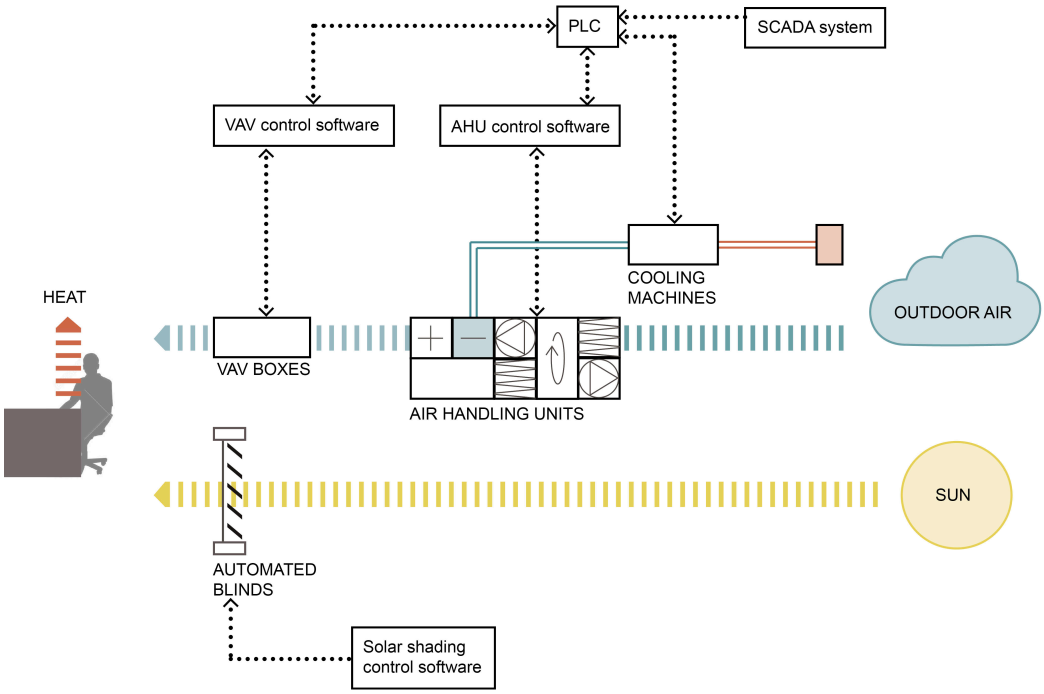
CHALMERS
UNIVERSITY OF TECHNOLOGY



Night cooling optimization using post processed control systems data

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

ANNA LARSSON

Department of Civil and Environmental Engineering
Division of Building Technology
Building Physics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
Master's Thesis 2015:103

MASTER’S THESIS 2015:103

Night cooling optimization using post processed control systems data

Master’s Thesis in the Master’s Programme Structural Engineering and Building Technology

ANNA LARSSON

Department of Civil and Environmental Engineering
Division of Building Technology
Building Technology
CHALMERS UNIVERSITY OF TECHNOLOGY

Night cooling optimization using post processed control systems data

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

ANNA LARSSON

Examensarbete 2015:103/ Institutionen för bygg- och miljöteknik,
Chalmers tekniska högskola 2015

Department of Civil and Environmental Engineering
Division of Building Technology
Building Physics
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Overview of control systems in the office building analysed in case study.
Department of Civil and Environmental Engineering. Göteborg, Sweden, 2015

Night cooling optimization using post processed control systems data

Master's thesis in the Master's Programme Structural Engineering and Building Technology

ANNA LARSSON
Department of Civil and Environmental Engineering
Division of Building Technology
Building Physics
Chalmers University of Technology

ABSTRACT

Carbon emission reduction and energy efficiency are highly important goals for the built environment, and society as a whole. One way that the building sector works with improving energy efficiency is advanced control of, among other things, airflow, heating, cooling and solar shading. When these control systems are installed there is often a possibility to gather historical data, and this study examines the possibility to use that data in combination with a building energy simulation to analyse the systems control and find potential improvements.

Night cooling, to decrease the cooling need in buildings by over-ventilating at night with cool outdoor air, was used as an example of a systems control function to be evaluated and potentially improved. A case study was carried out, where the night cooling function in an office building located in Göteborg was examined. As a first step a building energy simulation was done using post processed control systems data as input, and the simulation was calibrated to come as close as possible to the measured behaviour of the building. As a second step different alterations to the night cooling control were evaluated using the calibrated model. The alterations were evaluated by comparing three different indicators for energy efficiency; bought energy, electricity cost and specific energy use according to Swedish building regulations. This was done to investigate if prioritizing different indicators would lead to different optimal night cooling strategies.

The study suggests that the building performance for all indicators can be improved, even though the studied building is new and built with a high aim when it comes to control and energy efficiency. Proposed alterations are to make sure that the active cooling is completely disabled during night cooling, and to limit the airflow to avoid the peak when the night cooling initiates. There are some differences between the results of the different indicators, but for this studied building the difference is not large enough to lead to different night cooling strategies.

