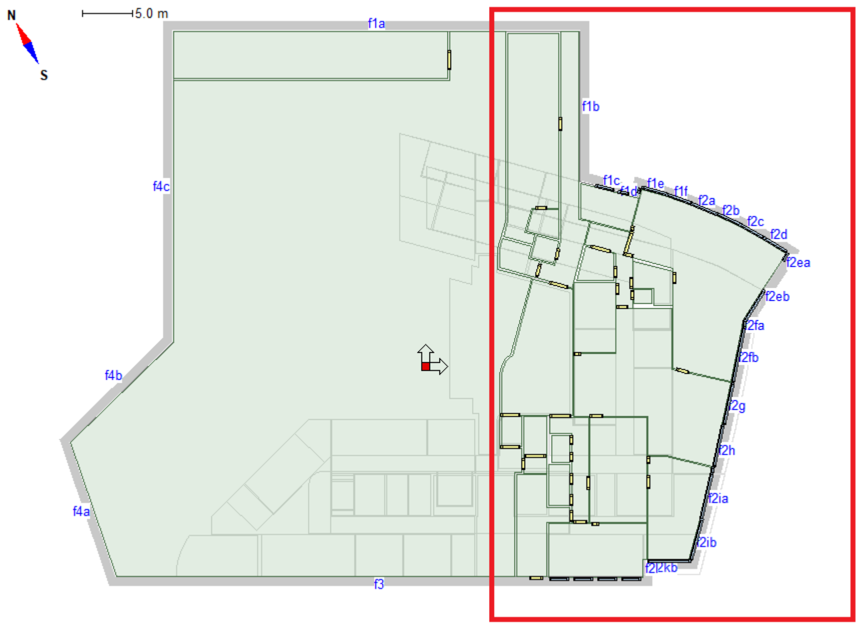


Figure 3.10: The red area show the part of the basement floor where the laboratories are located in the floor plan of IDA-ICE

In table 3.4 the equipment values for each floors electrical meters is rendered in W/m^2. The values are calculated based on the measured data shown in table 3.3, and based on the schedules for zone control from the BOS. The values in table 3.4 and 3.5 are calculated based on equation 3.2 [2].

$$Power[W/m^2] = \frac{\sum E_{consumption}[kWh/year]}{A_{floor}[m^2] \cdot h_{work}[hours]} \cdot 10^3[W/kW] \tag{3.2}$$

- Power [W/m^2] - The power per square meter
- $\sum E_{consumption}[kWh/month]$ - The summation of energy consumption per month registered in the electrical meter
- $A\_floor[m^2]$ - The surface area per floor where the energy consumption takes place
- h_work[hours] - Estimated number of operating hours per year in the control system, approximately 2871 hours

Table 3.4: Internal gains from equipment in W/m^2 for each floor of the office building

Floor	*Description*	*Power per square meter [W/m^2]*
U1	Technical	86.49
1st floor	Technical	7.31
2nd floor	Technical	8.82
3rd floor	Technical	8.63
4th floor	Technical	13.65

The electricity consumption connected to the technical equipment is generally as seen from table 3.4, more or less the same. The biggest difference is the laboratory facility at the underground level. Also, the 4th floor seems to have higher consumption compared to the other floors. One plausible explanation is that the computer usage or any other equipment at that floor is more in use as a cause of the type of business operation may differ from the other floors.

In figures 3.11 and 3.12, the implementation process of internal gains from equipment is shown. The floor area is used to calculate how big the internal gains from equipment is for each room. The schedules are set between 06:00 to 19:00 during weekdays in order to simulate the possible internal gains. In figure 3.12, the model parameters that changes is the number of units, the schedule, and the emitted heat per unit. The advanced section will be neglected, including the long wave radiation fraction, the liquid water emission per unit, the dry steam emission per unit, the CO_2 per unit and the utilization factor is set to 1. By setting the utilization factor to 1, involves that the share of heat and other emissions are 100% emitted to the zone, in this case, only the heat [20].

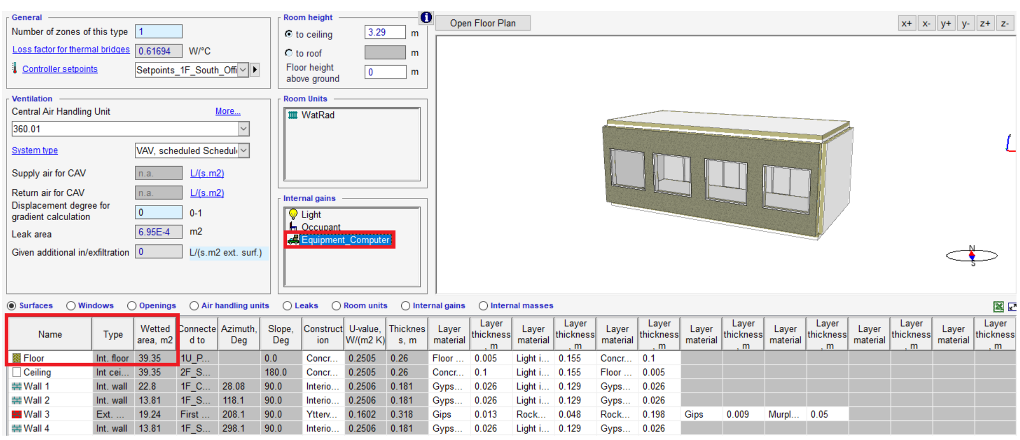


Figure 3.11: The red areas shows where the floor surface area is gathered from, and where the equipment is implemented into the model (IDA-ICE)

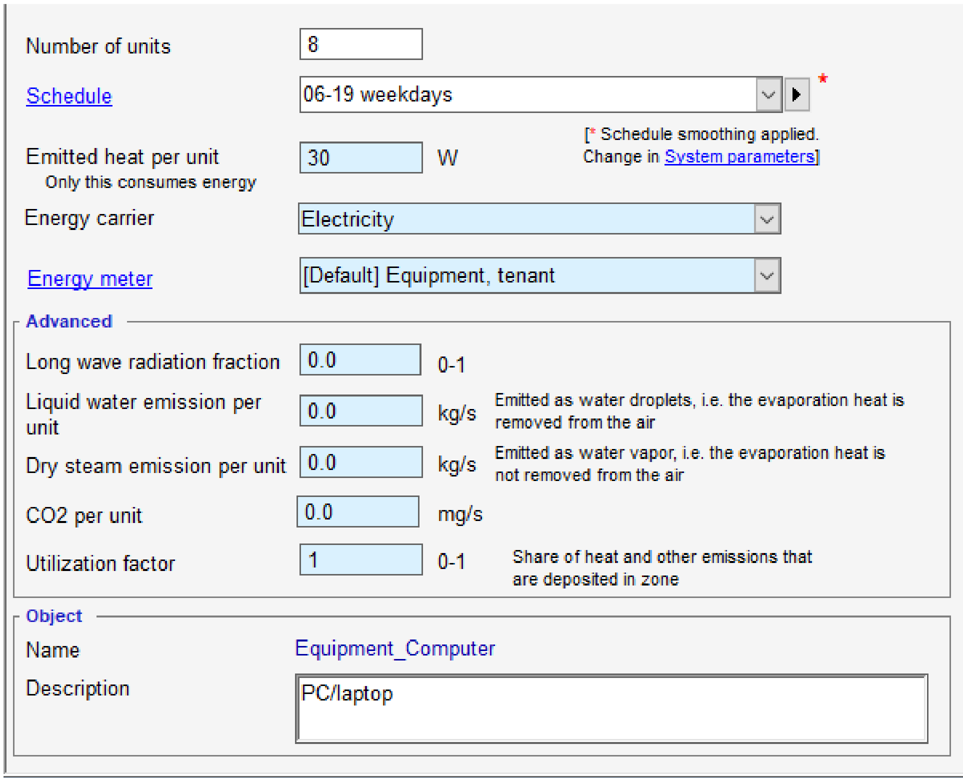


Figure 3.12: The model parameters for the internal gains from equipment in IDA-ICE

Calculating the power emitted from lighting, the floor area becomes different from what was accounted for the equipment. The lighting applies for all floor surfaces in the building, making it distinct from the equipment calculations. The floor area of the entire basement facility with parking spaces, labs and offices, amounts to 2929 m^2. The other levels of the building remains the same at 1506.1 m^2 per floor level. These values were found from the IDA-ICE floor plan.

As seen from the table 3.5, there is no usage of lighting that is above 6 W/m^2, which was the values assumed from NS3031 [1]. It can therefore be assumed that the lighting should be reduced to the values that are rendered in table 3.5. The values are changed in the IDA-ICE model, although it is assumed that the effect of the implementation only reduces the electricity consumption for lighting in the used energy folder of the results in the program. The schedule for lights is the same as for the internal gains. The electricity consumption is calculated based on the hours of usage, and therefore assumed to be sufficiently accurate for the simulation purposes.
For simulation purposes, the lighting were set to have 100% energy conversion over to heat, while it is possible to assume that the building is equipped with LED lights. If this is the case, the heat gain from LED lighting would be closer to 20% [21]. This would most likely induce a lower degree of heating in regards of the internal gains from lighting.

Table 3.5: Internal gains lighting in W/m^2 for each floor of the office building

Floor	*Description*	*Power per square meter [W/m^2]*
U1	Lighting	2.18
1st floor	Lighting	2.09
2nd floor	Lighting	1.78
3rd floor	Lighting	1.69
4th floor	Lighting	2.02

3.3 Scheduling occupancy

The chapter "Scheduling occupancy" focus on how the building's internal gains from occupants can be improved through using BOS measurements to get a more accurate representation of the building. As previously known, the occupancy is stochastic, and therefore unpredictable. The possibility of scheduling the occupancy based on the measurements at the building site through CO_2 sensors and presence detectors, may help creating a more accurate image on the usage of the office building [2].

It is assumed that all floors of the office building are occupied at all working hours. Some differences in heat from occupants can be linked to that some floors does not have occupants for the period when the measurements were undergone. If there was less occupants in the building than the IDA-ICE model assumed during simulations, this can potentially cause differences in regards to heating demands. Found in the building owners homepage, some parts of the basement, 1st floor and 3rd floor are currently vacant [22].

3.3.1 ISO-17772-1 vs. NS3031

Normally when buildings are being sized in the design phase, it is common to use schedules for occupancy such as NS3031 [16]. The main reason for using NS3031 in calculating energy performance including occupancy, is because the Norwegian building code demands this in § 14-2 subsection 4 [23].
From the early stage of the modeling process, the NS3031 standard has been used for scheduling occupancy in IDA-ICE. However, it is mentioned in that particular standard that the data that is given are compiled for documentation of energy performance with standardized conditions. They will hereby not represent real life ratios, and cannot be compared with the measured energy consumption [16].

The NS3031 schedule for occupancy is shown in figure 3.13, in light green for the office building. the occupancy is given in W/m^2 rather than a ratio between 0 and 1. The international standard ISO 17772-1:2017 is recommending that occupant schedules and internal loads are known, these should be used for calculation of the energy performance [24].
In figure 3.14 the occupancy schedule from the ISO 17772-1:2017 is shown. This schedule is based on a ratio between 0 and 1, where 0 is no occupancy and 1 is full occupancy, both depending on the amount of occupants given for that particular room in the office building.
ISO 17772-1:2017 uses a diversity factor when scheduling occupancy. The diversity factor is defined by the ratio of the sum of the maximum demands for the various parts of the system to the concurrent maximum demand of the entire system [25]. The ISO 17772-1:2017 states that the default occupant schedules are examples that can be used as input to calculate the energy use in a building [24].

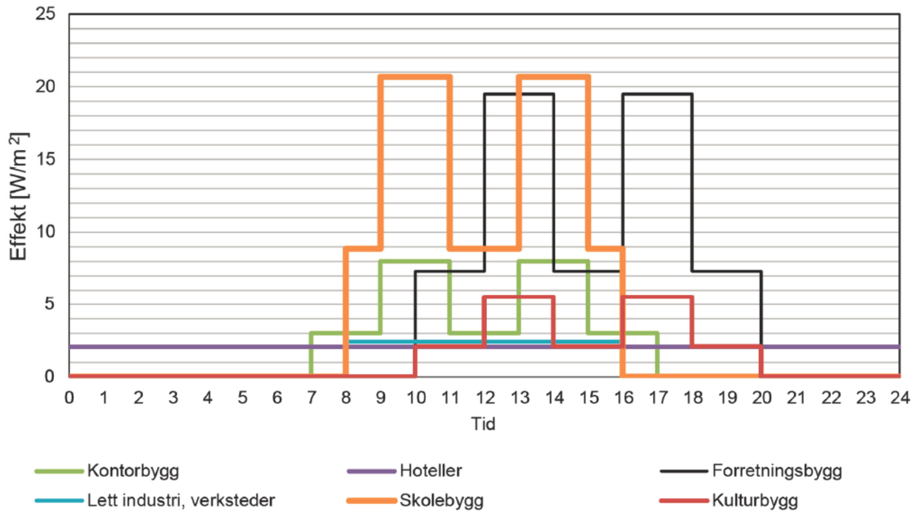


Figure 3.13: NS3031 Norwegian standard for calculating energy performance of buildings - method and data, office building shown by the green line [16]

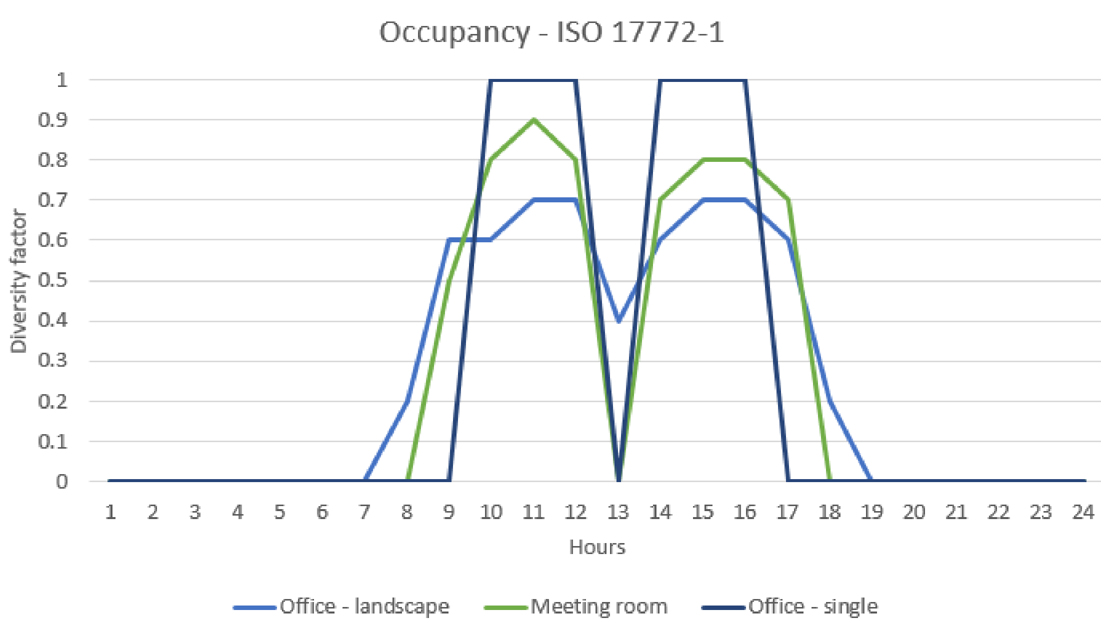


Figure 3.14: ISO-17772-1 Energy performance of buildings - Indoor environmental input parameters for the design and assessment of energy performance of buildings [24]

Both schedules operate with different criteria for occupancy scheduling, and are set for a 24 hour period. Additionally it is possible to see that the main occupancy load for office buildings is solely during the work hours from 07:00 to 17:00.
However if one standard should have been chosen in the early design stage, it should have been the ISO 17772-1:2017. The main reason for this selection would be on the basis of that ISO 17772-1:2017 takes the different room types of the office building into consideration. The intention of presenting these two standards is to compare them with the occupancy schedule that is made based on measurements from the BOS [2].

When comparing the NS3031 with both ISO 17772-1 and NS3701, which is the Norwegian passive house standard [26], the highest energy demand comes from the NS3701 regarding occupancy contribution. While the ISO standard have higher energy for occupancy than NS3031. With this in mind, using different occupancy schedules for the model may increase internal gains, and reducing the heating demand in the best case scenario [27].

3.3.2 Occupancy from ventilation air flow rates

The office cell and the co-working spaces are controlled by presence detectors. This means that the ventilation will turn on whenever there is someone in that particular space the sensor covers. It is not possible to determine whether or not there are several people in the room, or only one person. But as an assumption the occupancy of both office cells and co-working spaces are considered to be at maximum level when the ventilation air flow rate is at maximum stage. The averaged ventilation air flow rate for office cells and co-working spaces are calculated by using the Matlab code in appendix D, and extracting measurements from the real office building at ONV12E, as mentioned earlier in chapter 3 during the design of ventilation strategy. The meeting room occupancy will be modeled based on a different criteria, and will be elaborated in section 3.3.3.

In figures 3.15 and 3.16 the averaged ventilation air flow rates are shown. They will be further used in order to calculate the maximum and minimum presences in the two room types. The measurement extraction are gather from the BOS, and the rooms chosen is shown in table 2.1 [2].

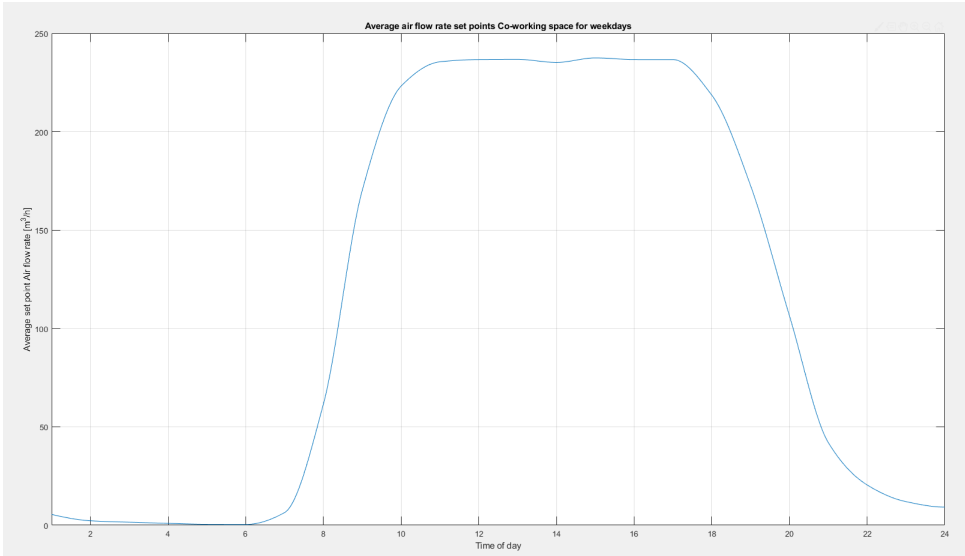


Figure 3.15: The air flow rate average from four co-working spaces for determining occupancy (Calculated in Matlab)

As we can see from the co-working spaces and office cells in figures 3.15 and 3.16, the ventilation air flow rates corresponds well with the schedules for occupancy shown in section 3.3.1. However, some differences appear in both co-working spaces and office cells during the lunch hours. It is assumed that many of the occupants are eating their lunches at the desks in the office cells, and in the co-working spaces for those who occupies this area.

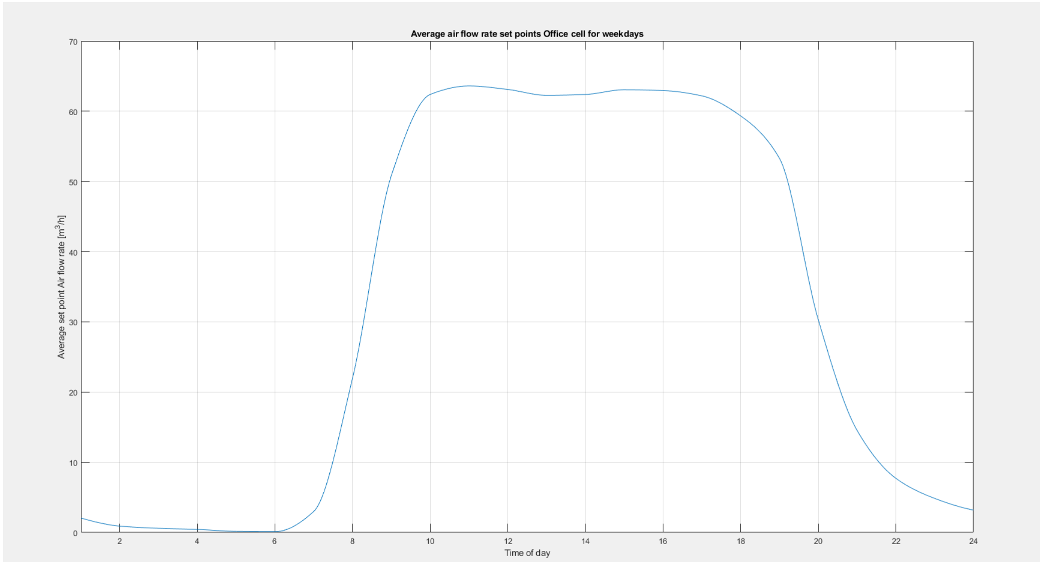


Figure 3.16: Office cell averaged air flow rates per hour for determining the occupancy in the office cells (Calculated in Matlab)

In table 3.6 the percentage of occupancy is calculated based on the averaged air flow rates of the extracted room measurements. The percentage is calculated based on that each hour makes a percentage of the maximum ventilation air flow rate during the 24-hour period average. This strategy was chosen in order to try to model the presence of occupants through finding out how the ventilation system adapted to the increasing or decreasing indoor air quality demand. In this case this was based on presence detectors. It could therefore be assumed that the different rooms have occupancy at different hours of the day and therefore the percentage is not on/off, but goes up and down depending on the average occupancy. Hopefully this will lead to a more accurate representation of the office building occupancy.
Equation 3.3 shows the thought process of calculating the percentage of occupancy for each hour of an averaged work day based on air flow rate at a particular hour divided by the maximum air flow rate for the entire period.

$$Occupancy[\%/hh:mm] = \frac{Airflow_{hh:mm}[m^3/h]}{Airflow_{max}[m^3/h]} \cdot 100\% \tag{3.3}$$

- Occupancy [%/hh:mm] - Calculated percentage of occupancy
- Air flow$_{hh:mm}$ [m^3/h] - Air flow rate at a particular time of the day
- Air flow$_{max}$ [m$^3/h$] - Maximum air flow rate through the entire calculation period

Table 3.6: Percentage of occupancy in office cells and co-working spaces based on the averaged air flow rates from the BOS [2]

Time of day [hh:mm]	*Office cell[%]*	*Co-working spaces [%]*
01:00	0.0	2.3
02:00	1.4	0.9
03:00	0.9	0.6
04:00	0.7	0.4
05:00	0.2	0.2
06:00	0.2	0.2
07:00	4.7	2.7
08:00	34.6	26.0
09:00	80.0	71.7
10:00	98.1	94.0
11:00	100.0	99.2
12:00	99.2	99.6
13:00	97.9	99.7
14:00	98.1	99.0
15:00	99.2	100.0
16:00	99.0	99.6
17:00	97.8	99.6
18:00	93.3	92.0
19:00	83.8	72.6
20:00	47.6	44.8
21:00	22.9	17.7
22:00	12.1	8.6
23:00	7.6	5.0
00:00	5.0	3.9

3.3.3 Meeting room occupancy

The meeting room has a different strategy for obtaining sufficient indoor air quality, and it is therefore chosen to model the occupancy differently from the office cells and co-working spaces. The main reason for doing this, is to see if there are any major differences in how the occupancy schedule will appear. The occupancy schedule will hopefully show a curve that are more or less equal to the ventilation air flow rates for the meeting room shown in figure 3.17.