Key words: Post processing, night cooling, free cooling, energy modelling, energy simulation, sensor logs, building automation, HVAC systems control

Optimering av nattkyla genom efterbehandling av data genererad i styrsystem

Examensarbete inom masterprogrammet Structural Engineering and Building Technology

ANNA LARSSON
Institutionen för bygg- och miljöteknik
Avdelningen för Byggnadsteknologi
Byggnadsfysik
Chalmers tekniska högskola

SAMMANFATTNING

Att minimera energianvändning och utsläpp av växthusgaser är högt prioriterade mål för byggsektorn och samhället i stort. En av metoderna som används för att minska energianvändningen i byggnadsbeståndet är att installera avancerad styrning av till exempel luftflöden, värme, kyla och solskydd. När ett styrsystem är installerat finns ofta en möjlighet att samla historisk data och denna studie undersöker möjligheten att använda den datan i kombination med energiberäkningar för att analysera styrningen och hitta potentiella förbättringar.

Nattkyla, en metod för att minska kylbehovet i en byggnad genom att överventilera nattetid med kall utomhusluft, användes som ett exempel på styrfunktion att utvärdera och eventuellt förbättra. En fallstudie gjordes, där nattkylan i en kontorsfastighet i Göteborg undersöktes. I ett första steg gjordes en energiberäkning där efterbehandlad data från styrsystemet användes som indata, och modellen kalibrerades för att komma så nära byggnadens uppmätta beteende som möjligt. I nästa steg testades möjliga förändringar av styrningen, med hjälp av den kalibrerade modellen. De potentiella förändringarna utvärderades genom att jämföra tre olika indikatorer för energieffektivitet; köpt energi, energikostnad och specifik energianvändning enligt BBR (Boverkets byggregler). Motivet till detta var att undersöka om de olika indikatorerna ledde till skilda optimala nattkylefunktioner.

Studien indikerar att den studerade byggnadens styrning kan förbättras med avseende på alla tre indikatorerna, trots att byggnaden är ny och projekterad med högt ställda mål för styrning och energieffektivitet. Föreslagna förändringar är att helt stänga av den aktiva kylningen nattetid, och att begränsa luftflödet för att undvika den skarpa toppen när nattkylefunktionen går igång. Vissa skillnader fanns mellan de jämförda indikatorerna. Dock var inte skillnaden tillräckligt stor för att den optimala nattkylefunktionen skulle se olika ut beroende på val av indikator.

Nyckelord: Efterbehandling av data, nattkyla, frikyla, energiberäkning, byggnadsautomation, installationsstyrning

Contents

Preface

In this study a potential use for gathered control systems data is explored. This is done by post processing the control systems data from an office building located in Göteborg and use it to evaluate the night cooling function in the building, in terms of energy efficiency. The aim was to find improvements for the night cooling, as well as to investigate if different ways to define energy efficiency leads to different optimal night cooling strategies.

This thesis has been carried out at the division of Building Technology at Chalmers University of Technology, with Associate Professor Angela Sasic Kalagasidis as supervisor. The work was done in close cooperation with Bengt Dahlgren AB, where Max Tillberg has been supervisor and support during the process.

I want to thank Max Tillberg and Angela Sasic Kalagasidis for great support as supervisors. I would also like to thank Lars Nilsson and all the other engineers and technicians involved with the building studied in this thesis for taking time to share their knowledge.

Göteborg May 2015
Anna Larsson

Notations

Roman upper case letters

Q	Energy
Q_{el}	Electric energy
T	Temperature
$\dot{V}$	Volumetric supply air flow

Roman lower case letters

c_p	Specific heat capacity
t	time

Greek letters

ΔT	time
ρ_{air}	Specific heat capacity

Abbreviations

AHU	Air handing unit
VAV	Variable Air Volume, variable air flow
IDA	IDA Climate and Energy, a building energy simulation software
NaN	Not a Number
BBR	Building regulations by the Swedish National Board of Housing, Building and Planning
SCADA	Supervisory Control And Data Acquisition
SMHI	Swedish Meteorological and Hydrological Institute
API	Application Programming Interface
PLC	Process Logic Controller
COP	Coefficient Of Performance
UTC	Coordinated Universal Time

1 INTRODUCTION

1.1 Background

Carbon emission reduction and resource efficiency are important goals for the built environment, and society as a whole. A lot of effort is put into developing new technologies for better building performance in these areas, especially when it comes to energy efficiency and building automation. In the mean time it is important to improve not only the technology, but also the way it is used.

Buildings with modern installations and control systems often have the possibility to gather historical data, such as temperatures, flows, set points, control signals and energy consumption. These provide the possibility to examine an existing building and come closer to the reality with the analysis, compared to an idealized theoretical model. If good methods are developed the gathered datasets could be used to improve the use of already installed technical systems.

In this thesis night cooling is used as an example of an energy savings strategy that could be examined this way, and potentially improved. Night cooling is a method used to decrease the cooling need in buildings, by over-ventilating a building at night with cool outdoor air. This way some of the accumulated heat in the thermal mass of the building is removed, thereby decreasing the need for active cooling the following day. In addition to lowering the total energy use, night cooling also shifts the energy use from day to night and helps to even out the overall power demand. However, with the standard methods used by operation technicians to evaluate the performance of a building it is hard to say if the chosen night cooling function for a certain building really has the desired effect.

It is also possible that the ideal way to use a strategy like night cooling may vary depending on the aim. One aim could be reducing the amount of bought energy to the building, another could be lowering peak power demand. Other possible aims are reducing the Specific Energy Use according to Swedish building regulations (BBR), or reducing energy cost.