The CO_2 concentration in a room where a ventilation system has been installed, will normally obtain a stationary CO_2 level after a given time [2]. Depending on the number of air shifts for the CAV, the level of CO_2 will stabilize at a certain plateau. For the VAV - it is possible to assume that the ppm level will be regulated in regards to a maximum level of CO_2 in the meeting rooms, and therefore obtain curves that stabilizes below the set point ppm value. By this the number of people can be estimated based on the slope of these curves, and also when the maximum ppm level has been reached and also when it declines [28]

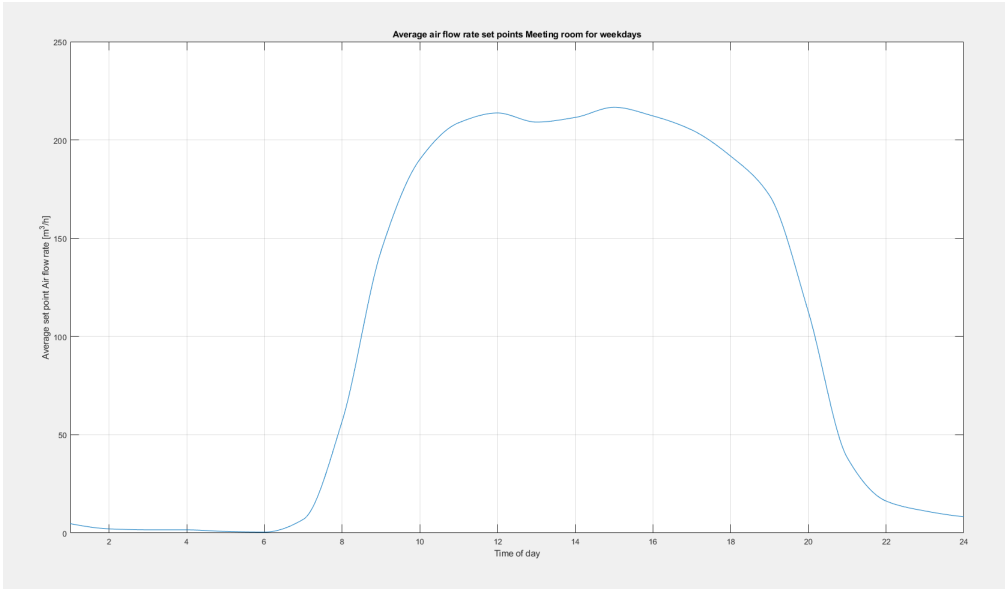


Figure 3.17: Meeting room averaged air flow rate for each hour of the day to determine meeting room occupancy (Calculated in Matlab)

From the scientific article ”Indoor occupancy estimation from carbon dioxide concentration” [29], the indoor occupancy is modeled based on CO_2 measurements. In this case the measurements experiences spikes in concentration which then leads to necessary smoothing of the CO_2 data [29]. The method used in this thesis is a little bit more simplified. The smoothing of spikes, is here undergone through averaging the CO_2 values throughout an entire year.

The meeting room occupancy will be attempted to model through CO_2-measurements from the four meeting rooms shown in table 2.1. The CO_2 ppm levels are extracted from the BOS, and the average per hour is found through using the same Matlab-code as for the ventilation air flow rates shown in appendix D. The idea is that at a certain level of CO_2, there will be no occupants present. This level will be between 500 to 600 ppm depending on the room type, such as for meeting room 101 in figure 3.18.
The lowest CO_2-value will be the deciding factor for non-occupancy meaning it will be considered as off in the control system. The maximum CO_2 value will be considered as the maximum amount of people sized for that particular room type.

The hypothesis for creating the curve for occupancy, is that the CO_2 scheduled occupancy will be more accurate than the ventilation air flow rate scheduled occupancy. This is because the CO_2 level are more likely to show whether or not there is an occupant in the room, while the ventilation system will more or less be on during the entire day, and will thereby not be completely turned off. It is also better for estimating the amount of people present, by determining the level of CO_2 produced.
A normal CO_2 level in the atmosphere is usually between 300-350 ppm from measurements [30]. However, the meeting rooms tend to obtain a stable level slightly above the 500 ppm limit level, as levels between 600-800 ppm are typical values for office buildings [30] & [2].

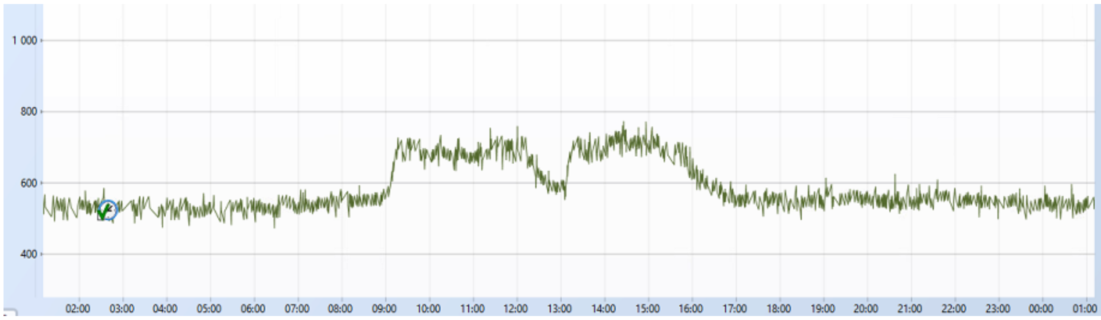


Figure 3.18: CO_2-level during a regular workday at meeting room 101

The CO_2-level must be considered as increasing or decreasing. Because of that when the occupants enters the room, there will be a lower CO_2-level than when the occupants exits the meeting room. In figure 3.19 it is possible to see that the lowest CO_2-level occurs at around 07:00, which is just before occupants starts entering the room. The highest levels of CO_2 occurs right before the lunch break. From the figure it is possible to see that the CO_2 ppm level accumulate during the work day, and that the CO_2 concentration decreases around 15:00-16:00 when people starts exiting the meeting room.

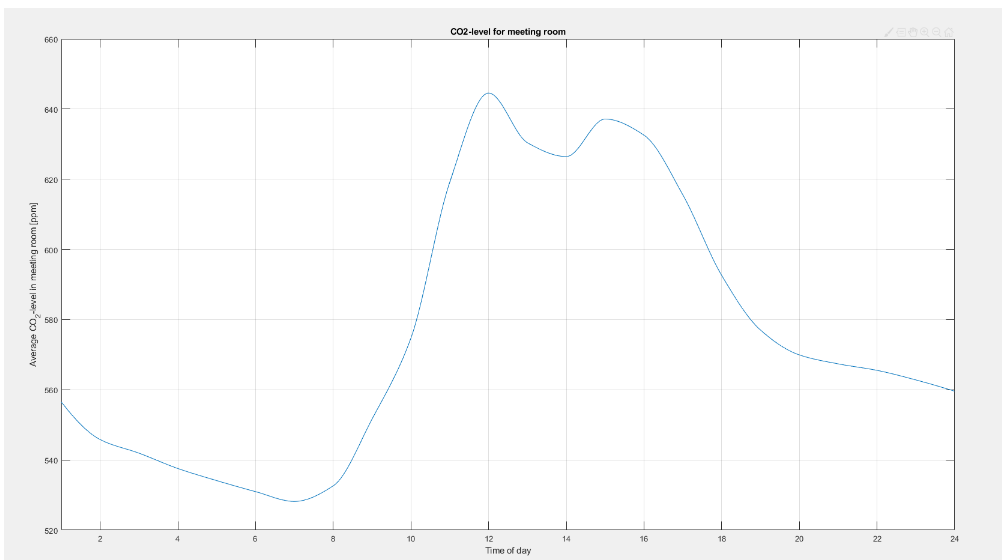


Figure 3.19: CO_2-level during a workday from Matlab-averaged CO_2-values (Calculated in Matlab)

From considering the accumulation factor of CO_2, it is necessary to determine occupancy schedules at a different perspective than for the ventilation air flow rate modeling of occupancy. This will indicate that whenever the slope is increasing, a certain amount of people enters the meeting room. Whenever the slope is declining, there must be people exiting the room. The slopes shown in figure 3.20 shows them hourly, and will be the determining factor for deciding the amount of people present in the room.

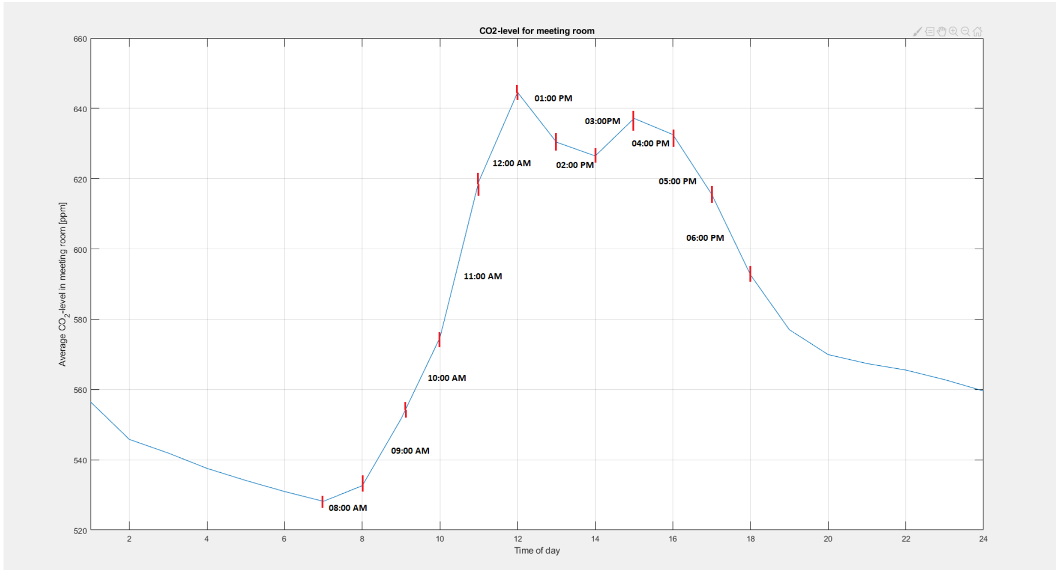


Figure 3.20: CO_2-level slope for deciding the amount of occupants (Calculated in Matlab)

The calculation of inclination and declination are based on equation 3.4, where m is the gradient [31]:

$$m = \frac{\Delta y}{\Delta x} \tag{3.4}$$

- Δy - Difference in CO_2-level, in ppm
- Δx - Horizontal run, difference in time from one work hour to the next
- m - Gradient for the slope

In order to recalculate the averaged values into a diversity factor between 0 and 1, it is considered to determine the amount of people in the room based on which working hour has the highest inclination number. From figure 3.19 the highest inclination number occurs between 10:00 and 11:00.
The assumption involves that during this hour the meeting rooms experience maximum occupant capacity, which will indicate a diversity factor of 1. This inclination number will therefore be the deciding factor for the calculation of the other work hour periods of inclination.
During a period of inclination, such as the period from 12:00 to 13:00, there will be a negative diversity factor. In order to compensate for this, the diversity factor during periods of declination will be calculated based on the highest declination instead of considering the inclination.
This calculation procedure will hopefully create an amount of occupants at 12:00 which may be 100% of maximum, and then when the declination period occurs, the amount of people will be reduced by the steepness of the declination. This means that the steepest declination slope will be considered as zero occupants, and that the other declination curves will be based on the steepest one. As seen in figure 3.20, the declination slopes had to be taken until 18:00 in order to find the steepest declination slope. The calculation of reduction

in occupancy connected to declination is shown in equation 3.5, and has been created with the platform of the inclination equation [31].

$$Occupancy_{declination} = \frac{((1 - \frac{\Delta y_t}{\Delta y_{steepest}}) \cdot 100\%) \cdot m_{previous}}{100\%} \tag{3.5}$$

- Occupancy$_{declination}$ - Diversity factor for occupancy declination slope
- Δy_t - Difference in CO_2-level [ppm] at the given time [hh:mm]
- $\Delta y_{steepest}$ - Steepest declination curve CO_2 difference [ppm] for determining the zero occupancy diversity factor
- m$_{previous}$ - Gradient for the previous hourly inclination slope given as a diversity factor for occupancy [%]

In table 3.7 the final diversity factors for occupancy for an averaged working day in the meeting rooms is shown. Outside the working hours, the CO_2 level is neglected, as it takes time before the CO_2-level declines to the minimum amount. Some of the reason for that it takes long for the CO_2 ppm level to decline, is that after 19:00 the ventilation system is turned off, which does not grant an opportunity to air out the excessive CO_2. In figure 3.21 the table is shown as a figure where the chart illustrates the schedule that will be implemented into IDA-ICE for the meeting rooms.

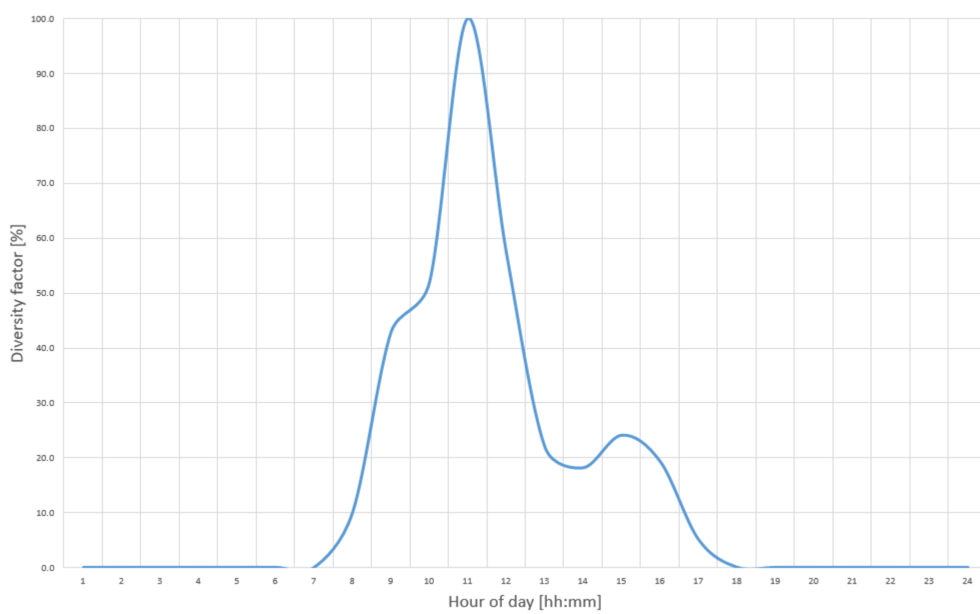


Figure 3.21: Occupancy schedule for meeting room showing the diversity factor in %

Table 3.7: Diversity factor for occupancy given in % for meeting rooms determined by CO_2-level measurements extracted from the BOS compared with scheduled meeting room occupancy by ventilation air flow rates [2]

Time of day [hh:mm]	*Meeting room CO_2[%]*	*Meeting room Ventilation [%]*
01:00	0.0	0.4
02:00	0.0	0.2
03:00	0.0	3.6
04:00	0.0	26.8
05:00	0.0	66.3
06:00	0.0	87.8
07:00	0.0	96.4
08:00	10.0	98.7
09:00	42.9	96.6
10:00	52.0	97.6
11:00	100.0	100.0
12:00	57.2	97.9
13:00	21.9	94.6
14:00	18.1	88.3
15:00	24.1	79.0
16:00	19.2	51.9
17:00	5.0	17.7
18:00	0.0	7.6
19:00	0.0	5.2
20:00	0.0	3.9
21:00	0.0	2.2
22:00	0.0	1.0
23:00	0.0	0.8
00:00	0.0	0.7

3.3.4 Implementing the final occupancy schedules in IDA-ICE

The final occupancy schedules are implemented into the detailed model in IDA-ICE in order to model the internal gains as accurately as possible. The office cell and co-working spaces were implemented with the schedules shown in table 3.6. They were modeled with the ventilation air flow rates in mind. The meeting room occupancy schedules were implemented into model based on CO_2-measurements, and the values are shown in table 3.7.
All rooms occupancy schedules were implemented with values between 0 and 1, depending on the degree of presence. The office cells, co-working spaces and meeting rooms obtain these schedules in the model. The other rooms have either no occupancy at all, such as the shafts and elevators, and some rooms have NS3031 values as they are to small to be considered for evaluation for this thesis work. The results from modeling through CO_2 and ventilation air flow rates will be analyzed in chapter 4, and discussed in chapter 5.

3.4 Technical improvements and alternations of the model

This section elaborates on the minor improvements of the building model, in order to obtain more accurate simulation results. By improving radiator net power, adding free cooling, and additionally implementing floor heating in the wardrobes.

3.4.1 Radiators and convectors evaluation and improvements

From the results shown in chapter 2 from the specialization project, it is considered to investigate the radiator net power in order to reduce the ventilative heating demands that were higher than expected in the results [6]. The main part of this section is to elaborate on the radiator modeling in the IDA-ICE model.

In the model, some of the main issues concerns the peak demand for heating in the building during winter. From the master thesis ”Reduksjon av effekttopper i kontorbygg” by Marie Sveen Olsen, peak load measurements were done in February 2018 [4]. The results showed that the peak load was at maximum 220 kW, which gives a good indication to what the demand for heating should be expected to be regarding the simulation results. The thesis recommended that a hot water storage facility should be installed into the thermal energy system in order to reduce the peak heating demands.
However, this will not be tested in this thesis, but could be of interest to further examine in future theses [4]. As the heat pump unit has a nominal heating capacity of 230 kW, the peaks should be covered at least during the periods when the measurements were done [7].

As seen from earlier, the radiator net power was assumed to be 185 kW from examining the project work of Alfstad [7]. Contrarily, it has been discovered that the heating power of each radiator has been implemented wrongly into the model, as the net power should be per square meter. As seen in figure 3.22, the adjusted net power of the radiators increases to 8.9 kW/m^2. This, will hopefully reduce the necessary ventilative heating of the AHU as the radiator can cover the peak demands.
Ideally, the radiators are to be placed underneath the windows in every room. However, it has not been prioritized to investigate all rooms placement of radiators. Furthermore, it will be considered to neglect placement of the radiators for simplification purposes.

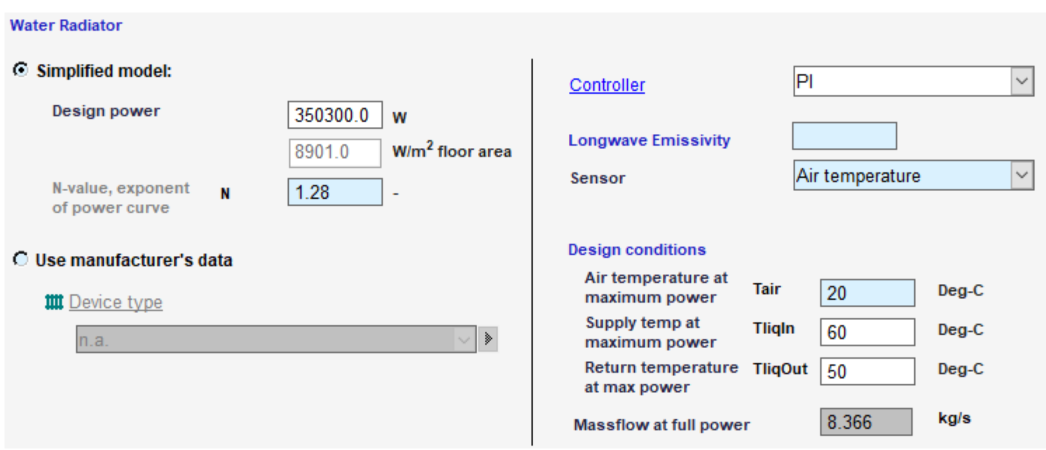


Figure 3.22: The adjusted net power of the radiators implemented in IDA-ICE

The convectors were not a part of the evaluated net power demand coverage in the specialization project of Alfstad [7], and it was therefore chosen to not include this part in the modeling. Instead, the radiators cover the demand from both convectors and radiators.

The temperature compensation curve of the radiator heating circuit were initially modeled as a separate curve that were attached to the PI-regulator for hot control of the hot water accumulation tank which served all zones. The temperature compensation curve is originally in the model as shown in figure 3.23. Now, the zone heating is the only part that will be effected by the temperature compensation curve, with the exception of the floor heating in the Atrium. The schedule that is also shown in figure 3.23, enables the heating towards the zone to be regulated for when it should be delivered. For the heating with regards to temperature set points, this is controlled for each zone. In figure 3.24, the implemented temperature compensation curve for heating is shown. The compensation curve is retrieved from the specialization project of Alfstad [7].

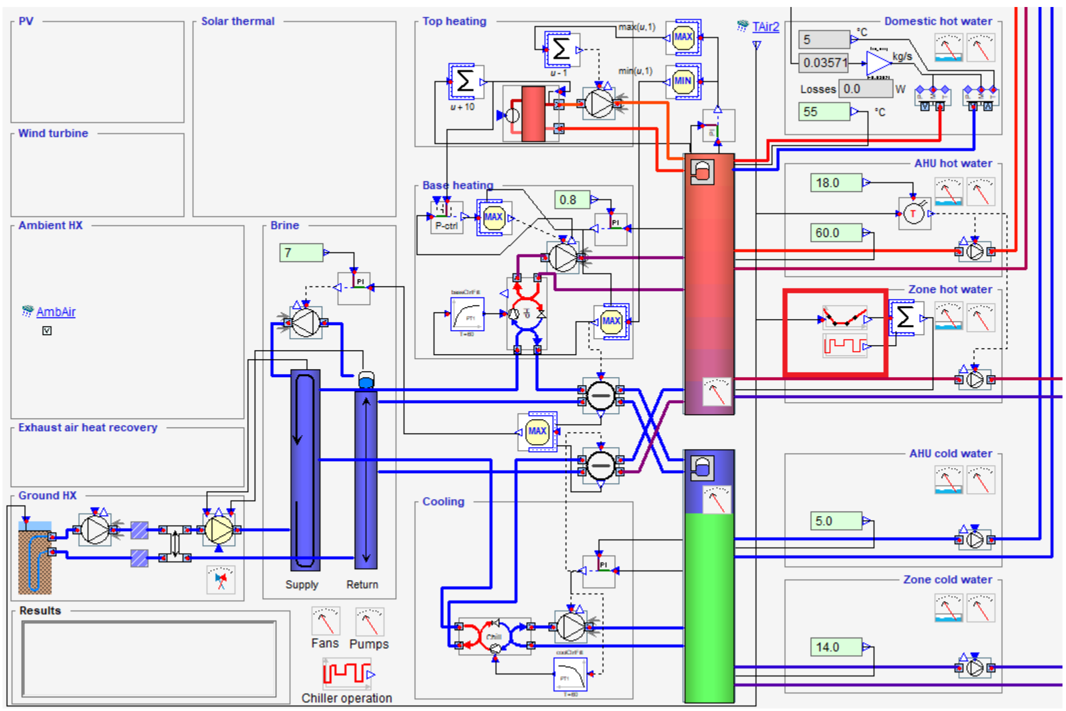


Figure 3.23: The location of temperature compensation curve for heat supply of the radiators in the ESBO plant model in IDA-ICE (marked in red)

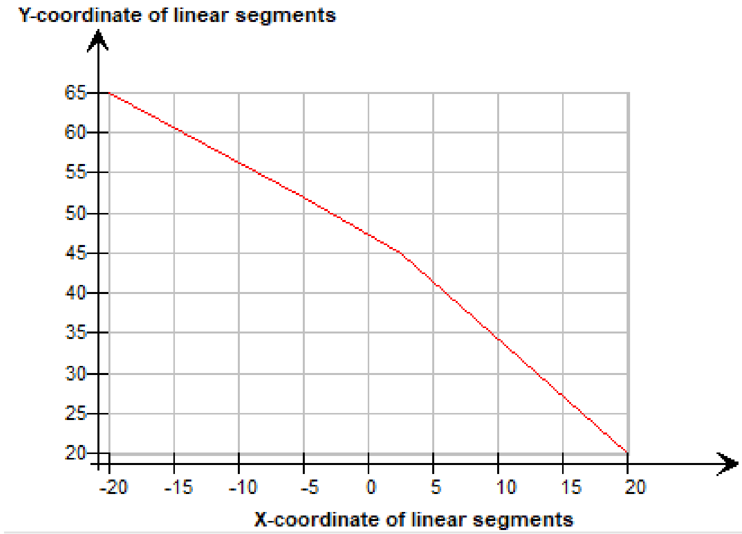


Figure 3.24: The temperature compensation curve for heat supply of the radiators (IDA-ICE)

3.4.2 Floor heating in the wardrobes

In order to increase the zone heating, and to reduce the ventilative heating, the wardrobe area in the model has been equipped with floor heating. The floor heating in the wardrobes is also a part of the real office building at ONV12E, and were therefore added to the model in order to achieve more accurate simulation results. The wardrobe floor heating were modeled with the same heating capacity as the floor heating of the Atrium, although the heating demand will most likely be less than the demand for heating in the Atrium [2].

3.4.3 Additional modeling data

The parameters of the detailed simulated model is shown in appendix A, B, and C. These appendices give central information about the model both in terms of construction parameters, the thermal energy system and the weather data used in that particular model. If any of the modeling steps seems unclear, it is recommended to see the specialization project "Simulation-Based Building Integration of a Multifunctional Heat Pump System" by Mathias Metlid [6] as well as the master thesis of Florent Dulac [1] on the building envelope modeling process.
Moreover, the appendix D renders the Matlab code used for extracting the CO_2 measurements as well as the air flow rates. Otherwise, appendix E show the As-built report from COWI, which is used for comparison of the simulation results [3].

3.4.4 Simulation input summary

A summary of the most central simulation input data for the detailed model are rendered in table 3.8 and 3.9. The tables shortly summarizes the different zone parameters and component parameters that has been implemented.

Table 3.8: A summary of the most central simulation input data for the detailed model at zone level

Zone	***Occupancy***	***Equipment & Lighting***
Office	Ventilation air flow rate scheduled	Electrical meter - floor level
Co-working space	Ventilation air flow rate scheduled	Electrical meter - floor level
Meeting room	CO_2 measurements scheduled	Electrical meter - floor level
Laboratories	Not modeled - NS3031	Electrical meter -zone level

Table 3.9: A summary of the most central simulation input data for the detailed model in regard of components

Component	***Description***
Radiators	Adjusted heating capacity to enable better temperature adjustments and reduce ventilative heating
Temperature compensation curve	For radiators in order to improve temperature set points optimal adaptation
Fan and heat exchanger operation	Set to only operate during the working hours in order to reduce ventilative heating
AHU 360.05	Removed heating and cooling coil with the intention to reduce ventilative heating in the model
Ventilation - zone level	Implemented based on air flow rates extracted from the BOS, balanced within the zone

4 Results and analysis from the different modeling strategies

In chapter 4: ”Results and analysis from the different modeling strategies” the simulation results are compared with the measurements from the master thesis of Alfstad [5] to evaluate accuracy and validity. The results are analyzed through comparison and by examining different rooms as well as complete floor levels in order to determine how the different modeling parameters have affected the simulation outcome. The simulations that have been executed is accounted for in table 4.1, in terms of the use of measurements instead of standards.

Table 4.1: Comparison between the different testing procedures in IDA-ICE in order to assess the high ventilative heating

Model	***Internal gains***	***Ventilation***	***Envelope***	$T_{setpoints}$	***Duration [h]***
Balancing air flows	BOS	BOS VAV scheduled -balanced	As-built [3]	BOS scheduled	50
CO_2	BOS	VAV CO_2 controlled	As-built [3]	BOS scheduled	50
Radiator capacity	BOS	BOS VAV scheduled	As-built [3]	BOS scheduled	50
Simplified model	On/off scheduled	On/off CAV - balanced	Simplified [14]	NS3031	0.33
Detailed model	BOS w/ occupancy	BOS VAV Scheduled -balanced	As-built [3]	BOS scheduled	56.8

4.1 Testing procedure results from assessing the ventilative heating

In this part the different testing procedure outcomes are clarified through results and an analysis. The most central heating and cooling results are shown in table 4.2. The results are mainly concerned around the zone heating/cooling and AHU heating/cooling.

Table 4.2: Comparison between the different testing procedures for the detailed model in IDA-ICE in order to assess the high ventilative heating

Description	*Balancing air flows [kWh/year]*	*CO_2 [kWh/year]*	*Radiator [kWh/year]*
Zone cooling	36 755.0	10 312.1	10 392.4
AHU cooling	26 574.0	14 087.7	13 858.2
Total cooling	**63 329.0**	**24 399.8**	**24 250.6**
Zone heating	161 501.0	143 552.0	292 629.0
AHU heating	286 445.0	420 500.0	358 105.0
Total heating	**447 946.0**	**564 052.0**	**650 734.0**

The main differences shown in table 4.2, are the zone cooling, as well as the big differences in ventilative

heating from the air handling unit. In the balancing of the air flows, where air supplied are the same as the air extracted for each individual zone, the AHU heating is 286 445.0 kWh, which is through this testing procedure the closest value compared with the measurements from the simulation testing.
Increasing the radiator capacity was done before introducing the balancing of the air flows, and has as a consequence higher ventilative heating. This is connected to that more air is leaking through the building envelope.

4.1.1 Radiator capacity

The radiator heating seen in the table 4.2 was 358 105.0 kWh, which is too high compared with the measurements by Alfstad [5] at 87 500 kWh for ventilative heating. Increasing the radiator capacity consequently led to higher zone heating considering the radiators has capacity to cover more of the heating demand in the building.
Even though increasing radiator capacity led to and enhanced possibility to cover peak demands of the building, the electric heating peak demand arose to 103.5 kW, while district heating peak demand were 474.5 kW. In reality, the peak demands should be covered by the heat pump, not the district heating. The maximum heat supplied comparing all zones of the model show a maximum heat supplied of 189 W/m^2.

The air handling units were to some degree affected by increasing the radiator capacity as it was previously tested. From table 4.3, the ventilative heating from each air handling unit of the building are experiencing a great deal of variation from 103 241 kWh for 360.01 to 46 311 kWh for the parking garage AHU.
The different air handling units supply air to their assigned vertical section of the building, and it might be fair to assume that 360.01 has a bigger surface area to cover for each floor [1] & [2]. It is most likely also covering an area that are faced towards an external surface.

Table 4.3: Air handling units energy from increasing the radiator capacity

AHU	*Heating [kWh]*	*Cooling [kWh]*	*AHU heat recovery [kWh]*	*AHU cold recovery [kWh]*
360.01	103 241	3 258	276 356	299
360.02	96 833	3 196	246 229	230
360.03	61 627	3 212	268 838	259
360.04	50 093	3 058	293 436	291
360.05	46 311	1 135	166 590	376

As seen from the table 4.3, the AHU 360.05 still has ventilative heating, as the heating coil was not turned off during the simulation. But it is expedient to show the results from it, as it show how much the ventilative heating can be reduced by removing heating from the parking garage facility of the office building.
As seen in the table, the AHU cooling is not of a significant value as it amounts to about 3 000 kWh per AHU. The cooling will be at a higher level in the final results shown in chapter 4.2, as the internal gains have been modeled correctly here. The AHU heat recovery is as seen larger than the ventilative heating, and it will also be reduced when the air flow balancing has been initiated in the model.

4.1.2 CO_2 ventilation

The attempt to regulate the entire building through CO_2-sensors went more or less as expected, as it increased the ventilative heating substantially. The testing resulted in reaching its all time high in regards of a ventilative heating demand of 564 052.0 kWh.
As seen in table 4.2, the total heating is lower than for the radiator but still higher than both the balancing of the air flows as well as the measurements done by Alfstad shown in table 2.3. The maximum heat supplied to a single zone was found to be 357.9 W/m^2. This is the highest value of the three strategies in regards of the testing procedures.

From the strategy of using VAV with the software set CO_2 level, did not work out. The air handling units were operating at all times. This was caused by the effort of maintaining a satisfying ppm level of CO_2, which made the air flow rates higher than what they should be. Since the ventilation system was not balanced on a zone basis at this time, it only made the leakage heat losses through the building envelope bigger.
As seen in table 4.2, the zone heating is at its lowest for the CO_2 control strategy at 143 552.0 kWh. The ventilative heating overruns the radiator heating because of the CO_2 strategy, and this may be the main reason for the low radiator heating from the simulation.

In table 4.4 the results for the five different air handling units are shown for the CO_2 controlled testing. The ventilative heating has the highest value for AHU 360.01 and 360.02, which are quite similar with the other two testing procedures.
The heat recovery is less than for the balancing of the air flow rates. This might be caused by that the internal gains had been modeled when the testing for balancing of air flows was undertaken. The table indicate that the CO_2 control strategy led to high AHU heating, considering the air flow rates are higher than for the other modeling strategies results.

Table 4.4: Air handling units energy from CO_2 control

AHU	*Heating [kWh]*	*Cooling [kWh]*	*AHU heat recovery [kWh]*	*AHU cold recovery [kWh]*
360.01	127 738	3 344	236 052	242
360.02	132 233	2 985	161 624	144
360.03	64 328	3 349	260 098	227
360.04	50 271	3 267	290 968	267
360.05	45 929	1 143	166 970	372

4.1.3 Balancing air flows on zone level

From balancing the air flows, the AHU heating is reduced significantly as seen from table 4.2. When air is no longer leaking through the building envelope, the heating demand is at a lower level than before the balancing were initiated. From the zone heating, the radiators have a lower degree of heating than the measurements indicate.
The radiator heating should be around 246 710 kWh. In the table it is simulated to be 161 501 kWh, which is much lower than expected. This may be connected to that the model in IDA-ICE has better insulated building envelope than the real office building at ONV12E. Also, the part of the model that has unintended openings, are set to adiabatic zones in the IDA-ICE model. This will then indicate a lower degree of heat loss in the model.

The simulation revealed that the maximum heat supplied to a zone were 183,5 W/m^2. This means that the peak heating demand for the model has been reduced by forcing the air handling units to supply and extract air in the same zone. By this, there is a minimum of air leakage, as well as most of the air passes through the heat recovery in the air handling units. The simulation results regarding the air handling units are shown in table 4.5.

Table 4.5: Air handling units energy from balancing the air flows

AHU	*Heating [kWh]*	*Cooling [kWh]*	*AHU heat recovery [kWh]*	*AHU cold recovery [kWh]*
360.01	93 637	5 247	583 117	814
360.02	45 738	5 300	424 911	376
360.03	35 648	10 606	438 606	318
360.04	68 178	4 117	392 438	415
360.05	43 241	1 305	169 494	319

The results from the table makes it clear that the balancing of air flows had an improving effect on reducing the ventilative heating of the office building. An overall comparison with the simulation results from testing the increased radiator capacity shows that the ventilative heating has been reduced on most of the air handling units.
The heat recovery has increased for this particular testing as well. This is connected to that the testing with balancing of air flows was done after the internal gains were modeled in the IDA-ICE parameters of the simulation process. Increased internal gains led to higher demand for ventilative cooling and likewise a higher degree of heat recovery in the air handling units.

4.1.4 Infiltration losses and delivered energy

In table 4.6 the infiltration losses are shown for each of the ventilative heating reduction strategies. The balancing of air flow rates has shown to be efficient in order to reduce the infiltration losses due to air leakages. The main problem with the model was in general to extract and supply air between different zones, as it led to over-pressure in each zone.
Moreover, this made hot air leak out of the building envelope. The difference in infiltration losses during heating between the radiator capacity and balancing air flows shows that the strategy of balancing the air flows worked in regards to reduce infiltration losses.

The CO_2 control has quite low infiltration losses, such that it show a positive value. The reason for these results remain unclear, but considering the air flows have been CO_2 controlled, they might use both supply and extract in this case as well. By this over-pressure inside each building zone has been avoided. During heating the balancing of air flows infiltration losses are about - 3 891 kWh, while the CO_2 control has a positive value of 1 372 kWh. The positive value may also be caused by some sort of under pressure during the summer, which creates a suction of hot air in through the building envelope.

The biggest difference between the three different strategies appears to be during cooling in regards of balancing air flows and CO_2 control. While the increasing of radiator capacity seems to differ the most from the two others during what IDA-ICE labels as ”Rest of time”. It is fair to assume that ”Rest of time” is when there is no need for neither cooling nor heating.

Table 4.6: Infiltration losses with the three strategies in comparison

Description	*Radiator capacity [kWh]*	*Balancing air flows [kWh]*	*CO_2 control [kWh]*
Total	-208 000	-16 537	76
During heating	-167 375	-3 891	1 372
During cooling	-4 018	-9 050	1 740
Rest of time	-36 606	-3 595	-3 036

When the three ventilative heating assessment strategies are compared with the consideration of delivered energy, it is possible to notice that the final step, which is the balancing of the air flows is not the most energy efficient option in this case. As seen in table 4.7 both the peak demand and the total delivered energy is the largest for the balancing of air flows, and the lowest for the CO_2 control.

Table 4.7: Comparison of delivered energy for the three options

Description	*Radiator capacity*	*Balancing air flows*	*CO_2 control*
Total peak demand [kW]	789.40	928.40	582.4
Total delivered energy [kWh/m^2]	96.52	118.60	84.45
Total delivered energy [kWh]	812 971.90	999 333.9	711 393.7

If the values in the table are compared with the previous simulation run undergone in the specialization project [6] shown in chapter 2, it is clear that the energy demand has increased. From 89.4 kWh/m^2 to the highest of 118.60 kWh/m^2. This can be more or less explained by that the internal gains that were modeled in the master thesis based on the electrical meters of the real office building, has made the electricity consumption increase.
If the balancing of air flows is compared to the increased radiator capacity and CO_2 control, the two strategies have values more close to the specialization project modeling, while balancing air flows has higher values since the internal gains were modeled previous to this simulation run [6].

4.2 Results and analysis of the final improved IDA-ICE energy model

In chapter 4.2 " Results and analysis of the final improved IDA-ICE energy model" the final simulation results are analyzed from the completed IDA-ICE model of the office building. These results mainly focus on determining if assessing the ventilative heating problem succeeded, as well as looking into the internal gains with special focus on the occupancy modeling strategies.

4.2.1 Sensitivity analysis of the simulation results in regards to the thermal energy system measurements

I table 4.8 the final simulation results are shown. They are in this table compared with the measurements that Alfstad analyzed in her master thesis [5]. From the initial view of the simulation results, the outcome looks promising. The local cooling is deviating by 68%, contrarily for ventilation cooling the results are more or less sufficiently accurate with a simulated result of 24 581 kWh and a measured result of 21 290 kWh.

This may indicate that the modeled internal gains for the office building are accurate enough in regards of cooling.

Table 4.8: Comparison between the measured data from ONV12E and the simulated energy consumption from implementing measured data in the final IDA-ICE model, [5]

Description	*Measurement [kWh/year]*	*Simulation [kWh/year]*
Local cooling	5 946	1 903.8
Ventilation cooling	21 290	24 581
Process cooling	87 371	34 241
Total cooling	**114 607**	**60 725.8**
District heating	**40 680**	**21 062.8**
Ventilation heating	87 500	94 558
Floor heating	15 825	27 996.5
Radiators & convectors	246 710	177 075
Snow melting	66 670	-
Total heating	**416 705**	**299 629.5**
Domestic hot water	**65 485**	**64 084**

The simulated process cooling is still lower than what should be expected from the measurements with a value of 34 241 kWh. The results should have been 87 371 kWh. The difference in process cooling might be connected to different internal gains or alternating set points for temperature in the laboratory where most of the process cooling takes place.
In total, the cooling demand amounted to 60 725.8 kWh for the simulation, and 114 607 kWh from the measurements. This means in total that the simulations deviated by 47.1%. The main cause for deviation was connected to the big difference in process cooling.

The district heating is from the simulation 21 062.8 kWh, which is about half of what the measurements indicate. The district heating is generally used in the model when peak demands are larger than what the radiator capacity and the ventilative heating are capable of covering.
For the real building, the district heating is only applied when the heat pump is not operating, such as when maintenance is due [5]. The difference among the simulation results and the measurements can be linked to the increased radiator power, as it was increased during the modeling procedure in the master thesis.

Throughout the master thesis work it has been one of the main goals to reduce the ventilative heating. As mentioned in the specialization project, the ventilation heating has been overestimated in the previous simulations [6].
From the final simulation results shown in table 4.8, the ventilative heating has been significantly reduced. The simulated ventilation heating is now 94 558 kWh, while measurements indicate 87 500 kWh. This leads to a deviation of 8%, which is accurate enough for the modeling undergone in this master thesis.

The floor heating amounted to 27 996.5 kWh for the final simulation. If compared to the measurements for floor heating, the deviation is about 77%. The floor heating in the model has been simulated with floor heating both in the Atrium and wardrobes, and the demand for floor heating could most likely have been lower if there were radiators in the Atrium and wardrobes.
The differences between simulation and measurement can in this case be caused by different modeling strategies of the floor heating in terms of surface temperature regulation. Additionally, the office building at

ONV12E has a temperature compensation curve, while it was not possible to model this curve in particular for the floor heating.