1.2 Purpose and objective

The aim of this thesis is to:

- Improve the way night cooling is used in an office building in Gothenburg.
- Examine whether the choice of indicator to compare has an effect on the outcome, by evaluating the possible new control strategies in terms of bought energy, cost and Specific Energy Use according to BBR.

1.3 Limitations

To define the scope of this study the following limitations have been made:

- All investigations are carried out for the year 2014. This limitation is due to lack of historical data, since data gathering system in the studied building is quite new. The developed methods could however be used for larger time samples if data had been gathered.

- Only one specific building is studied, and the conclusions may not be valid elsewhere.

2 METHOD

2.1 Interviews with stakeholders

To get a broad picture of the stakeholder views on the use of gathered data, and night cooling in particular, interviews were made with different actors. The stakeholders could be divided into these categories:

- *Technicians*
  System operators that deal directly with the systems and solve immediate problems.

- *Representatives of building owners*
  Facilities managers and technical managers with the responsibility to, for example, minimize overall cost and carry out energy efficiency programs.

- *Third party system operators*
  Providers of external control services, that controls energy use and indoor climate remotely with cloud services.

The interviews are described in chapter 4.

2.2 Data collection and processing

An office building located in Mölndal was chosen for a case study, and data was collected from the control systems logs. Since the actual effectiveness of night cooling is highly dependent on the response of control systems and technical installations this thesis aims to work with a real building, rather than idealized models.

Some of the datasets, particularly the control systems logs, were very large. Performing measurements every 5 seconds over a 14 months period these logs contains over 7 000 000 000 data points per logged sensor or signal. The programming language Python and the data analysis library Pandas, together with an SQLite database were chosen as tools to process the data. The Python distribution Anaconda, specially intended for scientific computing was used, with IPython Notebook as user interface.

Python is a widely used general-purpose programming language, with good readability. It is supported across many types of applications and has numerous well maintained extension libraries for different purposes. Python, together with a selection of libraries intended for scientific computing, is provided in the open source distribution Anaconda by the company Continuum Analytics. For most data processing tasks in this thesis the data analysis library Pandas was used. Pandas is developed for handling and analyzing large volumes of data from different sources, and has good functionality for time series. The full list of libraries and versions can be seen in the appendix, and this setup for data processing will be referred to as “Pandas” in the following chapters.

Initially the work with Pandas served to understand the building and how the night cooling had operated during 2014. In later stages it was used to transform the sensor data into in-data files, fan curves, supply temperature curves and other input to the simulations described in chapter 2.3.

Even though the control systems logs were the main source of data, some complementing methods were used, also described further in chapter 2.3. Datasets regarding weather and electricity price were taken from external resources. Reference measurements were conducted in the building as complement, to investigate aspects of the building where logs were not available.

2.3 Simulation and comparison of operation cases

A building energy model was made for the building in the case study, using simulation software IDA Indoor Climate and Energy (IDA). IDA is a dynamic multi zone simulation tool used in the building industry to simulate and study energy use and thermal comfort. As a tool it is transparent and flexible and as a user it is possible to provide your own time series data for multiple variables such as airflow, control signals, weather, automated lighting and shading, and different kinds of internal gains.

A few important simplifications were made in the IDA model. The model only consists of one zone, an entire office floor. This floor is then assumed to be representative of the whole building, and the air is assumed to mix completely in the zone. In reality an office floor is divided into two different office landscapes and a number of smaller rooms. The building also has a quite complex air handling system, with two air handling units working in parallel. They are simplified and modeled as only one air handling unit. The same method was applied to the multiple cooling machines installed in the building.

The IDA model was then calibrated to represent reality in an adequate way, using gathered data on the real behavior of the building, a process more closely described in chapter 5.3. Different operation cases were then tested and compared to the current one. As a first stage different extremes were tested, such as removing the night cooling function altogether, or letting it run totally unlimited. As a second stage 3 different control parameters were varied individually in a sensitivity analysis. As a third stage the strategies that looked promising in the sensitivity analysis were combined and studied in a few different operation cases.

When calibrating the model and comparing the different alternative operation cases two sample time-spans were used, 3:rd to 4:th of June 2014 in order to study and understand the behavior over the course of an office day, and 1:st to 31:st of June to study the behavior over a longer time.

3 THEORETICAL BACKGROUND

3.1 Night cooling

Night cooling is a method used to decrease the cooling need in buildings, by over-ventilating a building at night with cool outdoor air. This way some of the accumulated heat in the thermal mass of the building is removed, thereby decreasing the need for active cooling the following day. It is typically used as a strategy in office buildings, since they are not occupied at night and are used in a predictable way. In addition, fairly sophisticated control is required, which is more common in new office building than for example residential buildings. Typically the control methods and set points are designed along with the building. The set points are later adjusted when the building is taken into operation, as well as continuously during it's use.

Night cooling is sometimes referred to as free cooling, but actually requires energy to run the fans. The strategy is therefore decreasing a buildings energy use only if the amount of energy used for the fans is smaller than the avoided energy use in the cooling machines. To ensure that the night cooling has the intended effect a control system is used where a number of conditions have to be fulfilled for the night cooling to activate. There are different methods available on the market, and some control mechanisms are described below:

- *Time schedule*
  The night cooling function is allowed to activate during a certain time period, that may be different on working days and weekends. During that time window the system checks if the conditions to allow night cooling are fulfilled or not, either once in the beginning or multiple times in the allowed period.

- *Cooling need indicator*
  Some method is typically in place to determine whether there will be a cooling need the following day or not. For example there may be a condition set on the indoor temperature, that states that the night cooling function is allowed to *start* if the indoor temperature is *above* a specified value. Other possible options are conditions on outdoor temperature, or methods using weather prognosis.

- *Outdoor temperature security limit*
  The night cooling function is allowed to *start* if the outdoor temperature is *above* a specified value. If the night cooling activates when the outdoor temperature is too low problems can occur, for example damages resulting from too high relative humidity indoors. The assumption is also made that if the outdoor temperature at night is very low the cooling season have not really started, and if the night cooling is triggered it may be due to an out-of-the-ordinary event (for example many visitors in the evening) and there will in fact not be a cooling demand the following day.

- *Benefit limit*
  The night cooling function is allowed to *start* if the difference between indoor and outdoor temperature is *larger than* a specified value. The energy removed is directly proportional to the temperature difference, and if the difference is too small the obtained cooling effect may not be worth the spent fan energy.

- *Indoor temperature stop*
  The night cooling function is *stopped* if the indoor temperature falls *below* a certain value. A low stop temperature means allowing more heat to be removed, providing a larger stored cooling effect, but maybe risking comfort problems the following morning.

3.2 Electricity market and costs

The aim of this thesis is to compare night cooling strategies in terms of both energy use and cost. In addition to lowering the total amount of bought energy, night cooling also shifts the energy use from day to night, when the energy cost is typically lower. The use of district cooling complicates this relationship, but the building studied for the case study has installed cooling machines. Thus both the fan energy and the energy for the cooling machines are bought from the electricity grid.

Different types of price plans can be chosen, but to actively work with moving electricity consumption in time an hourly variable price plan is preferable. A number of utility companies in Sweden provide deals where the hourly price on the Nordic electricity market is used as a base, with added profit margins for the seller. To examine the economical benefit of the night cooling strategies this kind of price plan was assumed for the case study, even though this was not implemented in the studied building at the time. The electricity price used in this study follows the model used by Eriksson et al (2013) that consists of hourly spot price, a utility company margin, transmission fee and cost for energy certificate and energy tax. VAT is not included since the case study in this thesis concerns a company. In this study an example price from a large utility company is used.

Table 1: Electricity price components

Component	Price	Source
Spot market electricity price	varying	Dataset from NordPool spot market
Utility company margin	0.029 SEK/kWh	EOn customer service
Energy tax	0.294 SEK/kWh	EOn customer service
Energy certificate	0.028 SEK/kWh	EOn customer service
Transmission fee	0.27 SEK/kWh	Göteborg Energi

On the Nordic electricity spot market the electricity resellers and producers trade with electricity to be produced the coming 24 hours. In figure 1 it can be seen that the prices are significantly lower during the time when the night cooling function is active.

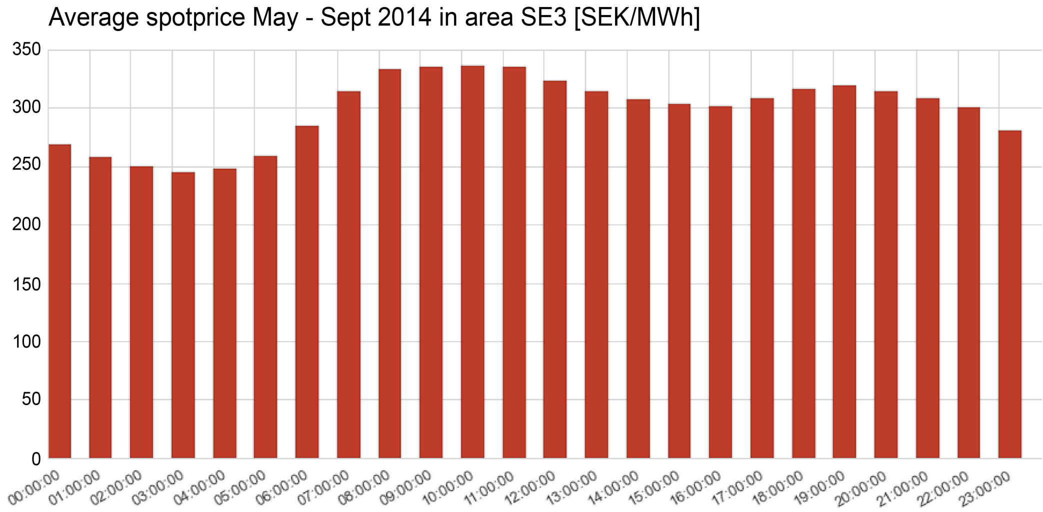


Figure 1: Average hourly electricity price May-Sept 2014 in market area SE3, where Gothenburg is located.

3.3 Specific Energy Use in Swedish building regulations

When discussing the energy efficiency of a building the Specific Energy Use as defined in BBR is commonly used. The Specific Energy Use is defined as a buildings energy use expressed in kWh/m2 of heated floor area and year. The energy used by the occupant is not included, but only the energy for heating, hot water and ventilation. Different rules for maximum allowed Specific Energy Use apply depending on location and main heating energy source of the building, and since the aim is to discourage the use of electricity as energy carrier the rules are stricter for that type of building.