In figure 4.1 the difference between the measurements and the simulation in IDA-ICE are illustrated in a pole diagram. From the figure, the biggest differences amount through the radiators and convectors for heating and the process cooling. Consequently as the radiators should be increased in the simulation, the low radiator heating can be caused by a too well insulated building envelope in the model as IDA-ICE is additionally neglecting losses through door openings. This will be further discussed in chapter 5.
The process cooling demand from the simulation is lower than the measurements, which means that the internal gains should be increased. In this case the internal gains from equipment could be concentrated towards the laboratories alone so that the same energy consumption from equipment only applies for the laboratories at the basement floor level.

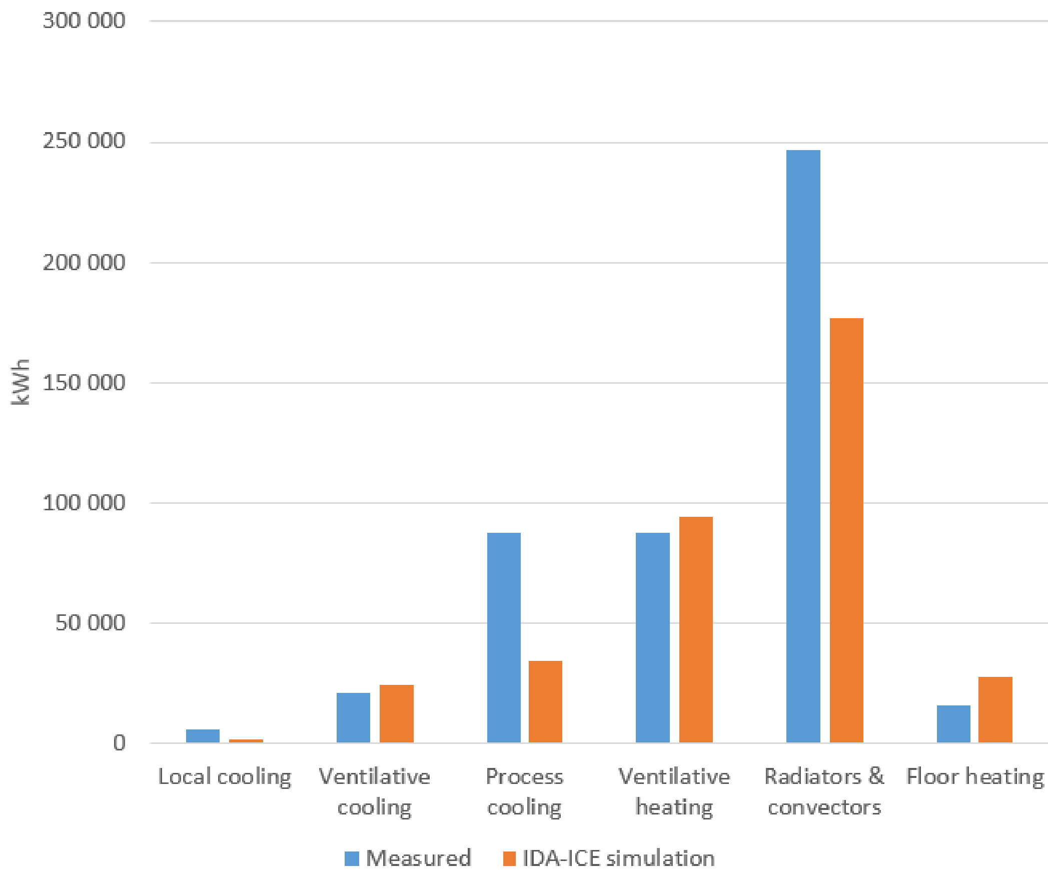


Figure 4.1: Projected heating and cooling for IDA-ICE simulation compared to Alfstad's measurements [5]

The radiators and convectors thermal energy usage shows from the simulation 177 075 kWh, while measurements are showing 246 710 kWh. This gives a deviation of 28.2%. The accuracy of the energy demand for radiators can be considered accurate enough, although the results should be closer to what the measure-

ments indicate. The cause of different results in regards to simulation versus measurements, can be related to that the IDA-ICE model has a better insulated building envelope. The snow melting facility has not been modeled in IDA-ICE, and it is mentioned in the table only to be clarified as a part of the total heating in the measurements.
The total heating demand for the simulation was 299 629.5 kWh, which is significantly lower than the measured values at 416 705 kWh. This accordingly gives an overall deviation for heating to about 28.1%. One of the possible causes of this is the snow melting facility at ONV12E, which was not included in the IDA-ICE model. The residual difference is from the disparity in radiator heating, which will be further commented in chapter 5.

The domestic hot water demand is accurately enough modeled, as the simulations give 64 084 kWh compared to 65 485 kWh from measurements. The domestic hot water demand is modeled based on the measurements, and it should therefore not come as a surprise that the measurements and the simulations are more or less equal.

The total heat delivery for ventilation heating and radiator heating was 349 299 kWh for the measurements of Alfstad [5]. While the simulation results calculated a heating demand for ventilation and radiator heating at 299 629.5 kWh, which is significantly lower than the measurements indicate. However, the measurements includes a testing period during the two first months of operation which is during May and June of 2017. During this period all valves were open and maximum heating and cooling were running in order to regulate the system [5]. Also the electricity consumption did not get started before the first of July, which reduced the cooling demand the first months of the simulation considering equipment data were lower for these months [5].

4.2.2 Sensitivity analysis of simulation results compared to Simien As-built simulation

The Simien simulation As-built report by Haavi and Fjær [3] was initially used to size the buildings energy need for heating and cooling. In this section the As-built report is compared to the IDA-ICE simulation in order to detect differences, and to use it for validation and verification of the simulation model. The comparison is illustrated in a pole diagram shown in figure 4.2.

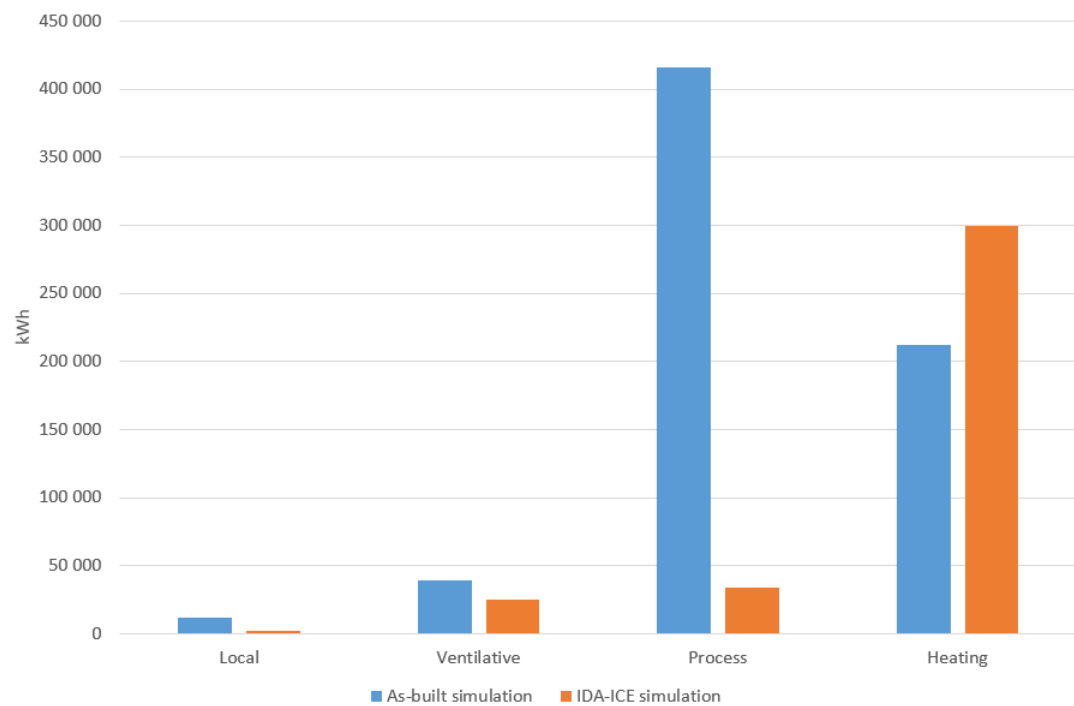


Figure 4.2: Projected heating and cooling for As-built simulation [3] compared to IDA-ICE simulation

From the pole diagram it is clear that the simulations have some major differences regarding the demand for cooling. As seen from the measurements of Alfstad, the As-built simulation deviates from the measured process cooling by 79%. While for the IDA-ICE model, the process cooling is 47.1% which is too high, but still closer to the measurements than the As-built simulation. This comes from that the process cooling demand were highly overestimated in the projection stage [5]. The process cooling could be increased especially for the laboratories in particular to be able to increase the simulated process cooling. Two of the laboratories experiences maximum temperatures up to 40 ^{o}C, which means that it is possible to further increase delivered cooling to these zones in the IDA-ICE model.

The heating demand is more or less the same for both Simien and IDA-ICE. Both software estimate a lower heating demand than what the measurements indicate. The Simien simulation deviates by 65%, while the IDA-ICE model deviates by 16,8%. This indicate that the model is valid and verified in terms of sufficient accuracy when comparing it with the Simien software. Nevertheless, the modeling parameters between the two programs are widely different, which creates uncertainties in comparing the results. The main point of this comparison is to evaluate how to better size the heating and cooling demand through using detailed measurements instead of sizing heating and cooling based on standards.

4.2.3 Simplified model vs. Detailed model

Comparing the detailed model with the simplified model, the results showed that there was significant differences in terms of cooling. Both local and ventilation cooling were higher in the simplified model than in the detailed model, quite similar with the As-built simulation. The differences are shown in figure 4.3. In this case, the heating demand is largely underestimated in the simplified model in terms of that the heating is through ideal heaters and coolers, as well as that the ventilation system is constant air volume instead of variable air volume.

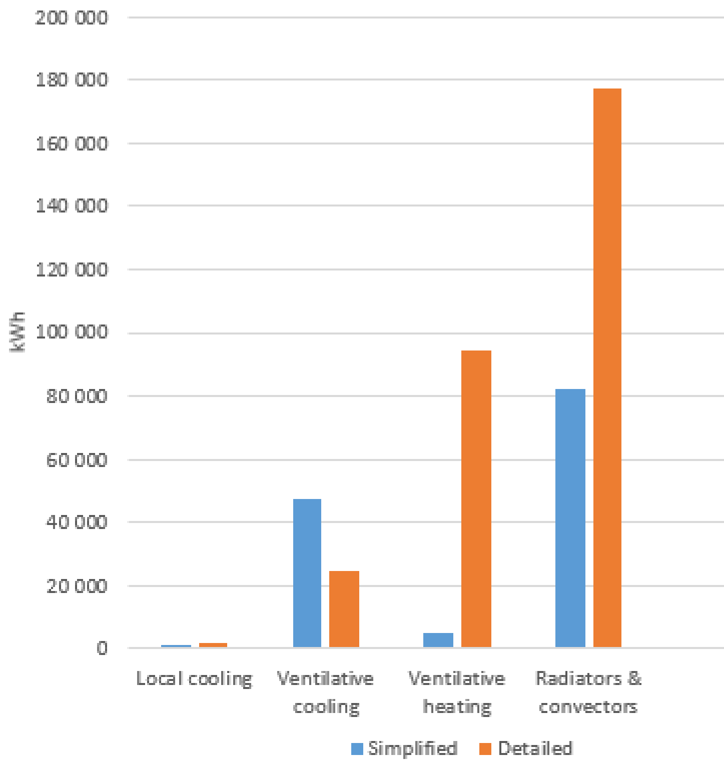


Figure 4.3: Projected heating and cooling for simplified model compared to the detailed model

4.2.4 Energy consumption for each floor level compared with the measured energy consumption

In this section the energy consumption is analyzed at each floor level to enable the comparison between the measurements from electrical meters and the simulation results. This will be helpful in order to indicate to what degree the modeling of equipment and lighting has been successful.

In table 4.9, the energy consumption for each floor level is shown with respect to local heating - in the shape of radiators and floor heating, and local cooling through the modeled local cooling units. Infiltration has also been included in the table to compare heat loss for each floor level, and in order to detect faults in the model.

The basement has the lowest energy consumption for local heating units at 13 704.9 kWh. The main reason for this is that the internal gains from equipment is the highest at this floor level. Also, the basement has the parking garage as well, which does not contain local heating units. From the results it is also noticeable that the local cooling units for the basement has the highest amount of energy in regards of cooling. This is also connected with the high degree of heating from equipment at the basement level with a local cooling at 1 812.4 kWh.

Table 4.9: Energy consumption from local heating and cooling units per floor level of the simulated improved model at ONV12E

Floor level	*Local heating unit [kWh]*	*Local cooling unit [kWh]*	*Infiltration* [kWh]
Basement	13 704.9	1 812.4	265.0
1st floor	47 846.9	67.1	13 155.0
2nd floor	17 167.2	11.3	642.7
3rd floor	14 766.9	11.7	596.0
4th floor	18 804.3	1.2	1 485.4
5th floor	16 662.5	0.0	888.7

From the 2nd floor an up to the 5th floor, the heating and cooling are more or less the same, which is as expected. It is to a bit peculiar that the 5th floor has the same amount of heating as the rest of the office floors, considering that the 5th floor has less floor area, no general heating, and is where the air handling units are located.
But it is also worth to mention that this part of the building has external walls in both northern, southern, eastern and western directions which increases the heat loss as well as a minimum of window surface for solar heating.

The 1st floor has the highest energy usage for local heating units with 47 846.9 kWh, which is majorly higher than the other floors. To begin with this might appear somewhat odd, but the logical explanation would be that the Atrium is considered as part of the first floor even though its zone stretches all the way up to the 4th floor ceiling.
Additionally, the amount of local cooling is higher for the 1st floor, which may come from heat rising towards the Atrium ceiling creating a higher cooling demand.

The values for infiltration seems more or less consistent for all floors with the exception of the 1st floor where the Atrium is included. Because of the Atrium, it is natural that the 1st floor has higher infiltration losses, considering the Atrium glass facade has higher heat losses than the remaining facades. The 4th floor has slightly higher infiltration losses than the other floors, which is somewhat strange.
The high losses of the 4th floor might be explained by that parts of the 4th floor roof is external, and therefore the losses are higher here than for the other floors. This can also be seen for the infiltration losses for the 5th floor, which is slightly higher than floors 2nd and 3rd.

The energy consumption per floor level for equipment and lighting is compared with the electric meter measurements per floor in table 4.10. The measurements in table 4.10 is rendered from table 3.3.
The reason for representing the equipment and lighting in this table from the simulation results, is mainly to check if the internal gains from equipment and lighting has been modeled correctly in the IDA-ICE model. If the simulation results are not more or less the same as what the measurements indicate, this would mean that the scheduling and the energy consumption modeled has been faultily implemented.

Table 4.10: Energy consumption from equipment and lighting per floor level of the simulated improved model at ONV12E

Floor	*Equipment [kWh]*	*Measured$_{Equipment}$ [kWh]*	*Lighting [kWh]*	*Measured$_{Light}$[kWh]*
Basement	130 292.5	110 254	21 234.3	18 322
1st floor	20 735.8	24 849	9 814.7	9 033
2nd floor	23 479.0	29 950	7 808.2	7 719
3rd floor	24 856.2	29 327	7 204.2	7 326
4th floor	37 244.2	46 367	8 705.4	8 713

The basement energy consumption for equipment and lighting has the highest usage compared to all floors of the building. The equipment energy consumption is high due to the computer lab in the basement, which has a high electricity consumption. The lighting is also high, which comes from that the parking garage has a bigger floor area than for the other building floors.
Comparing the simulated equipment usage with the measured usage, it is a deviation for the simulation at 18,2%, which is accurate enough for the master thesis simulation. The lighting deviates by 15.9%, which is also an acceptable value.

The 1st, 2nd and 3rd floor has more or less the same consumption for both equipment and lighting, with small deviations between measurements and simulation results. The 4th floor experiences a higher demand for both equipment usage and to a certain degree, lighting.
The simulation estimations are deviating from the measurements by 19.7%, which is acceptable. It is however somewhat odd that the usage of equipment for this floor level is higher than for the other floors.

4.2.5 Used energy

In table 4.11 the used energy is shown in kWh/m^2, and the peak demand in kW. From the table it is possible to see that the highest energy demand of the building is the HVAC auxiliary, which is related to the operation of the air handling units. Electric heating is also one of the main energy consumption posts in the table, as this is related to the heat pump unit operation.

Table 4.11: Delivered energy per square meter

System	*Used energy [kWh/m^2]*	*Peak demand [kW]*
Lighting, facility	6.8	16.85
Electric cooling	0.2	47.54
HVAC aux	25.4	118.5
Electric heating	17.1	104.4
District heating	2.5	671.2
Equipment, tenant	28.1	70.35
Total	**80.0**	**1028.8**

The equipment energy demand is higher in energy demand than the other systems in table 4.11. This is related to the high electricity consumption from equipment, especially in the laboratories. District heating were not in use for the majority of the simulation run, however some of the peak demands which exceeded

the heat pump capacity made the district heating run at some times during the simulation, which lead to an energy usage for district heating at 2.5 kWh/m^2 during a peak load of 671.2 kW.
Most likely these peak values are connected to an implementation error in the weather data file.

The peak demands appear to be within reasonable limits from the simulations with the exception of the district heating, which has a higher peak demand than the heat pump heating capacity. This is not the case in reality, where the heat pump is sized to cover the entire heating demand at all times.
The district heating should only be in operation when the heat pump is due for maintenance. The highest peak load should not exceed 220 kW, which means that there is some faults in the IDA-ICE model that has not been accounted for [4].
The electric heating has a peak demand of 104.4 kW that is more within the expected limits regarding peak loads. The highest demand for heating is during the period of January, where the district heating is mainly operative.

One of the main problems with heat supply exists in the Atrium where heating demand is high. From the simulation, the heat supplied to the Atrium is 132.3 W/m^2. One explanation of the high heating demand is that in the IDA-ICE model there is radiators placed in zones that should not have heat supplied. For instance the toilets and corridors. In these zones there has not been modeled any internal gains from neither occupants or equipment, which means that the radiators modeled here must cover all the heating demand for the room. These zones should not be heated, but only benefit from excess heat leaking from adjacent offices, meeting rooms and co-working spaces.
It could therefore be beneficial for future simulations in such buildings to model occupancy schedules for toilets and corridors as well, but that these schedules should show opposites from the occupancy schedules in the offices, meeting rooms and co-working spaces during work hours. This would mean that if an occupant is not present, the occupant should either be in the corridors, copy room or in the toilets with the exception of during the lunch break.

Furthermore, it would be best to model this based on presence detectors in all zones of the building, but it would be somewhat difficult to go through with. The peak loads can be explained by that the radiators are placed in corridors, copy rooms and toilets without having any internal gains from occupants, which leads to high peak loads.

The reduction in peak loads will most likely affect the heating demand for the systems energy shown in table 4.12. The table represents a summary of the systems energy from the IDA-ICE simulation. For the zone heating the consumption should be about 240 000 kWh according to the measurements by Alfstad [5].

Table 4.12: Systems energy

Description	*Systems energy [kWh]*
Zone heating	177 075
Zone cooling	34 241
AHU heating	94 558
AHU cooling	24 581
Domestic hot water	64 084
Cooling	58 822
Heating	335 717

Figure 4.4 shows the radiator heating during a year long simulation. From the graph the highest heating

demand occur in January at about 32 000 kWh. From the measurements the combined ventilative heating and radiator heating adds up to 53 660 kWh during January. The AHU heating for January in the simulation is shown in table 4.6 and amounts to about 32 000 kWh as well, meaning that the heating demand for January for the simulations with regards of ventilative heating and radiator heating is 64 000 kWh.
This indicates that even though the heating demand estimation in total is lower for the simulation, if the two are compared for a single month the results may indicate otherwise. Comparing it with the As-built simulation, the total heating demand from ventilation and radiators for January were 35 673 kWh [5].

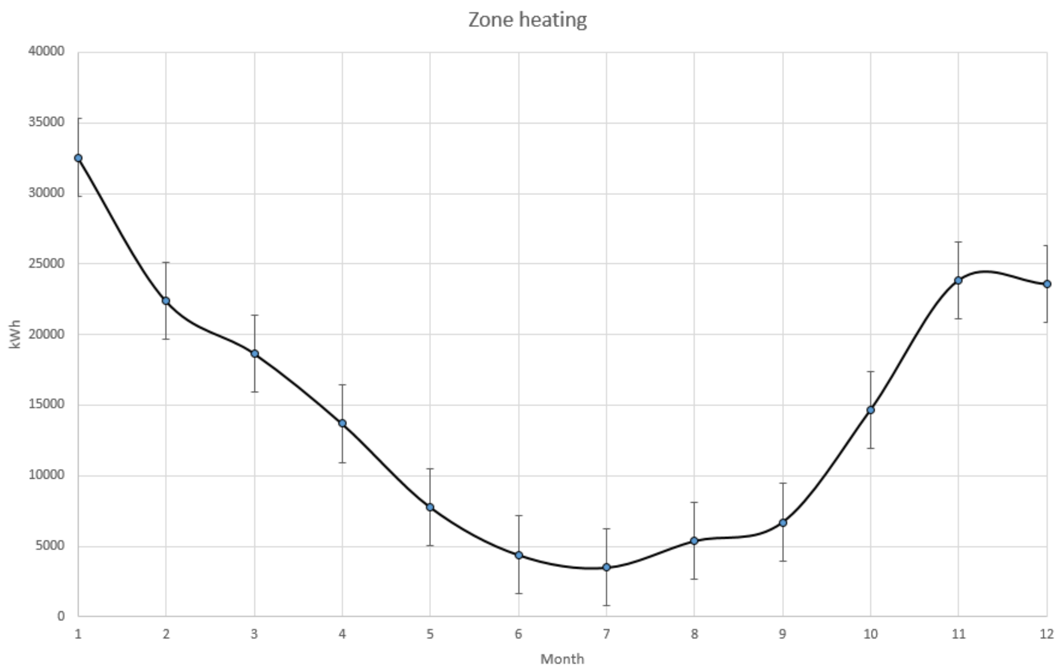


Figure 4.4: Zone heating per month of the year

In figure 4.5, the cooling demand for the 12 month simulation is shown. The local cooling units, which this applies for, are placed in the meeting rooms and laboratories. From the figure it is clear that the cooling demand is not a seasonal need. The cooling demand will in this case depend on the usage of equipment, as it applies for the cooling units at the selected zones.