As a continuation of that idea special rules apply to electricity used for comfort cooling. When calculating Specific energy use for buildings that are not using electricity as main heating source, but still uses electricity for cooling, that electricity should be multiplied by a factor 3. According to Boverket (2015) this rule does not apply to free cooling strategies, and the extra fan energy needed for that purpose is only counted once.

The building studied in this thesis is such a building, and taking the Swedish regulations into account it is possible that a different night cooling strategy is preferable, compared to if all electricity is valued the same.

3.4 Previous studies

In this section a short overview of some previous studies on calibration of building energy simulations and night cooling control optimisation is provided.

When calibrating a building energy model to a measured performance of a building Coakely et al (2012) proposes a method of 4 steps. An initial data gathering phase, where building data is obtained, processed and stored in a database is followed by the development of an initial building simulation. After that a probable range of variation is determined for the input data and a series of trials are generated. A simulation is then run for each trial. As a final stage the best fitting trial is selected.

Another study by Lain and Hensen (2006) aims to prove possible effects of night cooling ventilation in an office building. They conclude that the electrical energy consumption of the fans is very important, and that the benefits of night cooling can be balanced out by the needed fan energy. It is also pointed out that information exchange is an important factor when working with energy efficient systems and that it requires better cooperation of all participants in the building design, construction and maintenance, compared to less advanced systems.

There are several ways to deal with finding optimal solutions in a situation where there are multiple objectives, and many variables to test. One way is to systematically do sensitivity analyses for the studied variables. But if the simulation can be controlled programmatically more advanced optimisation algorithms are possible. Kajl et al (2005) investigates the use of a multi-objective genetic algorithm to optimise a series of HVAC set points with respect to energy use and thermal comfort. The method starts with a random initial generation of trials, containing different combinations of set points. Offsprings are created from the best two options, and they are compared with both of their parents to select the two best solutions among the four parent-offspring solutions. The algorithm then continues this way for a set number of generations.

4 INTERVEWS WITH STAKEHOLDERS

The interviews were of informal character, since they were intended as a prestudy to get a broad picture. The questions were adapted to the different interviewees, but the following questions were generally included:

- What data is gathered today in the buildings you work with? At what frequency is it collected, and how long is it stored?
- How is that data used today?
- How will data collection and analysis for the buildings you work with be carried out in the future?
- Do you use night cooling in the buildings you work with? In that case, how is it configured and why?

In the coming sections the answers will be presented as a general impression of the opinions of the interviewees.

4.1 Technicians and systems operators

Not all buildings the interviewees work with have the capacity to store data. But when stored data exists the ease of access is very important. Typically the technicians need historical data when things go wrong and the building users complain, and the data is used to track errors in the systems. This typically happens quite fast, and the interviewees seldom see the need to store detailed data longer than 2-4 weeks. Where night cooling is used the configuration is done based on experience and trial-and-error.

4.2 Facilities managers and representatives of building owners

The representatives of building owners currently had very different levels of data gathering, largely depending on the type of buildings they managed. The current data collection varied from only energy meters for billing, sometimes serving more than one building at once, up to frequencies of ten minutes across very large sets of sensors and signals. A common focus was to have the gathered data easily available, intended as a tool for cost-analysis, to motivate the technicians to work with improvements, to find anomalies and to hand to consultants when working with bigger changes.

All interviewees wanted to gather more data in the future and had ongoing projects to increase the accessibility and the amount of gathered data. All interviewees had recently made investments to increase control and involvement in the operations of their buildings, and saw it as a future area for work with energy efficiency. Some expressed the need for better ways than normal year correction to determine if their energy performance was above or below previous years, and wished for effect signatures and continuous monitoring of SFPs.

The use of night cooling varied. Some did not believe it had any effect, some used it widely. Sometimes it was not used as an energy savings method but rather as a way to achieve an acceptable climate at all, due to high internal loads. The configuration of the night cooling was done based on experience and trial-and-error.

4.3 Third party systems operators

A provider of external control services, that controls energy use and indoor climate remotely with cloud services, is interviewed. Their system analyzes the gathered data automatically and continuously. After that the data is stored for building owners, and the third party company's own personnel, to look at for follow up. The data at that stage is not very detailed, but instead aggregated to daily maximum, minimum and average values. When the system is first installed at a customer the third party operator use the gathered data to work actively with setting up the system correctly, but after that the system is meant to work on its own with only simple input from the client if something changes in the use of the building.

The data gathered by the system is primarily intended for the system itself and the intention is that the optimization process is taken care of automatically by the system. Other use of the data is not emphasized, since the intelligent system is meant to replace them.

The system has a night cooling function that is developed and configured by their team of systems developers. An essential part of the system is to predict the coming heating and cooling need, and that functionality is also used to determine if the night cooling function is activated or not. Other control parameters for the night cooling are said to be based on experience, and are not optimized or analyzed further.

4.4 Interview conclusions

The general conclusions from the interviews are that when there is a pressure to decrease energy use it becomes essential to optimize the functions of the installed systems. When the really low hanging fruit is already taken care of it becomes more interesting to gather and analyze systems data. Different actors see different kinds of use for the data, but nearly everyone see the need and possibility to develop ways to store it and work with it.

Regarding night cooling very few of interviewed stakeholders expressed any reasoning behind their choices other than experience. The ones that implemented night cooling did not choose control parameters based on any calculations and did not prioritize to verify if it saved energy or worked in an optimal way.

5 CASE STUDY

5.1 Short overview of Kängurun 18

Kängurun 18 is an office building constructed in 2009, located near Mölndal. It is inhabited by the building technology consultancy company Bengt Dahlgren AB, that also run the building operations on behalf of the property owner. The building was constructed with a very high aim and is one of the more energy efficient offices in Sweden. According to the energy follow-up conducted last year the building used 37 kWh/m^{2}year facilities energy and 38 kWh/m^{2}year occupancy energy during 2013.

The building is cooled with the supply air and has a variable air volume ventilation system (VAV-system) that operates based on presence, temperature and CO_2 levels. VAV supply air units with integrated sensors are placed in all relevant zones. Two air handling units serve the building, and work together to create the flow requested by the VAV system. When the requested flow is higher than one AHU can comfortably supply the second one activates and shares the load. Cooling machines that also functions as air source heat pumps supply the AHUs with heating and cooling. For the heating season the rooms are equipped with radiators supplied with district heating, but no room cooling is provided other than the supply air. The building has very efficient automated external solar shading, and uses night cooling to minimize the use of the cooling machines.

Figure 2: The office building Kängurun 18

5.2 Systems control and data collection in Kängurun 18

In the following section the control systems and set points in Kängurun 18 are described, and a short overview of the data storages in the building is provided. Only the systems relevant for the cooling season are dealt with.

5.2.1 Systems control and comfort cooling set points

The two main ways to control summertime indoor climate in the studied building are the automated solar shading and the VAV system that supplies cool air. An illustration of the technical systems controlling those applications can be seen in figure 3 below.

Citect Facilities, the SCADA system, is mainly intended for monitoring and handles for example alarms and short term follow-up on the performance of the building. Some parameters, for example the main night cooling settings and the operation schedules, are also set through the SCADA system. The building has a PLC that handles the overall systems control and manages the communication between, among other things, the cooling machines, AHUs and VAV system. Even though some settings can be made through the SCADA system the control is mainly handled in the PLC. The PLC is less vulnerable and the systems control in the building will keep working even if the SCADA system for example has a server malfunction. The VAV-system and the air handling units have specialized control software provided by the manufacturer. They can be accessed directly, but are also controlled automatically by the PLC. The automated blinds also have a control software provided by the manufacturer. It has not been accessible and the settings have instead been assumed, a process described in chapter 5.3.6.

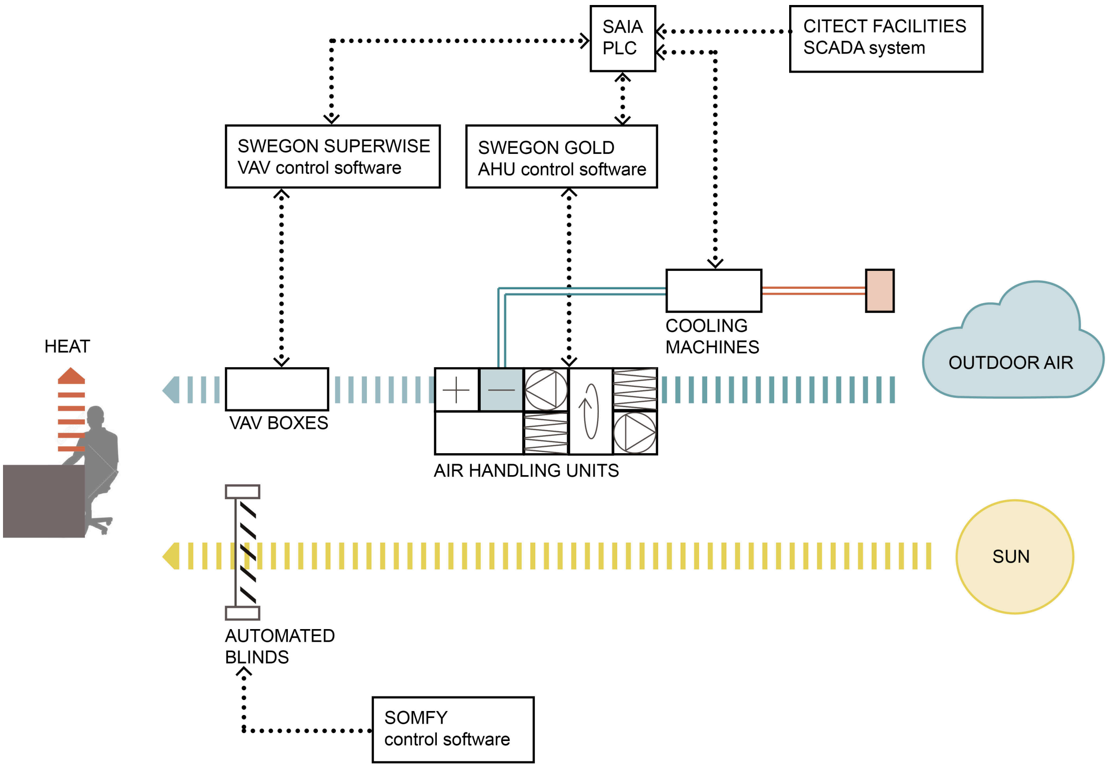


Figure 3: Control systems

As can be seen in the figure the control system consists of multiple software's and applications, and the functions of the system are not very well documented. In the construction documents it is described and specified what is asked for in terms of functions and performance, but there is very little documentation of changes made in implementation and after the building was commissioned. As a result of the lacking documentation it is hard to be absolutely certain of how the control system is configured today, and how it was configured during the summer 2014. The software's in AHU, VAV and SCADA-systems are meant to be set up by contractors and manufacturers according to the specifications in the construction documents, but it is often not clear how the settings actually work, and malfunctions seem common. During most of the time this study was carried out the software interface to the AHU settings was, for example, offline. An estimation has been made by looking at the interfaces that are available, studying the gathered data, and interviewing product manufacturers and the responsible engineers at Bengt Dahlgren AB.