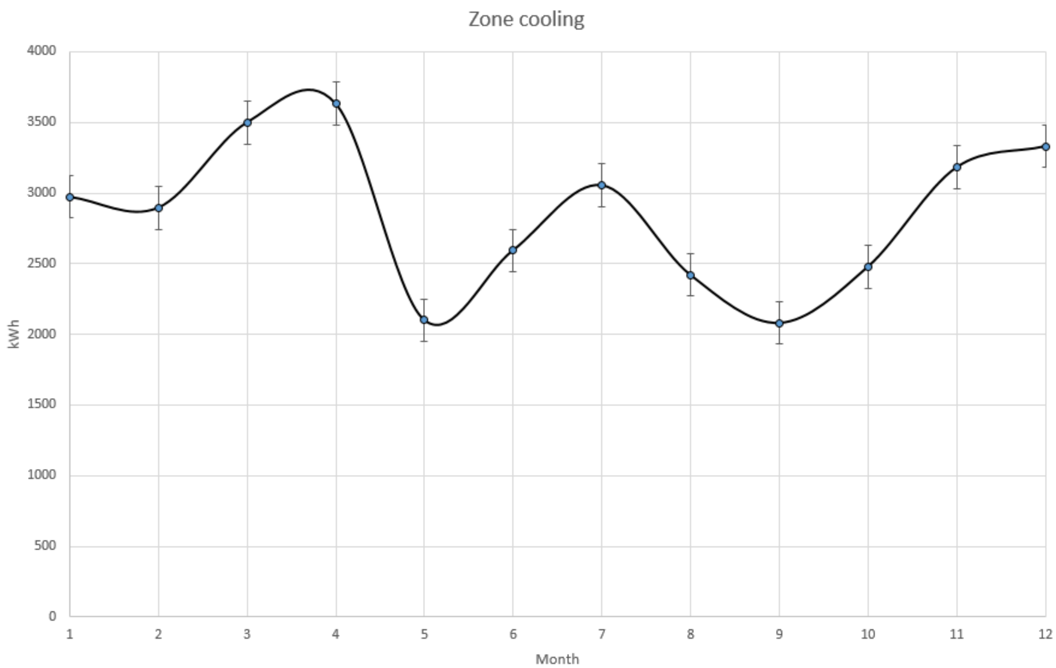


Figure 4.5: Zone cooling per month of the year

The air handling unit heating is sketched in figure 4.6. The heating demand is at its highest during January, and the graph has some similarities with the graph for radiator heating shown in figure 4.4. The AHU heating is modeled in IDA-ICE to only apply heat when the radiators are not capable of covering the peak heating demands. As seen from the AHU heating figure, the problem-months are January and February, while the remaining months have a more stable level of heat supplied from the AHU heating coil.

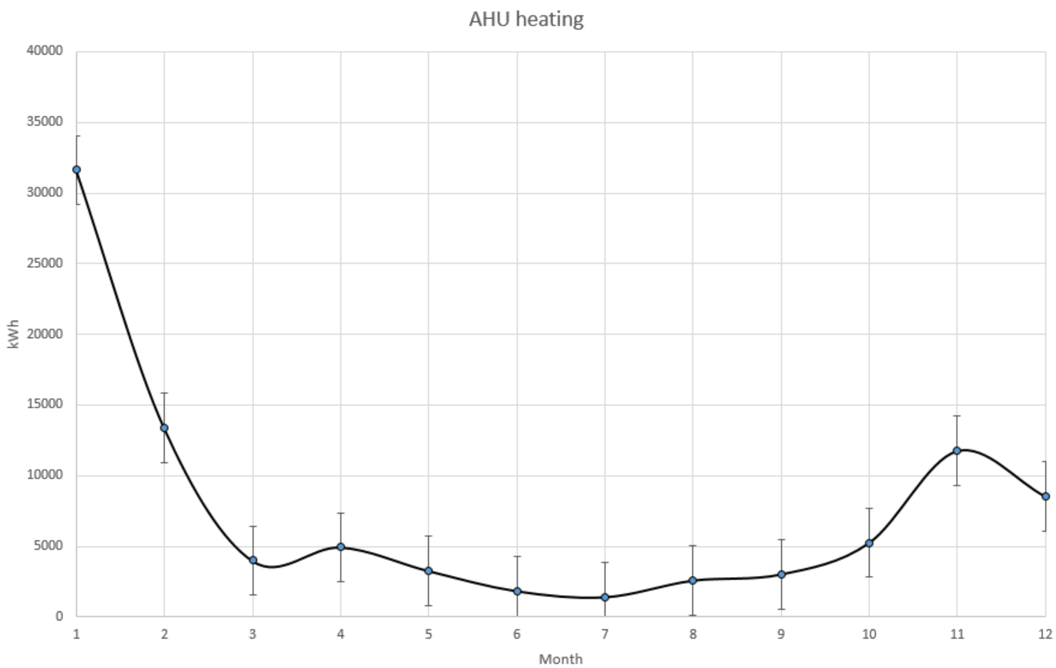


Figure 4.6: AHU heating throughout the year

The peak cooling demands from ventilative cooling is shown in figure 4.7. The graph show the total cooling demand for each month of the year, and helps illustrating when the need for cooling is at its highest. The figure show that the main need for cooling occurs during the month of July. The ventilation cooling applies for all rooms where the temperature regulation has an upper limit regarding temperature set points. The illustration of ventilative cooling corresponds well with what was expected when considering the weather profile for ONV12E.

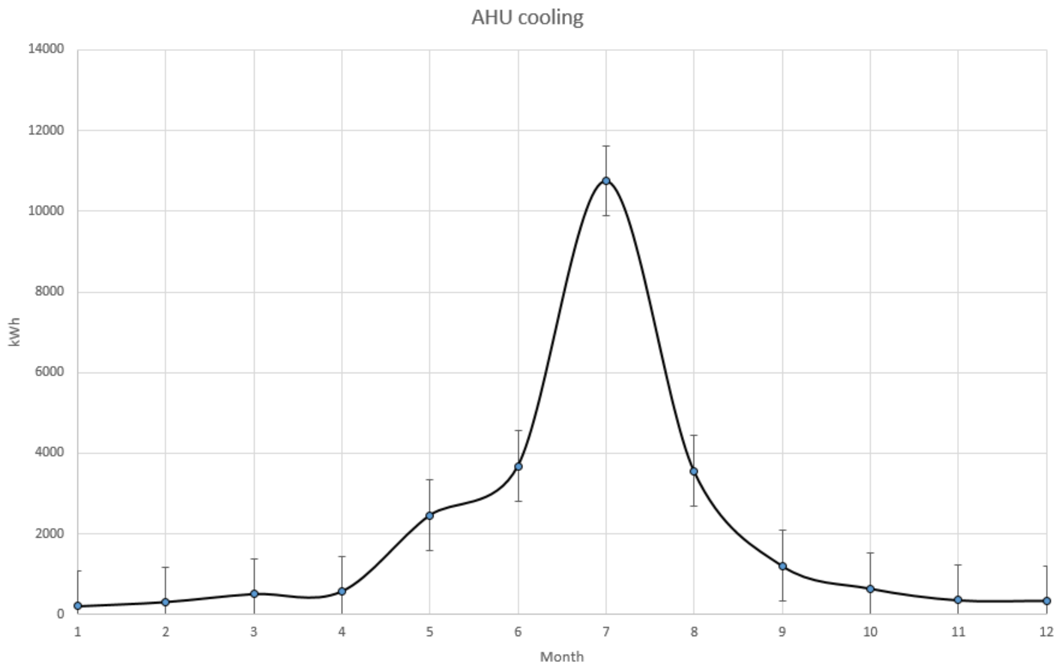


Figure 4.7: AHU cooling for each month of the year

The Utilization of free energy is an important factor in order to achieve a high energy performance building. In figure 4.8 the utilization of free energy from ground heat is shown. The heat pump extracts heat from the boreholes during periods of high heating demand, while delivering heat back to the boreholes during cooling mode in the summer months. The graph corresponds well with that assumption, and it is therefore possible to assume that the simulation has gone well in regards of heat pump operation.

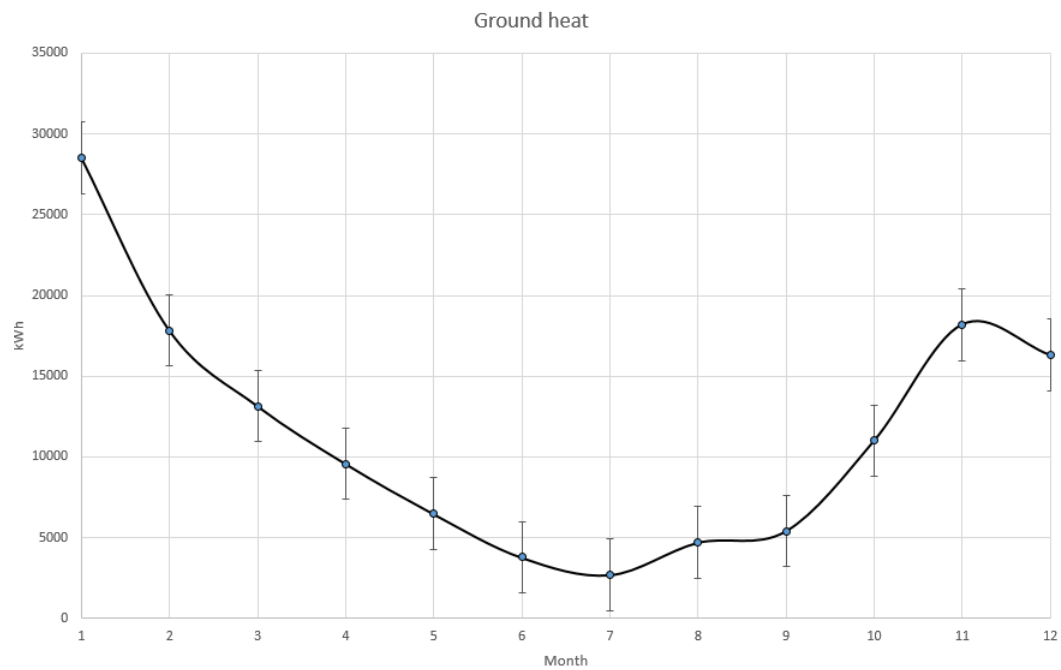


Figure 4.8: Ground heat per month from the boreholes

The utilized free cooling for the heat pump is shown in figure 4.9. The highest utilization is during July and complies with that the cooling demand is the largest during July. The maximum cooling extraction from the boreholes is about 12 000 kWh. Comparing the IDA-ICE results with the measurements for the period March to May, the heat delivered to the boreholes is 1 333 kWh. The level of utilized free cooling are in the simulation period March to May beneath 2 000 kWh per month, which in this case is more than measured. On the other hand, the first year of operation the building did not deliver the same amount of heat that was extracted. Because of this the measurements will be different than what the simulation shows [5].

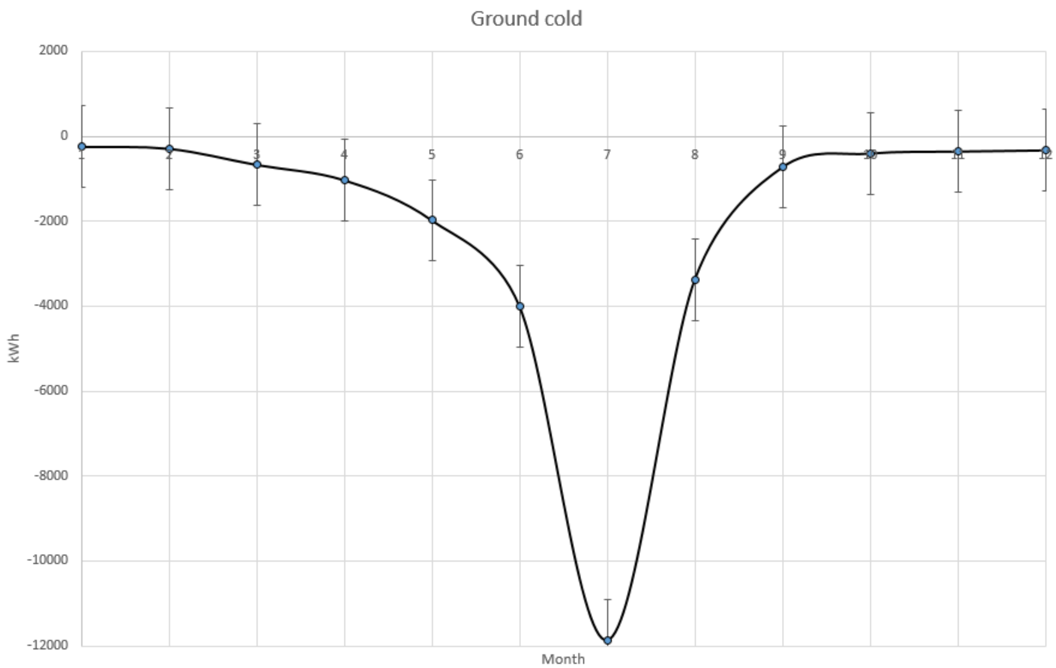


Figure 4.9: Utilized free cooling per month from the ground source boreholes

During supply and extraction of ventilation air, the heat from the extracted air goes through the heat recovery wheel of the air handling units. Most of the heat is recovered during high heating months such as January. At the most 148 000 kWh of energy is recovered in the heat recovery wheel in all air handling units combined. The heat recovery is illustrated in figure 4.10.

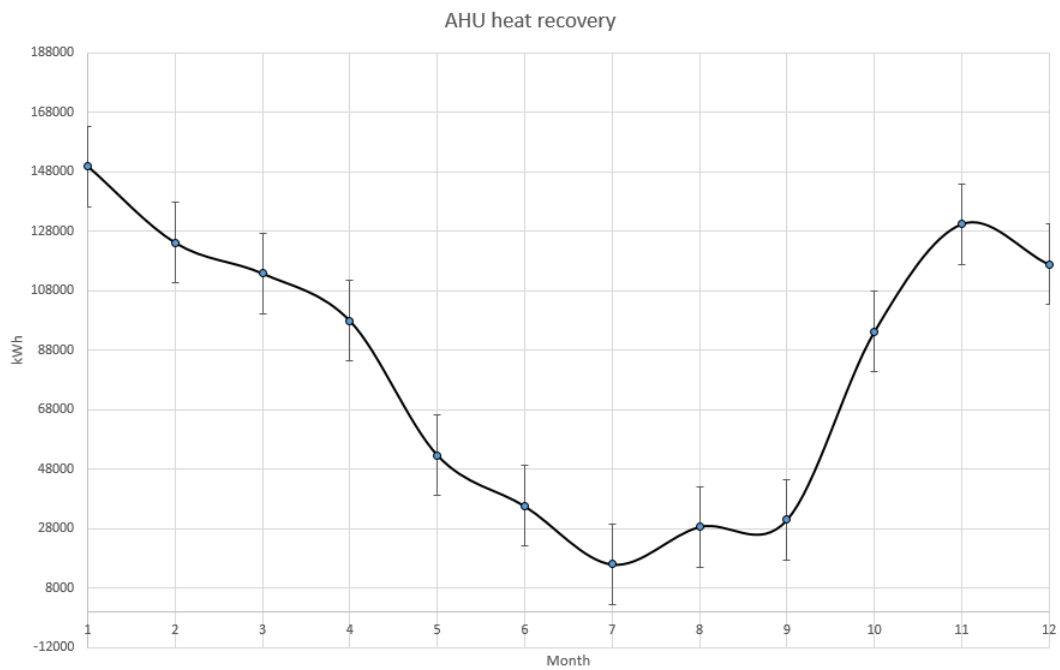


Figure 4.10: Heat recovered from the air handling units per month

As seen from figure 4.11, the distribution losses in the thermal energy system stays between 5 200 kWh and 1 800 kWh. The heat losses are most likely connected to the piping supplying hot water towards the radiators in the zones, and the heating coils in the air handling units. Much of the distribution losses are considered heat that is lost during the distribution towards zones. In the model this accounts for 50% of the losses. This means that half of the distribution losses are not utilized as heat. The distribution losses could affect the heating demand towards the radiators. If the distribution losses could be measured in the building operation system [2], the modeling could have more accurately estimated the losses and furthermore increased the heating demand in the energy calculations of IDA-ICE.

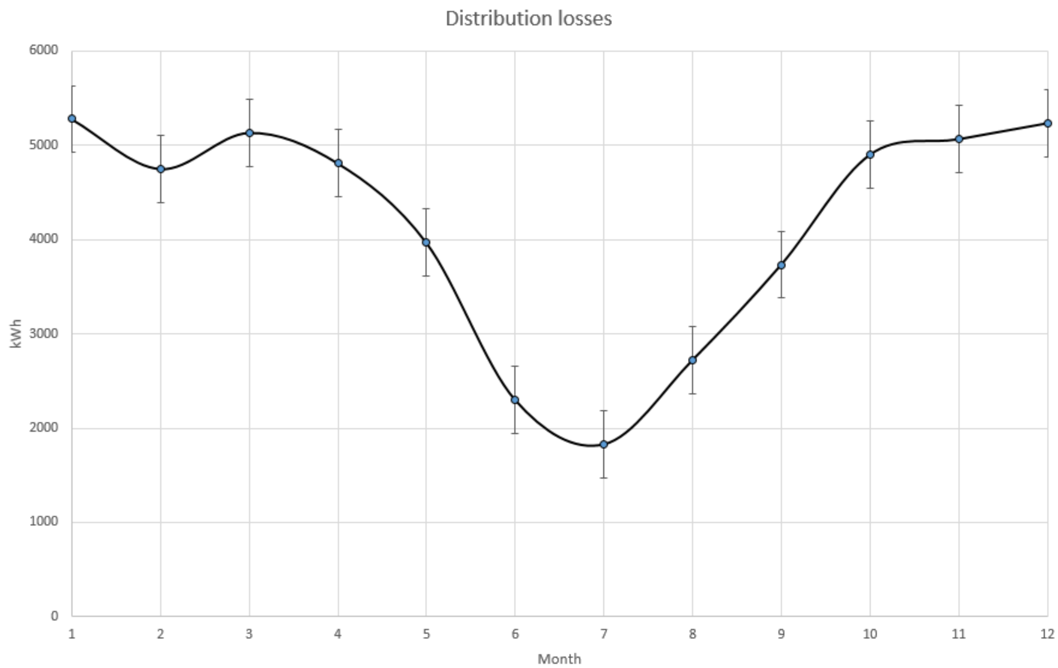


Figure 4.11: Distribution losses in the thermal energy system per month

The infiltration losses for the entire office building is shown in figure 4.12. The infiltration losses is at its highest during January at 2 465.3 kWh. The infiltration losses are more or less as expected considering it should be lowest during July. The infiltration losses are at its lowest during September, which is somewhat odd considering the temperature difference in September compared to the temperature differences in July. The infiltration losses are at a satisfying low level, which indicates that the building model in IDA-ICE has no openings that creates a high heat loss.

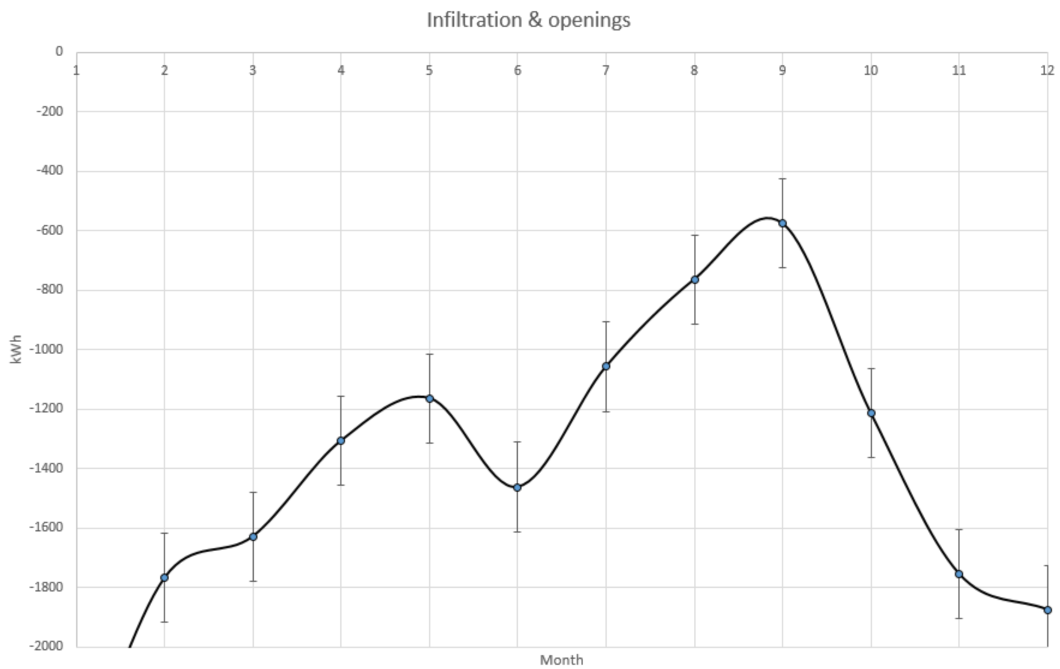


Figure 4.12: Lost energy through infiltration and openings per month of the simulation period

The electric heating of the office building show the electricity consumption of the heat pump unit in regards of heating. This will be the electricity used for supplying heat to the radiators, floor heating and heating coils of the ventilation system in the IDA-ICE model. Figure 4.13 shows the electricity consumption per month of the year with respect to heating. The maximum electricity consumption for heating has amounted to 25 000 kWh. This number fits well with the 64 000 kWh of heat delivered from the radiators and the ventilation heating, considering the heat pump has a COP of 2.6 for heating [7]. The electric heating curve otherwise matches with the other simulation results.