The control methods and set points that are assumed to have been in use during the summer 2014 for the cooling and air supply in Kängurun 18 are described in table 1 and 2 and figure 4 below. Some of these set points also affects the heating systems but only the functions related to cooling and ventilation are described here. The information sources are noted, where "Data" means that the information is obtained by analysis of the gathered datasets and "Interface" indicates that the information is read from the relevant control systems interface.

Table 2: Daytime set points

Method	Set point value	Source	Comment
Ventilation schedule	Weekdays 07:00-17:00 Saturdays -off- Sundays -off-	Data	Can be manually started outside of office hours
Maximum airflow	Limited in the AHUs to a total of 8200 l/s. Also limited individually in the rooms.	Data	
Minimum airflow	2000 l/s	Data	
CO2 control	700 - 1000 ppm	Interface	
Room temperature span, when presence in room	22 - 23 °C	Interface	
Room temperature span, when empty	Days: 21 - 24 °C nights and weekends: 19 - 26 °C	Interface	
Supply air set point	Baseline set point 16°C, but adjusted as a function of both return air temperature and outdoor temperature.	Interface and Data	The set points read in interfaces does not match gathered data, this is later covered in chapter 5.3.7.

Table 3: Night cooling set points

Method	Set point value	Source	Comment
Ventilation schedule	Weekdays 01:00-07:00 Saturdays 03:00-07:00 Sundays 02:00-07:00	Data	
Maximum airflow	Limited in the AHUs to a total of 8200 l/s. Also limited individually in the rooms.	Data	
Minimum airflow	2000 l/s	Data	
Indoor temperature, start if	> 23.4 °C	Interface	Mean value of centrally placed sensors
Outdoor temperature security limit, start if	> 10.5 °C	Interface	
Benefit limit	5°C	Interface	
Room temperature set point	22 °C	Interface	The VAV system requests airflow to achieve this value, thereby controlling the airflow rate.
Supply air set point	Outdoor temperature + 0.6 °C	Interface	This method is intended to make sure that no active cooling takes place at night. The 0.6 °C are an estimation of the temperature increase caused by the fans, done by the responsible technician.