Comparing the electric heating of January with the electric meters in the building operation system, the electricity consumption for the simulation is approximately 25 000 kWh for January, while the electric meter 390.001-RE01_E connected to the heat pump shows about 45 339 kWh [2]. This also indicates that the sizing of the heating demand is lower than what the reality shows in the measurements. It is important to mention that the electricity towards the heat pump includes cooling as well, but it could be assumed that the electricity demand for cooling is significantly lower than the electricity demand for heating.

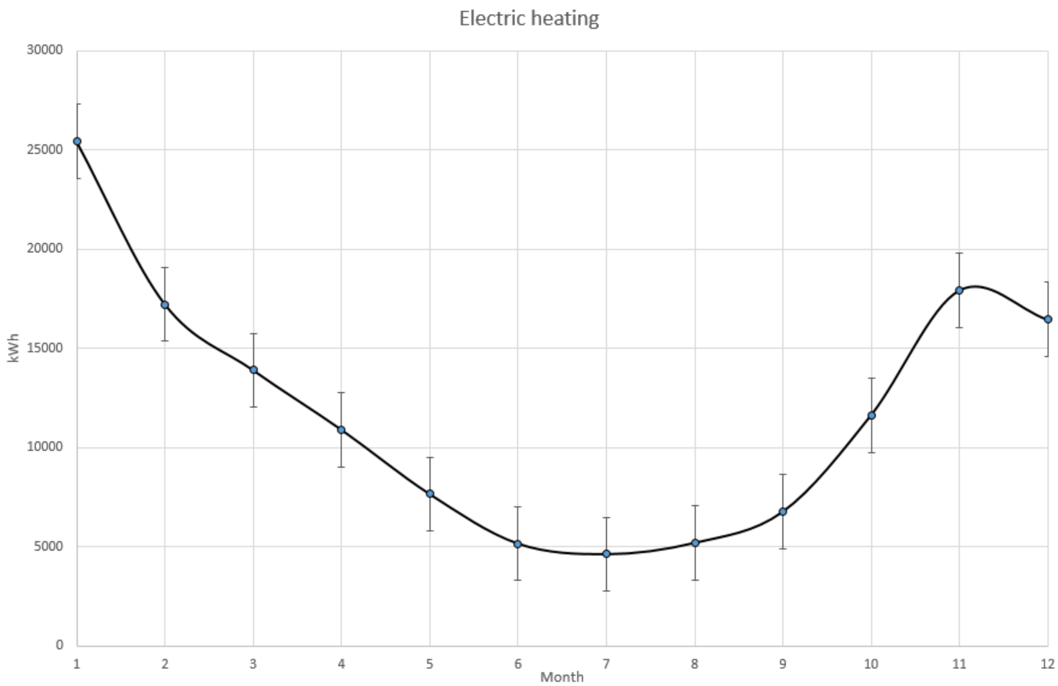


Figure 4.13: Energy used for electric heating

Examining the building operation system [2] showed that the air flow rate maximum and minimum set points in the laboratories were higher than what had been sized in the IDA-ICE model. The consequence of this modeling made the temperature in the laboratories exceed the 24 ^{o}C limit and reached approximately 40 ^{o}C before establishing equilibrium. When introducing cooling panels in the laboratories, the cooling demand increased by over 10 times as high as measured. With further testing it showed that increasing the air flow rates to match the building operation system would benefit ventilative cooling, and reduce zone temperatures in the laboratories.
It has also been noticed that the BOS show a temperature between 40 and 50^{o}C during some hours of the day [2]. This would indicate that the temperature set points do not comply with the rest of the office building, or that the process cooling is not capable of covering the cooling demands.

In figure 4.14 the cooling for the building is shown with respect to the previous set points for air flow rates. The figure shows that the electricity per month is lower than the measurements indicate.

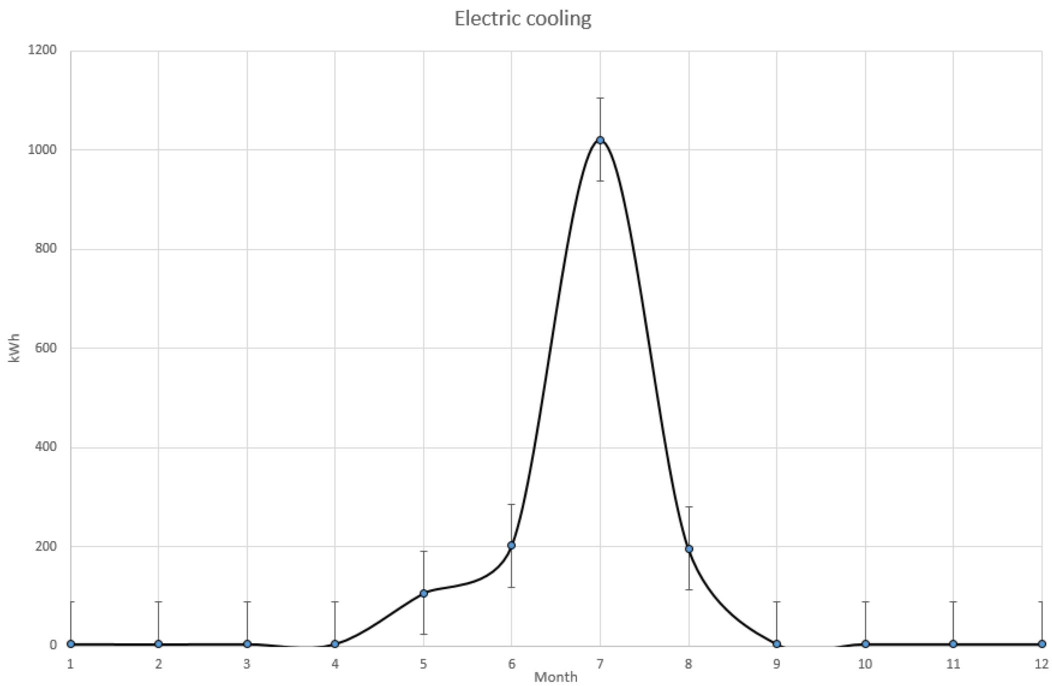


Figure 4.14: Energy used for electric cooling

4.2.6 Internal gains

In this section the internal gains from the simulation results is shown and compared with the measurements and expected input data. In figure 4.15 the energy input from equipment, lighting and occupants are shown. From the figure, the equipment has the highest energy consumption, while lighting and occupants have significantly less. The lighting should also be considered 80% less than what is accounted for in the table, as it is possible to consider the lighting to be LED, which indicates a thermal supply from lighting energy consumption at 20% [21].

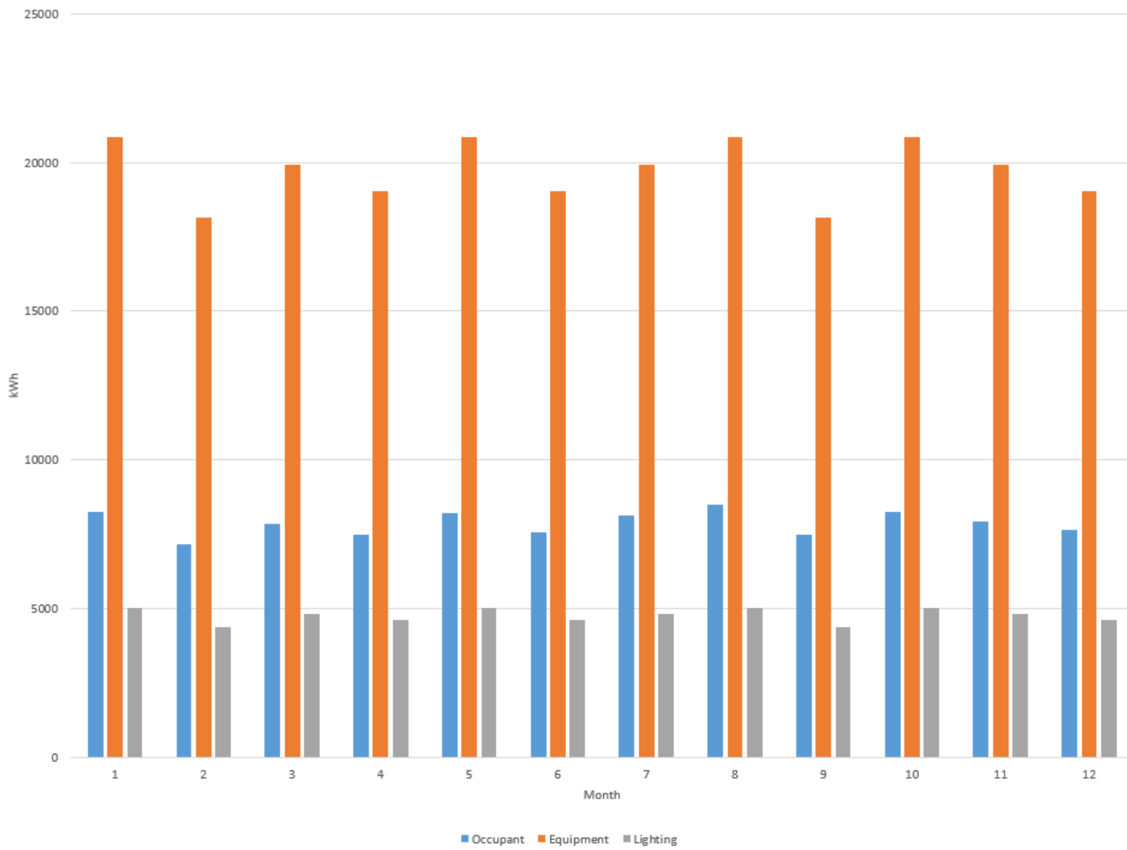


Figure 4.15: Energy used for the internal gains of ONV12E IDA-ICE model

Considering the equipment, the lighting and the occupant schedules are based on work days that goes through the entire year, it is possible to see from the figure that the internal gains are more or less at the same level through every month of the year.

To be able to compare the different scheduling solutions in regards of CO_2 measurements and the ventilation air flow schedule approach, it is decided to compare the three room types office, meeting room and co-working space. Three rooms at the 2nd floor has been investigated in regards of delivered heat, occupant hours and ppm level of CO_2.

The co-working space selected from the IDA-ICE simulation has 5 120 hours of usage, which is quite similar with the office room that has 5 145 hours of usage through a year. Both of the rooms should have approximately the same amount of hours considering both spaces are normally in use from 08:00 to 16:00. The meeting room chosen has 2792 hours of usage, which is significantly less than the the two other room types.
If the ISO 17772-1 schedule for occupancy had been used, most of these rooms would have more or less the same amount of hours. However, when using the CO_2 measurements for modeling occupancy of the meeting

room, it considers a more varying amount of people throughout the day, but also less hours of usage. It could also be possible that if the co-working spaces and offices were modeled based solely on occupancy detectors instead of ventilation air flow rates, that the number of occupant hours would be less.

The carbon dioxide maximum ppm levels are 1003 ppm for the co-working space while it is 1325 ppm for the office. The ppm level of CO_2 may depend on the volume of the room and also the density of occupants. The meeting room has a ppm level of CO_2 at 795, which looks promising considering the ventilation strategy of the meeting rooms. The meeting rooms normally stays around 600 ppm for most measurements done in the building operation system [2].

The maximum supplied heat to the co-working space is simulated to be 61 W/m^2, while the office space showed 44.56 W/m^2. These two zones has the same type of occupancy scheduling, but there is a big difference in room size and therefore also peak heating demand.
The meeting rooms has a maximum supplied heat of 58.65 W/m^2, and have a different occupancy scheduling. This may indicate that the internal gains from occupants modeled through measurements may not reduce peak loads in a significant manner, but that they reduce the general heating demand.

4.2.7 Air handling units

In table 4.13 the energy consumption for the air handling units are shown for the detailed model. The table renders the heating, cooling, heat recovery, cold recovery and fans of each air handling unit for the building model. When comparing the air handling units energy consumption with the results shown from the specialization project table 2.6, it comes clear that the energy from heating coils in each unit has been significantly reduced [6].

Comparing the air handling unit 360.01 from project work of the autumn of 2019 [6] to the current thesis work, it shows that the project results have a heating demand of 112 021.0 kWh, while the improved simulation shows an energy consumption in the heating coil of 45 163.0 kWh. Comparing project AHU with thesis AHU heating in total, the most significant difference occur for the totals, which amounts to 339 980.0 kWh in the project simulations, and 94 555.4 kWh in the thesis simulations.

Table 4.13: Used energy for the air handling units from the detailed model

AHU	*Heating [kWh]*	*Cooling [kWh]*	*Heat recovery [kWh]*	*Cold recovery [kWh]*	*Fans [kWh]*
360.01	45 163.0	4 019.6	324 772.0	256.8	67 665.0
360.02	17 379.7	4 144.0	232 357.0	73.1	48 922.0
360.03	7 674.6	13 576.0	220 595.0	17.0	40 230.0
360.04	24 338.1	2 839.8	180 017.0	65.2	38 503.0
360.05	0.0	0.0	33 681.0	247.1	17 453.0
Total	**94 555.4**	**24 579.4**	**991 422.0**	**659.2**	**212 773.0**

The cooling on the other hand has increased from 3094.0 kWh for 360.01 in the project work, to 4 019.6 kWh in the thesis simulations. This indicates that the internal gains has more or less been successfully modeled in the thesis detailed model. Total cooling has been doubled when comparing the project result with the thesis result. This may indicate that the increasing of internal gains has led to a higher cooling demand in the office building.

Furthermore, the heat recovery in the master thesis is noticeably higher than the project results represented. The heat recovery of the project showed that 360.01 has 262 886.0 kWh of heat recovery, while 360.01 in the thesis results had 324 772.0 kWh. The cold recovery however has not changed drastically between the two simulations, with the slight exception that the master thesis results had a minor decreasing. This may come from that the cooling demand is higher and therefore the amount of cold air is less.

The total energy consumption for fan usage has shown to decrease from the project to the thesis simulations. However, there are some air handling units that increases instead of decreasing for instance, 360.01. The total decreasing of fan usage may come from lower heating demand in the building as a consequence of adjusting the internal gains in the building. Also, the maximum supplied air flow for an individual zone in the model has been simulated to be 13.64 l/sm^2 for the corridor 2F_Corridors_1.
This further supports the hypothesis of that using no local heating units for the zones besides meeting rooms, offices and co-working spaces, leads to peak power demands for these zones in which the air handling unit is not capable of covering.

4.2.8 Peak demands

Comparing the peak during February with the measurements from the master thesis of Marie Sveen Olsen "Reduksjon av effekttopper i kontorbygg" [4], it is possible to identify differences between the simulation results and the measurements. From comparing peak demands it is possible to evaluate the accuracy of the simulation in regards of peak power demands in the office building.

Examining the figures 4.16, 4.17, 4.18 and 4.19. The peak demands are unrealistically high. From examining each zone in the IDA-ICE model, it was found that the stairs, elevators and toilets had been equipped with radiators for heating, but no internal gains from occupants or equipment. The radiators should not be modeled in these zones as they are not there in reality. Excess heat from offices and co-working spaces should enter these zones.
Removing the radiators showed that the heating demand increased slightly with heat leakage to the adjacent stairs, toilets and corridors. The figures are mainly shown to identify flaws in the modeling process as the results from showing the water based heating and cooling does not match the actual energy consumption. This may indicate that the heating and cooling capacity is a combination of ground source borehole energy and heat pump and liquid chiller capacity combined.

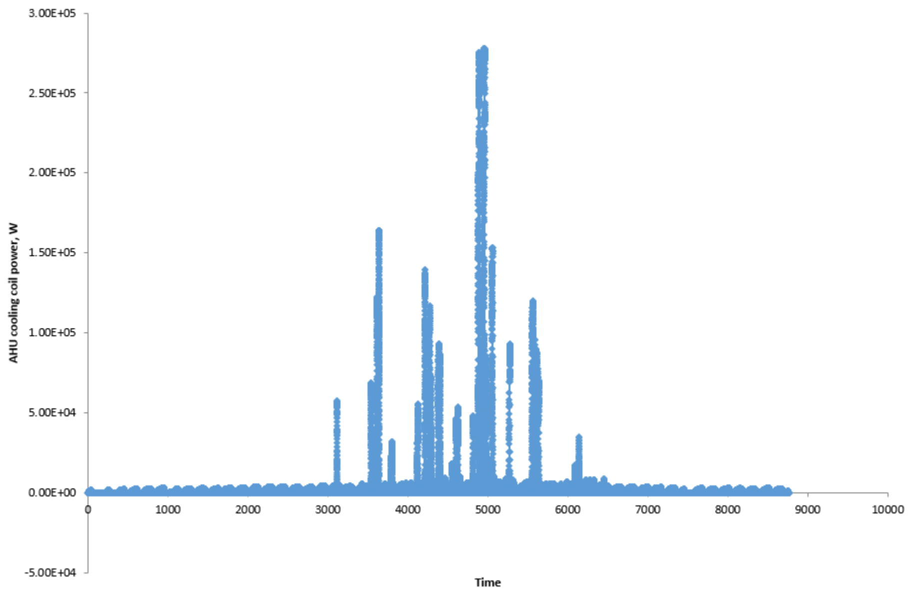


Figure 4.16: Peak demand for the AHU cooling coil power

In figure 4.16 the air handling units cooling coil power has peak values during the summer months, which appear to be correct considering the outdoor temperature conditions. The peak load amounts for the AHU cooling coil to be about 275 kW, which is within reasonable values.

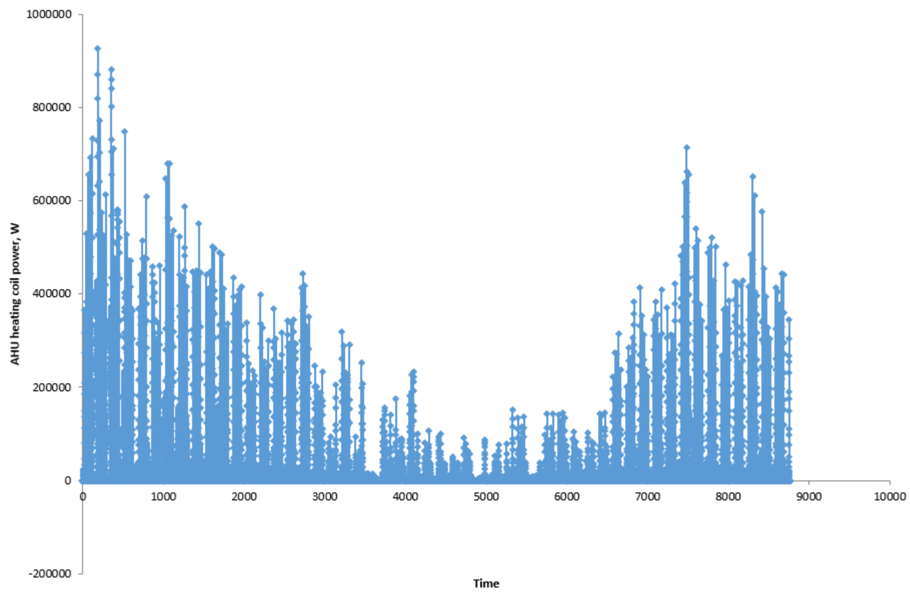


Figure 4.17: Peak demand for the AHU heating coil power

From the air handling unit heating coil power, it is shown in figure 4.17 that the peak heating demand occur during the month of January. The peak value amounts to approximately 9 750 kW, which is the maximum heat supplied by the AHU heating coil. This value appears to be unusually high, and can come from peak demands in different zones that do not have local heating units, including a low degree of internal gains. The shape of the peak demand throughout the year seems accurate in terms of the outdoor temperature conditions.

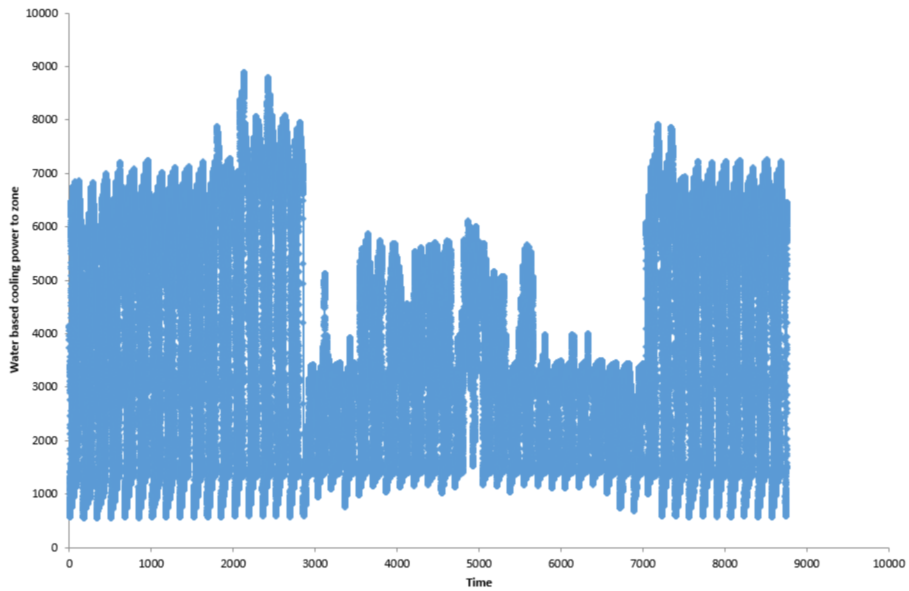


Figure 4.18: Peak demand for water based cooling power to zone

In figure 4.18 the peak value is about 9 kW, which is closer to the measurements in regards of cooling. This peak value is connected to the meeting rooms and laboratories, which are equipped with local cooling units.

The master thesis of Marie Sveen Olsen ”Reduksjon av effekttopper i kontorbygg” [4] shows that the electric circuits supplying the heat pump had a maximum heating demand of 92.4 kW as a maximum, while the peak demand for water based heating power to zone from the IDA-ICE measurements show a base value around 2000 kW, which is widely false. With a heat pump with a COP of 2.6 for heating this would indicate a peak power consumption on 770 kW which is approximately 8 times as high as measurements show from the electric circuit.
These simulation results are shown in figure 4.19. The figure also show high peak loads, which may indicate some sort of numerical error during the integration process in the model or a faulty implementation of the weather data file.

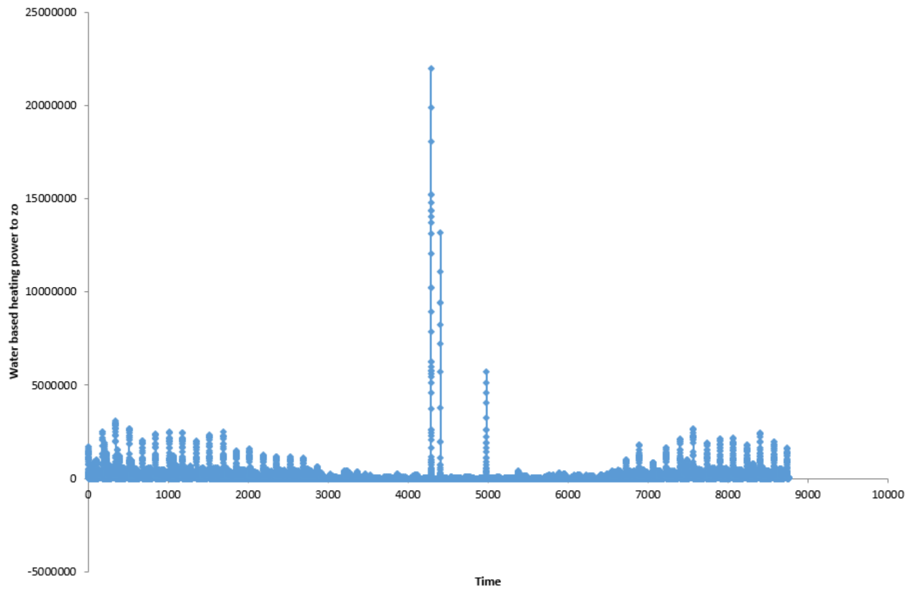


Figure 4.19: Peak demand for water based heating power to zone

In table 4.11, the peak demands for electric cooling is estimated to be 47.54 kW, which compared to the thesis of Marie Sveen Olsen [4] is lower than expected. However, the peak values from the thesis of Olsen is based on both the liquid chiller and the heat pump unit. If the peak values from table 4.11 are examined for the electric heating, it is possible to see that the heat pump unit has a peak demand of 104.4 kW, which is closer to what the thesis of Olsen indicates.
The peak demands from equipment is in table 4.11 simulated to 70.35 kW, while the measurements from the Olsen thesis show a peak at 4.2 kW for the third floor, which means that the peak values from measurements are lower than the simulated peak demands for equipment. The peak demands were not measured for an entire year, which means that some peak values could have been missed in the measuring process. The lighting peak demand was simulated to be 16.85 kW. Compared to measurements it shows that the lighting peak demands were approximately 34 kW and are almost double of what has been simulated [4].

Maximum heat supplied given in W/m^2 amounted to 179.8. The room for maximum heat supplied is the server room in the basement floor. The maximum heat here can be caused by that the room is not heated in any way.
The room has no heating units while there is a set point temperature which are the same as for offices, meeting rooms and co-working spaces. This means that the entire peak demand must be covered by the air handling unit, which causes large peak demands considering the temperature set points are difficult to maintain.

5 Discussion

The intention of this master thesis is to evaluate the results from the energy monitoring system with an IDA-ICE model of the office building. The thesis aim to model the AHU and in general the thermal energy system of ONV12E.
It is intended to conclude the specialization project that started with the thermal energy system, heat pump and temperature set points, and in conclusion try to model the office building as accurately as possible [6]. The results intends to be evaluated to what extent they can represent reality and support design.

5.1 Assessment of the heating demand

The radiators were by accident modeled wrong in the specialization project [6]. From the master thesis they are modeled more accurately in respect to a more precise investigation of the building operation system.
In the specialization project [6], the installed power of the radiators were misinterpreted, and therefore the ventilative heating had to cover the heating demand to a larger degree than necessary. This, because of that the radiators were implemented with a net power that was too low.
On the other hand the total heating demand of the model were much higher combined than what the measurements indicated. It is therefore possible to assume that the ventilation strategy had some implementation errors that led to the high ventilative heating demand.

Another factor that could have influenced the combined heating demand, were the COP factor of the heat pump. In most cases the COP will change during different weather conditions in regards of the outside temperature. However, in this case the heat source for the pump is the ground, which makes the temperatures stable throughout the year.
Moreover, the well insulated building envelope and the fact that all ventilation air is being extracted and sent through the heat recovery in the air handling units, makes the IDA-ICE model more energy efficient than the real building, which in this case should give a lower total heating demand than the measurements. When no air leaks through the facade, the demand for heating will be reduced.
Consequently, another factor that has not been taken into consideration when modeling ONV12E in IDA-ICE, is that the front entrance and any other entrances will open and close frequently throughout the day. With this in mind, visitors and workers will enter the building not through the parking garage solely.
Nevertheless it is also important to keep in mind that the only scheduling of rooms in the building has been the offices, co-working spaces and meeting rooms, which leaves some rooms unaccounted for in the IDA-ICE model. This could lead to some inaccuracies for the final simulation results. Consequently, the leakage factor for the building could be further examined to check if the buildings leakage numbers are the same as the model in IDA-ICE are set to.

Furthermore, the facade windows in the model are set to ”never open”, which means that the simulated model will have a minimum of heat loss regarded to occupants opening them. On the contrary the internal gains, mainly the occupant, could have been modeled in a too optimistic manner, creating a reduction in the heating demand for the simulation results.
In regards of evaluating the total heating demand, the thermal bridges could also have been further examined by doing actual measurements at ONV12E to check if the thermal bridges are estimated correctly in the model.

Otherwise can solar shading also be a contributing factor for the difference between measurements and simulation. This is caused by that the solar shading reflects sunlight that were to help heating the room in the winter in order to better regulate the degree of solar radiation and illumination. Furthermore, when it comes to internal gains from lighting, the heat gain will most likely have been overestimated both in the IDA-ICE model and in the Simien As-built simulation. Considering most lighting is LED and has a lower degree of transferable heat. This would have caused an underestimation of the heating demand of ONV12E.

When it comes to weather conditions, it is also possible that the radiator heating demand will depend on the weather conditions. The radiator heating can therefore be different when it comes to heat delivery as the weather data inserted are local weather conditions, but have been measured the year before the measurements for the energy were completed.
This may also explain the difference in radiator heating demand between measurements and simulation. Consequently it is not possible to solely conclude on that these factors alone are responsible for the gap between simulation and measurement, however they can explain some of the differences to a certain degree.

5.2 Air handling units

The balancing of air flows in each zone may induce higher air flow rates in the rooms which does not comply perfectly with the real building. By forcing the building model in IDA-ICE to have the same maximum supply air flow rate as the extract air flow rate depending on which value was highest at zone level, the air flow rates might have higher maximum air flow rates than the actual building.
On one hand this could have led to higher ventilation heating for the zones. On the other hand if the lowest value had been chosen for balancing supply and extract for each zone, the ventilation air flow rates would have been lower, which could have led to lower ventilation heating. This would contrarily have meant that some zones would have had a supply air flow rate of zero, which most likely would have led to less accurate results from the simulations.

However, defining the maximum air flow rate in the ventilation strategy modeling, may induce different ventilation air flow rates than what the real office building contains. This, because the maximum air flow rate will be different for some of the rooms chosen to examine compared to what the averaged values indicate.
Moreover it could have been considered to change the averaged ventilation air flow rates to a percentage of the averaged maximum instead of the given maximum from the building operation system. This could have resulted in a more accurate approximation of the ventilation air flow rates in the office building.

5.3 Scheduling occupancy for the meeting rooms

The CO_2 level slope assumption may cause inaccurate schedules for occupancy, considering it is based on hourly values. However, modeling on a more detailed level would create a higher amount of work for determining the different slopes if it were to be based on a minute-level instead of an hourly level. The level of detail would still be better, but it is considered to be sufficient in the thesis work to consider the occupancy on an hourly basis.

Furthermore if the ventilation system is capable of obtaining a ppm level of CO_2 below 640 ppm, which is the maximum for the averaged values. Consequently this may indicate that it could be up to 100% occupancy even if the calculations of inclination and declination states otherwise. If 640 ppm is the balancing point, it could be necessary to re-investigate the CO_2 scheduling procedure, and reorganize it with respect to the equilibrium of CO_2 in relation to amount of occupants in the previous work.

However, even if the CO_2-levels are stable around 640 ppm, the occupancy can be less than 100% , as the occupants are producing CO_2 and it is difficult to know for sure. It is therefore assumed that the occupancy schedules based on inclination and declination are sufficiently accurate for simulating the office building.

Likewise, the ppm-level of CO_2 outside the office building will also have an influence on how the occupancy schedules for the meeting rooms will take form. It was in the modeling and design process reviewed how the outside CO_2-level would influence the modeling of the slopes. Moreover, it was resolved by that the steady-state CO_2-level after working hours would be the defining level that would represent the same as the outside air ppm level. On the other hand it could have been a different value since the air handling units have been modeled to shut down after 19:00, and the outside air will in this case not be transported into the building after that particular hour during the weekday.
Conversely, the calculations are based on the steady-state CO_2-level and are considered sufficient for the simulation purposes of this thesis, at the same time it could be of interest to further investigate the causes of viewing the CO_2 measurements in a different more complex manner. One other factor that may affect the modeling of occupancy in the meeting rooms, is the placement of the CO_2 sensor node. If the sensor is to close to the supply air vent, the sensor would indicate fresher air than what the room total would indicate.
How the CO_2 sensor is placed will in this case influence the modeling of occupancy in offices and further influence the results. Notwithstanding, it is assumed that this has been taken into account when the sensor nodes were placed in the different zones of the building.
It should also be accounted for that the sensor may have measurement errors. While this may be true, the CO_2 measurements have been averaged over four meeting rooms, which decreases the possibility of measurement errors to some degree.

The results indicate that there are some differences between the NS3031, ISO 17772-1 and the scheduled CO_2 occupancy for the meeting room. It is considered most expedient to compare the ISO 17772-1 with the CO_2 schedules, considering they both operate on a room basis, while NS3031 considers occupancy to apply for the entire office building. The biggest difference between ISO 17772-1 and the self made CO_2 schedule, is mainly in the work hours after 12:00.
Both schedules give a maximum diversity factor at around 11:00, but the self made schedule are lowering the diversity factor to below 3 after lunch, while ISO 17772-1 increases to 0.8 after noon. The self made schedule are at it's lowest at 14:00 at about 0.2, while the ISO 17772-1 is set to 0 after noon until 14:00.
Even though this comparison may indicate differences in energy performance regarding occupancy between the Simien As-built report [3] and the IDA-ICE simulation, it will most likely have a small impact on the total energy consumption of the building. This, because the meeting rooms occupancy only applies for a small amount of the total rooms occupancy in the building.

5.4 Scheduling occupancy for the offices and co-working spaces

The reason for that it is difficult to model the office cells and the co-working spaces, is connected to that they do not have CO_2 sensors. On the other hand all three room types are equipped with a motion detector, however it is not possible to extract measurement data from these senor types, as they do not log their values in the building operation system.
Contrarily, the ventilation is indirectly connected to the motion sensor, and will throttle when the sensor detects motion. Likewise, the occupancy modeling through ventilation air flow rates are justified by using the ventilation system as an indirect link to the motion sensor. Moreover, this will enable the occupancy scheduling of the offices and co-working spaces.

It must be mentioned that there is some level of difficulty for modeling occupancy in the co-working spaces, as it is not possible to know the exact amount of occupants present at any given time. In the office cells there is usually only 1 or 2 occupants present at a time and hence more predictable. As the results showed a higher amount of hours in use, both the office spaces and co-working spaces would have more frequent usage than a meeting room, which in this context might be justified.
Conversely, it would be more expedient to investigate only one office space in order to determine when the person left the office and not, as averaging several rooms over a longer period of time would give more consistent and steady values. Consequently it could be of interest to average the measurements on a day-to-day basis to get more precise values for each day of the week.
On the other hand this process would be more time consuming, as well as that it would most likely not influence the energy performance in the simulations in a major manner.

It is worth to mention that in order to get the calculations to work out in Matlab, it was necessary to shave off some of the older data in order to get the time for each room measurement to match with each other. This may have lead to less data to evaluate. Contrarily the data that was removed was 72 hours of data on a two year long measurement time span. Therefore, it is considered not to have any major influence on the results calculated and implemented into the model.

5.5 Internal gains from the laboratories

The electricity consumption in the laboratories are significantly higher than the electricity consumption in the office areas of the building. Likewise, it was necessary to model the laboratories with higher internal gains than what the NS3031 sizes for regular office spaces.
This is connected to the earlier simulated low demand for ventilative cooling, as the cooling demand will increase for the laboratory zones of the building. The results showed that the ventilation cooling had increased for the laboratories, which could prove that the internal gains in this part have effected the cooling demand. On the other hand the strategy showed overheating in the laboratories, which can indicate a higher cooling demand than what has been simulated in the detailed model.

Contrarily it was chosen not to focus on further assessing the cooling demand, yet it could be interesting to elaborate on how to improve the cooling of the model to achieve satisfactory indoor temperatures in the laboratories.
As a result of high internal gains in the laboratories, it leads to lower radiator heating in the final simulation results. This is connected to that the high internal gains reduce the heating demand for the basement floor. Thus if the internal gains have been overestimated, the radiator heating demand would be more or less the same as the measurements states in the results chapter of the thesis.
On the other hand it might be possible to assume that the temperature criteria are stricter for the laboratories, and that the boundaries for temperature are more narrow than the other office building zones. If this was the case, the cooling coils would have to increase the delivery of cooling in order to sustain a satisfactory temperature level at all time. Nevertheless, from examining the results, the ventilative cooling has been simulated to be quite close to the same results as the measurements.
This would indicate that the internal gains modeling has been done correctly, and that there may be other issues that are the root for the high temperatures in the laboratories, most likely there is a lack of implemented cooling capacity in the model for these zones.

5.6 Electrical meters

In conclusion, it is worth to mention that uncertainty in measurements, incorrect wiring and the faulty values from June 2017 to June 2018 may have caused deviations in the simulation result for internal gains from equipment and lighting. These values were gathered from the electrical meters in the building operation system. Similarly, the weather data were gathered from 2017, while the electrical measurements were only available after June 2018. Furthermore, this could have caused some differences between heating and cooling demand in regards to the outside weather conditions.

6 Conclusion

The objective of the master thesis was to investigate and test how the BPS-tool IDA-ICE would enable an accurate representation of the office building at Otto Nielsens vei 12E through utilizing measurements solely, contrarily to using standards during the implementation process.
Measurements such as CO_2-level, ventilation air flow rates, electrical meters for equipment and lighting, were the most central input data for improving the model measurements. The final detailed model in IDA-ICE were compared with the As-built simulation in Simien [3], a simplified model [14] as well as measurements from the building operation system [2], thus to investigate to what extent the model were capable of displaying the actual energy performance of the office building.

To summarize, the following results were the most central when comparing the measurements with the detailed model:

- The simulated ventilative heating has been improved in the detailed model from a deviation of 289% in the specialization project [6] to a deviation of 8%
- Total heating demand in the simulation deviates from the measurements by 28.1%, which compared to the specialization project [6] is a decrease in deviation by 13.9%
- Total cooling demand deviates by 83% in the specialization project [6], while the detailed model deviates by 47.1%. This indicates that there have been improvements in the model, while it is still possible to increase the local cooling capacity in the model
- The used energy in the detailed model is in total 80 kWh/m^2 while the specialization project [6] simulated 89.4 kWh/m^2. Where the specialization project [6] is closer to the energy performance than the final detailed model

It was in the final simulation discovered that the fan and heat recovery operation was set to always on in the detailed model, which led to higher ventilative heating outside of working hours.
Moreover, it was found that the ventilation system for the parking garage did not need any heating or cooling of air, and the heating and cooling coils were by this turned off. Consequently, this led to a reduction in ventilative heating on around 20%. During the testing procedure for assessing ventilative heating, the results showed that the most efficient measure was to balance the air flows for individual zones.
Furthermore, the testing revealed that increasing the radiator capacity had some beneficial effect on reducing the ventilation heating.

The comparison between measurements from the building operation system and the simulations in IDA-ICE generally show that the heating demand is underestimated in the simulation. The main differences between the measurements [7] and the IDA-ICE simulation lies within the radiator heating, where the deviation between simulation and measurement is 28%. Meanwhile, the ventilation heating has been quite accurately modeled with a deviation of 8% in regards of the detailed model simulations.
Consequently, the cooling demand has been underestimated in the simulation mainly in regards of process cooling, which comes from the laboratories. Moreover the simulation results revealed that the laboratories experienced overheating during most hours of usage. This may indicate that the installed local cooling capacity for these zones has been modeled inaccurately.

On the contrary, comparing the Simien simulation [3] with results from IDA-ICE showed that the heating demand were to a bigger extent underestimated in the As-built report than in the IDA-ICE simulation. Additionally, the process cooling in the Simien simulation vastly surpasses the process cooling in the detailed model.

Likewise, the comparing was a good determinant for noting the similarity for measurements with the Norwegian standard, as Simien operates with input values based on the Norwegian standard [3]. Meanwhile, the total energy consumption from the IDA-ICE simulation revealed that the used energy was at 80.0 kWh/m^2, which compared to the As-built report indicated 67.2 kWh/m^2.
Modeling the internal gains based on measurements showed an improved effect on reducing the heating demand of the IDA-ICE model. As a result, the equipment energy demand has increased from the specialization project [6] to the master thesis simulation, which points out a significant impact from equipment internal gains when comparing table 2.5 with table 4.11.

Consequently it can be concluded with that the measurement based modeling is difficult to complete during a design phase of a building, and that it is generally complex to predict the energy performance and need of the building based on standards, even though it is a requirement by the Norwegian building code.
Using the simplified model instead of the detailed model, the accuracy of the simulation dropped significantly. On one side the simulation duration was reduced by a lot, but by reducing parameter implementations through measurements, a great level of detail is lost.

Conclusively, if the intention is to have an office building representing reality as accurately as possible, measurements and high attention to details will give a significantly more precise estimation of energy performance instead of using approximations based on standards.

7 Further work

As a proposal for further work, it could be of interest to look into a way of generalizing the occupancy schedules through CO_2 measurements and motion sensors.
By creating occupancy schedules based on these parameters, the investigation of improving the schedules given in NS3031 and ISO-1772-1 would be of interest in order to see if it is possible to size non-residential buildings in a more accurate manner.

Further work could as well look into the electrical consumption, and try to generalize internal gains from equipment and lighting from averaging typical electrical measurements from several office buildings and other non-residential buildings, to better determine what the heating demand of a typical building will be.
This would then be based on other buildings electrical consumption, and it would be necessary for those particular buildings to be more or less equal to the building that will be sized. It could be of further interest to explore how the different measurements could be examined, and how this would influence the sizing of the energy performance.
For example if CO_2 - measurements should be examined as inclination and declination, or if they should be considered in a different way. Further improvements of the IDA-ICE model of Otto Nielsens vei 12E could be to further calibrate the heat pump unit in the plant section of the BPS-tool IDA-ICE.
By this looking into the connections between the heat pump unit, the ground source boreholes, and the different recipients of the heat and cold delivery.

Additionally, to model the used energy of the office building more accurately, it would be beneficial to model the photo voltaic panels into the model as well. In the same way, the air handling units of the IDA-ICE model should be attempted to model at a more detailed level in consideration of operation and scheduling.
One of the major assessments regarding the process cooling would be to look into how the cooling demand could be sized in a more accurate manner. For the case of Otto Nielsens vei 12E, it would mostly concern the laboratories.

Moreover it could be of great interest to evaluate to what extent the different standards would enable accurate simulation results. To enumerate, the general idea would be to compare NS3031, NS3701 and ISO 17772-1 to see which standard that would give the most accurate representation of the energy performance at the office building.

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A Building parameters

Table A.1: U-values for floors, roofs and walls implemented into the detailed model with values taken from Energinotat [3]

Description	*U-value [W/m^{2}K]*
External walls above ground, binders with 48 mm studs and 50 mm masonry plate on the outside	0.16
External walls above ground concrete, binders with 48 mm studs	0.20
External walls above ground, technical room, binders with 48 mm studs	0.21
External walls above ground, intake chamber in the technical rooms, binders with 48 mm studs	0.39
External walls under ground level, parking	0.13
Compact roof over plan four	0.10
Compact roof over the intake chambers in technical rooms	0.20
Light roof over technical room, North	0.13
Light roof over technical room, South	0.10
External floor in plan 2 under the glass facade facing east	0.15
Underground floor	0.11

Table A.2: U-values for the windows and glass facades implemented into the detailed model with values taken from Energinotat [3]

Description	*U-value [W/m^{2}K]*
Facade:	
Triple glazing 6 mm: low-E + 4mm low-E+44.2 laminated -Ar Ultra	0.76
Triple glazing: 6 mm tempered low-E + 4mm low-E+44.2 laminated-Ar Ultra	
Insulated aluminum panel	
Triple glazing:6mm low-E + 4mm low-E + 44.2 laminated-Ar Ultra	0.77
Triple glazing: 6mm tempered low-E + 4mm low-E+44.2 laminated-Ar Ultra	
Triple glazing: 6mm tempered low-E + 4mm low-E + P7B glass-Ar Ultra	
Insulated aluminum panel	
Triple glazing: 6mm low-E + 4mm low-E + 44.2 laminated-Ar Ultra	0.68
Triple glazing: 6mm tempered low-E + 4mm low-E + 44.2 laminated-Ar Ultra	
Triple glazing: 6mm tempered low-E + 4mm low-E + P7B glass-Ar Ultra	
Triple glazing: 6mm low-E + 4mm low-E + 6mm float-Ar Ultra	
Triple glazing: 6mm tempered low-E + 4mm low-E + 6mm float-Ar Ultra	
Insulated aluminum panel	
Atrium:	
Triple glazing: 8mm low-E + 6mm low-E + 8mm float-Ar Ultra	0.75
Triple glazing: 8mm tempered low-E + 6mm low-E + 8mm float-Ar Ultra	
Triple glazing: 8mm tempered low-E + 6mm low-E + P7B glass-Ar Ultra	
Sliding doors:	
Triple glazing: 6mm tempered low-E + 4mm low-E + 44.2 laminated-Ar Ultra	1.1
Atrium roof:	
Triple glazing: 6mm tempered low-E + 4mm low-E + 44.2 laminated-Ar Ultra	0.85
Regular windows:	
Information unknown	0.81

B Thermal energy system data

Table B.1: Components in the heating system of Otto Nielsens vei 12E [5]

Component	*Description and function*
Heat pump/cooling	**General facts:** Covers the entire heating and cooling need for building E Produces excess heat to buildings A-D Working fluid R134a Piston compressors 2 x speed controlled and 1 x on/off controller Electronic valves Subcooler and desuperheater Evaporator and compressor, heat exchanger area: 37m^2 Heat delivery temperatures of 65^{o}C **Heating mode:** Nominal heat capacity of 230kW at 60/50^{o}C Nominal cooling capacity of 144kW at 3/0^{o}C **Cooling mode:** Nominal heat capacity of 290kW at 40/34^{o}C Nominal cooling capacity of 379kW at 16/10^{o}C
Domestic hot water system	**Hot water tank with integrated spiral:** Capacity: 550 litres Transfers heat for heating of hot tap water **Hot water tank with electrical heating:** Capacity: 380 litres Heating of hot tap water after the heat transfer tank
System for heating of ventilation air	Heating batteries (4 units) Sized inlet and outlet temperatures, 60/40^{o}C Aero tempers in the basement
Floor heating system	Floor heating in entrance hall Sized inlet and outlet temperatures, 35/30^{o}C Separate outdoor temperature compensation curve
Radiators and convectors	Room heating system Sized inlet and outlet temperatures, 60/50^{o}C

Table B.2: Components in the cooling system of Otto Nielsens vei 12E [5]

Component	*Description and function*
Local cooling system	Local cooling in meeting rooms Sized inlet and outlet temperatures, 14/18^{o}C
System for cooling of ventilation air	Cooling batteries (4 units) For cooling of the ventilation units Sized inlet and outlet temperatures, 10/16^{o}C
Process cooling	Sized inlet and outlet temperatures, 14/18^{o}C

	Fordamper	**Kondensator**
Varmevekslerareal [m^2]	37,13 m^2	37,13 m^2
Varmeoverførings-koeffisient [kW/m^2·K]	1,9	2,2
UA -verdi [kW/K]	70,1	82,2
Nominell kjøledrift		
Gjennomsnittlig temperaturdifferanse	**4,4 K**	**5,5 K**
t_{inn}	16°C	34 °C
t_{ut}	10 °C	40 °C
Delta	6 °C	14 °C
Fordampings-/kondenseringstemperatur	4,5 °C	43 °C
Nominell Varmedrift		
Gjennomsnittlig temperaturdifferanse[1]	**4,3 K**	**5,6 K**
t_{inn}	3°C	50 °C
t_{ut}	0 °C	60 °C (80°C max)
Delta	3 °C	10 °C
Fordampings-/kondenseringstemperatur	-3 °C	62°C

Figure B.1: General information about nominal values for heat exchangers in the heat pump unit [5]

C Weather Data

	Variables						
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s	Cloudness, %
January	-1.6	80.6	20.6	5.5	-0.9	0.5	76.6
February	-0.6	76.4	67.3	18.9	-2.2	1.2	64.3
March	1.0	71.4	121.6	47.9	-0.8	1.5	61.7
April	5.0	66.6	174.7	81.2	-0.4	0.7	57.3
May	9.2	70.7	172.1	118.3	1.1	0.3	63.3
June	12.8	72.7	150.0	141.7	2.4	-0.1	74.3
July	15.3	79.0	152.7	125.4	0.7	0.9	70.3
August	14.0	77.6	138.3	98.1	1.6	0.4	64.1
September	10.1	79.5	116.7	61.4	-0.9	1.5	65.7
October	5.3	80.3	85.5	29.0	-0.2	0.5	61.8
November	2.6	76.6	41.6	8.9	-0.0	0.8	74.6
December	1.3	75.6	13.1	2.4	-0.0	1.6	71.5
mean	6.3	75.6	104.6	61.8	0.0	0.8	67.1
mean*8760.0 h	54776.8	662357.5	916532.0	541206.0	397.0	7102.2	588180.0
min	-1.6	66.6	13.1	2.4	-2.2	-0.1	57.3
max	15.3	80.6	174.7	141.7	2.4	1.6	76.6

Figure C.1: Data for windspeed, humidity, temperature, radiation and cloudness for the TMY weather data [6]

	Variables					
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s
January	-4.6	73.6	18.3	5.2	-0.7	1.7
February	-0.8	79.4	34.4	20.0	0.4	1.5
March	2.1	75.1	50.0	44.5	0.3	1.6
April	3.7	74.7	64.7	78.4	0.5	0.4
May	9.7	66.3	111.4	101.8	0.1	0.2
June	12.3	71.3	148.2	112.1	1.0	-1.1
July	15.2	73.0	94.1	104.5	0.4	-0.2
August	13.2	78.7	73.4	76.6	0.5	0.2
September	12.5	83.5	45.4	49.2	0.1	0.6
October	4.9	76.1	132.7	26.2	-0.3	1.3
November	-0.0	80.8	22.9	7.0	-0.3	1.0
December	1.7	86.7	4.0	1.5	1.0	1.6
mean	5.9	76.6	66.9	52.4	0.3	0.7
mean*8760.0 h	51375.3	670706.3	585680.0	459128.0	2321.5	6386.2
min	-4.6	66.3	4.0	1.5	-0.7	-1.1
max	15.2	86.7	148.2	112.1	1.0	1.7

Figure C.2: Data for wind speed, humidity, temperature, radiation and cloudiness for the one year weather data [6]

D Matlab calculations for averaged air flow rates and carbon dioxide calculations

```
% code that plots measurements of air flow rates in offices, co-working spaces and meeting rooms in order to determine the occupancy schedules.

VentilationC106107b = strrep(VentilationC106107,',',','.'); % fill in measurement data here
DateString1 = VentilationC106107b(:,1);

VentilationC246247b = strrep(VentilationC246247,',',','.');
DateString2 = VentilationC246247b(:,1);

VentilationC372b = strrep(VentilationC372,',',','.');
DateString3 = VentilationC372b(:,1);

VentilationC4144153b = strrep(VentilationC414415,',',','.');
DateString4 = VentilationC4144153b(:,1);

xx1 = datetime(DateString1,'InputFormat','dd.MM.yyyy HH:mm:ss');
yy1 = str2double(VentilationC106107(:,2));
yy1 = yy1./100;

xx2 = datetime(DateString2,'InputFormat','dd.MM.yyyy HH:mm:ss');
yy2 = str2double(VentilationC246247(:,2));
yy2 = yy2./100;

xx3 = datetime(DateString3,'InputFormat','dd.MM.yyyy HH:mm:ss');
yy3 = str2double(VentilationC372(:,2));
yy3 = yy3./100;

xx4 = datetime(DateString4,'InputFormat','dd.MM.yyyy HH:mm:ss');     %Turning the date and time into matlab-language
yy4 = str2double(VentilationC414415(:,2));     %Creating the measurements into doubles instead of strings for coding purposes
yy4 = yy4./100;

z1 = table(xx1,yy1);
z2 = table(xx2,yy2);
z3 = table(xx3,yy3);
z4 = table(xx4,yy4);

TT1=table2timetable(z1);
DailyAvg1=retime(TT1,'hourly','mean');          %Finds the hourly average of each day
                                                %IMPORTANT!!! must make the four DailyAvg to start at the same hour in the workspace

TT2=table2timetable(z2);
DailyAvg2=retime(TT2,'hourly','mean');

TT3=table2timetable(z3);
DailyAvg3=retime(TT3,'hourly','mean');

TT4=table2timetable(z4);
DailyAvg4=retime(TT4,'hourly','mean');

VentilationM101_mean = timetable2table(DailyAvg1);
x1_old = table2array(VentilationM101_mean(:,1)); % x1(1:4159) for the first half of the year (summer)and x1(4159:8317) for the winter
x1=x1_old(1:8317);
x1_summer = x1(4159:8317);
x1_winter = x1(1:4158);
y1_old = table2array(VentilationM101_mean(:,2));
y1=y1_old(1:8317);
y1(y1==0) = 1;
y1_summer = y1(4159:8317);
y1_summer(y1_summer==0) = 1;
y1_winter = y1(1:4158);
y1_winter(y1_winter==0) = 1;

VentilationM267_mean = timetable2table(DailyAvg2);
x2_old = table2array(VentilationM267_mean(:,1));     %Adjusted so timetable dimension match
x2=x2_old(1:8317);
x2_summer = x2(4159:8317);
x2_winter = x2(1:4158);
y2_old = table2array(VentilationM267_mean(:,2));
y2=y2_old(1:8317);
y2(y2==0) = 1;
y2_summer = y2(4159:8317);
y2_summer(y2_summer==0) = 1;
y2_winter = y2(1:4158);
y2_winter(y2_winter==0) = 1;


VentilationM364_mean = timetable2table(DailyAvg3);
x3 = table2array(VentilationM364_mean(:,1));
x3_summer = x3(4159:8317);
x3_winter = x3(1:4158);
y3_old = table2array(VentilationM364_mean(:,2));
y3=y3_old(1:8317);
y3(y3==0) = 1;
y3_summer = y3(4159:8317);
y3_summer(y3_summer==0) = 1;
```

```
y3_winter = y3(1:4158);
y3_winter(y3_winter==0) = 1;

VentilationM467_mean = timetable2table(DailyAvg4);
x4 = table2array(VentilationM467_mean(:,1));
x4_summer = x4(4159:8317);
x4_winter = x4(1:4158);
y4_old = table2array(VentilationM467_mean(:,2));
y4=y4_old(1:8317);
y4(y4==0) = 1;
y4_summer = y4(4159:8317);
y4_summer(y4_summer ==0) = 1;
y4_winter = y4(1:4158);
y4_winter(y4_winter==0) = 1;

a = table(x1,y1,y2,y3,y4);  % all hourly values in the same plot for all rooms
table_co_working=fillmissing(a,'previous');                     %Fills the NaN with previous values
average_coW_vertical=mean(table_co_working{:,2:end},2);         %Find the average for each row
%std_coW = std(table_co_working{:,2:end},2);                     %Find the standard deviation, this code does not work at the moment



%Finding the weekdays:
Weekdays = ~isweekend(x1);
WeekdaysDate = x1(~isweekend(x1),:);     %Removes the weekends from the datetimes

 WD1 = Weekdays.*y1;      % Includes zeros and ones so that there is a difference between zero value and weekend
 WD2 = Weekdays.*y2;
 WD3 = Weekdays.*y3;
 WD4 = Weekdays.*y4;


WD1(WD1==0)=[];       %removes zeros from double to plot only positive values
WD2(WD2==0)=[];
WD3(WD3==0)=[];
WD4(WD4==0)=[];

WD1(WD1==1)= 0;       %removes ones and replaces them with zeros
WD2(WD2==1)= 0;
WD3(WD3==1)= 0;
WD4(WD4==1)= 0;

WD1 = WD1(1:5956);
WD2 = WD2(1:5956);
WD3 = WD3(1:5956);
WD4 = WD4(1:5956);


Weekdays_total_average=table(WeekdaysDate,WD1,WD2,WD3,WD4);
Weekdaysaverage_coW_vertical=mean(Weekdays_total_average{:,2:end},2);         %Find the average for each row for weekends

eightpmWD=nanmean(Weekdaysaverage_coW_vertical(1:24:end,:),1); %average for 20:00 every day
ninepmWD=nanmean(Weekdaysaverage_coW_vertical(2:24:end,:),1);
tenpmWD=nanmean(Weekdaysaverage_coW_vertical(3:24:end,:),1);
ellevenpmWD=nanmean(Weekdaysaverage_coW_vertical(4:24:end,:),1);
twelvepmWD=nanmean(Weekdaysaverage_coW_vertical(5:24:end,:),1);
oneamWD=nanmean(Weekdaysaverage_coW_vertical(6:24:end,:),1);
twoamWD=nanmean(Weekdaysaverage_coW_vertical(7:24:end,:),1);
threeamWD=nanmean(Weekdaysaverage_coW_vertical(8:24:end,:),1);
fouramWD=nanmean(Weekdaysaverage_coW_vertical(9:24:end,:),1);
fiveamWD=nanmean(Weekdaysaverage_coW_vertical(10:24:end,:),1);
sixamWD=nanmean(Weekdaysaverage_coW_vertical(11:24:end,:),1);
sevenamWD=nanmean(Weekdaysaverage_coW_vertical(12:24:end,:),1);
eightamWD=nanmean(Weekdaysaverage_coW_vertical(13:24:end,:),1);
nineamWD=nanmean(Weekdaysaverage_coW_vertical(14:24:end,:),1);
tenamWD=nanmean(Weekdaysaverage_coW_vertical(15:24:end,:),1);
ellevenamWD=nanmean(Weekdaysaverage_coW_vertical(16:24:end,:),1);
twelweamWD=nanmean(Weekdaysaverage_coW_vertical(17:24:end,:),1);
onepmWD=nanmean(Weekdaysaverage_coW_vertical(18:24:end,:),1);
twopmWD=nanmean(Weekdaysaverage_coW_vertical(19:24:end,:),1);
threepmWD=nanmean(Weekdaysaverage_coW_vertical(20:24:end,:),1);
fourpmWD=nanmean(Weekdaysaverage_coW_vertical(21:24:end,:),1);
fivepmWD=nanmean(Weekdaysaverage_coW_vertical(22:24:end,:),1);
sixpmWD=nanmean(Weekdaysaverage_coW_vertical(23:24:end,:),1);
sevenpmWD=nanmean(Weekdaysaverage_coW_vertical(24:24:end,:),1);


se1WD=std(Weekdaysaverage_coW_vertical(6:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(6:24:end,:)));   %Finds the error for each averaged value
se2WD=std(Weekdaysaverage_coW_vertical(7:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(7:24:end,:)));
se3WD=std(Weekdaysaverage_coW_vertical(8:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(8:24:end,:)));
se4WD=std(Weekdaysaverage_coW_vertical(9:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(9:24:end,:)));
se5WD=std(Weekdaysaverage_coW_vertical(10:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(10:24:end,:)));
se6WD=std(Weekdaysaverage_coW_vertical(11:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(11:24:end,:)));
se7WD=std(Weekdaysaverage_coW_vertical(12:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(12:24:end,:)));
se8WD=std(Weekdaysaverage_coW_vertical(13:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(13:24:end,:)));
se9WD=std(Weekdaysaverage_coW_vertical(14:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(14:24:end,:)));
se10WD=std(Weekdaysaverage_coW_vertical(15:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(15:24:end,:)));
se11WD=std(Weekdaysaverage_coW_vertical(16:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(16:24:end,:)));
se12WD=std(Weekdaysaverage_coW_vertical(17:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(17:24:end,:)));
se13WD=std(Weekdaysaverage_coW_vertical(18:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(18:24:end,:)));
se14WD=std(Weekdaysaverage_coW_vertical(19:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(19:24:end,:)));
se15WD=std(Weekdaysaverage_coW_vertical(20:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(20:24:end,:)));
```

```
se16WD=std(Weekdaysaverage_coW_vertical(21:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(21:24:end,:)));
se17WD=std(Weekdaysaverage_coW_vertical(22:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(22:24:end,:)));
se18WD=std(Weekdaysaverage_coW_vertical(23:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(23:24:end,:)));
se19WD=std(Weekdaysaverage_coW_vertical(24:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(24:24:end,:)));
se20WD=std(Weekdaysaverage_coW_vertical(1:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(1:24:end,:)));
se21WD=std(Weekdaysaverage_coW_vertical(2:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(2:24:end,:)));
se22WD=std(Weekdaysaverage_coW_vertical(3:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(3:24:end,:)));
se23WD=std(Weekdaysaverage_coW_vertical(4:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(4:24:end,:)));
se24WD=std(Weekdaysaverage_coW_vertical(5:24:end,:),1)/sqrt(length(Weekdaysaverage_coW_vertical(5:24:end,:)));

errorWD = [se24WD;se1WD;se2WD;se3WD;se4WD;se5WD;se6WD;se7WD;se8WD;se9WD;se10WD;se11WD;se12WD;se13WD;se14WD;se15WD;se16WD;se17WD;se18WD;se19WD;se20WD;se21WD;se22WD;se23WD];
uWD=[twelvepmWD;oneamWD;twoamWD;threeamWD;fouramWD;fiveamWD;sixamWD;sevenamWD;eightamWD;nineamWD;tenamWD;ellevenamWD;twelweamWD;onepmWD;twopmWD;threepmWD;fourpmWD;fivepmWD;si
tWD=[1:1:24];
tiWD=1:0.01:24;
uiWD=pchip(tWD,uWD,tiWD);
figure(1);
errorbar(tWD,uWD,errorWD);
xlim([1,24]);
xlabel('Time of day');
ylabel('Average set point Air flow rate [m^3/h]');
title('Air flow rate set points Office cell for weekdays with deviation');
grid on
figure(2)
plot(tiWD,uiWD);
xlim([1,24]);
xlabel('Time of day');
ylabel('Average set point Air flow rate [m^3/h]');
title('Average air flow rate set points Office cell for weekdays');
grid on
```

E Simien As-built report

SIMIEN
Evaluering TEK 10

Simuleringsnavn: Evaluering TEK10
Tid/dato simulering: 12:10 4/2-2018
Programversjon: 6.007
Simuleringsansvarlig: TOHA rev. MAFJ As-built
Firma: NTNU
Inndatafil: \\sambaad.stud.ntnu.no\linnca\Downloads\ONV 12E - R80 Energimerke.smi
Prosjekt: Otto Nielsens vei 12 - Bygg E
Sone: Alle soner

Energiramme (§14-4, samlet netto energibehov)	
Beskrivelse	Verdi
1a Beregnet energibehov romoppvarming	9,9 kWh/m²
1b Beregnet energibehov ventilasjonsvarme (varmebatterier)	8,4 kWh/m²
2 Beregnet energibehov varmtvann (tappevann)	5,0 kWh/m²
3a Beregnet energibehov vifter	12,3 kWh/m²
3b Beregnet energibehov pumper	1,9 kWh/m²
4 Beregnet energibehov belysning	12,5 kWh/m²
5 Beregnet energibehov teknisk utstyr	34,5 kWh/m²
6a Beregnet energibehov romkjøling	0,0 kWh/m²
6b Beregnet energibehov ventilasjonskjøling (kjølebatterier)	8,6 kWh/m²
Totalt beregnet energibehov	93,1 kWh/m²
Forskriftskrav netto energibehov	150,0 kWh/m²

Figure E.1: Simien As-built report total energy consumption [3]

Netto energibehov: ref. Energiramme §14-4 samlet netto energibehov	kWh/m²	m²	Sum
1a Romoppvarming	9,9	8940	88 506
1b Ventilasjonsvarme	8,4	8940	75 096
2 Varmtvann	5	8940	44 700
Sum termisk varme fra Energirammeberegning 6.7.2017	23,3		296 700

Figure E.2: Simien As-built report energy consumption for heating [3]

Energipost	Dim. effekt kW	Brukstid timer per år	Årlig termisk kjøling kWh/år	Andel av sum kjøling %
Ventilasjon	261	150	39150	8 %
Lokal kjøling	18	650	11700	3 %
Prosesskjøling	52	8000	416000	89 %
Sum kjøling			466850	100 %

Figure E.3: Simien As-built report energy consumption for cooling [3]

Mathias Metlid

Simulation-based building integration of a multifunctional heat pump system: Case of Otto Nielsens vei 12E

NTNU

Kunnskap for en bedre verden