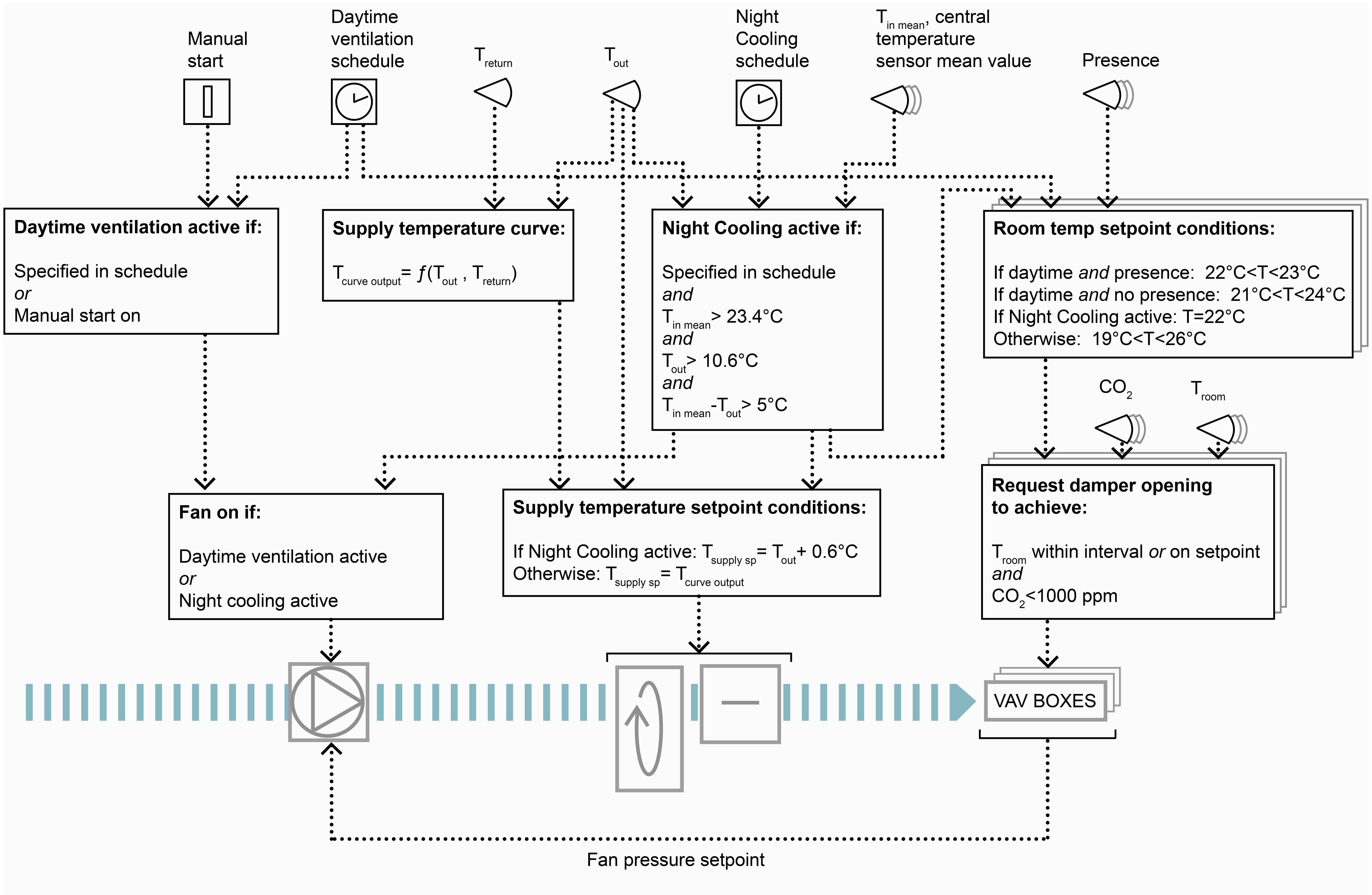


Figure 4: Cooling and ventilation control scheme

5.2.2 Data collection strategies and quality

Since this building is used as a test case by it's consultant company tenant multiple data collection systems exists. Two systems with different purposes and data quality were used for this thesis.

Citect Facilities trend logs
In the SCADA system used to monitor the building the short term history of a majority of all measured values, control signals and set points can be seen. In addition it collects long term trend logs for a subset of important functions, that are kept for 14 months. The data is stored in a proprietary database format but can be converted to a readable format through a tool provided by the product manufacturer Schneider.

Table 4: Citect Facilities trend logs meta data

Measurement frequency	**5 sec**
Measurement type	Instantaneous value
Time format	UTC
Content	- Main AHU measurements - Control signals - Outdoor sensors

Azure cloud storage
To provide better accessibility and a more complete set of measurements than the SCADA-systems logs an external cloud storage was created. Measurements from the SCADA-system are written to an online database with a ten minute frequency. These logs are intended for follow up and optimization of the building and are meant to be stored over long periods of time. However, this system is not fully implemented and only a subset of the available measurements and signals are stored. The azure cloud storage is accessible through a programming API, as well as via the Excel extension Power Query.

Table 5: Azure cloud storage logs meta data

Measurement frequency	**10 min**
Measurement type	Instantaneous value
Time format	UTC+1 (wintertime) UTC+2 (summertime)
Content	- Electricity meters - VAV systems signals for example rooms - Outdoor sensors

The data quality in the logs depends both on the collection strategies and the sensors themselves. Both logs gather only instantaneous values and not, for example, a mean value since the previous measurement. For the Citect trend logs with 5 sec frequency this probably has very little impact, but for the Azure storage with 10 min frequency this could mean that for example equipment start-up cycles are completely missed.

Another factor is sensor accuracy and how sensor malfunction is treated. According to the AHU manufacturer Swegon the temperature sensors in the AHU have an accuracy of +/- 0.5 °C. In most sensor malfunction cases the AHU cannot operate and gives a maintenance alarm. In some cases the sensor logs 0°C when broken. This is a potential source of error. Another set of important sensors are the electricity sub meters. Unfortunately the quality of that data is not very good, since they were set up to log only whole kilowatt hours without decimals.

5.3 Using collected data to model building in IDA

In the following section the process of modeling different aspects of the studied building in IDA, based on the gathered data, is described.

5.3.1 General data post processing strategies

The datasets that were very large and had a 5 seconds measurement frequency were aggregated to 5 minute frequency. This was done by the Pandas method “Resample”, calculating the mean value. All datasets were also normalized to the same timesteps, making all series start at 1 Jan 00:00 and then proceed with the same regular timesteps. This was done by interpolation between nearby measurements, or by filling out with NaNs (Not a Number markers) if data was missing. Datasets from different sources were stored with different time formats and this was solved by converting all measurements to UTC+2.

When the datasets were processed they were gathered in an SQLite database for easy access throughout the process. New datasets were also added to the database when new metrics were calculated.

5.3.2 Fan energy

The fan energy is an important part of examining night cooling, and to examine the electricity use of the night cooling functions a fan model based on the gathered data was made and inserted into IDA. The setup of the studied building, with two cooperating AHUs, is not supported in IDA and is unnecessarily complicated to model. Instead the two AHUs were approximated to work as one, which is also the intention with the building. The relationship between airflow and used electricity effect for the AHU system was calculated based on the gathered data on airflow through the AHUs and data from electricity sub meters, and approximated as a degree three polynomial with the least square method. A degree three polynomial was chosen since that is the available format for custom fan curves in IDA.

The combined AHUs in the studied building can give a maximum supply air flow of 12000 l/s. Flows that high are never reached in the current systems configuration, so measurements in that area are lacking. The assumption was made that the fitted polynomial curve is valid for flows all the way up to 12000 l/s, which gives a maximum of 50 kW used effect for the fans. Note that this effect in fact includes four fans, two supply air fans and two exhaust air fans. The fan model in IDA support fan curves that are normalized to the range 0 to 1, why this was also done with the custom fan curve using 50 kW and 12000 l/s as maximums.

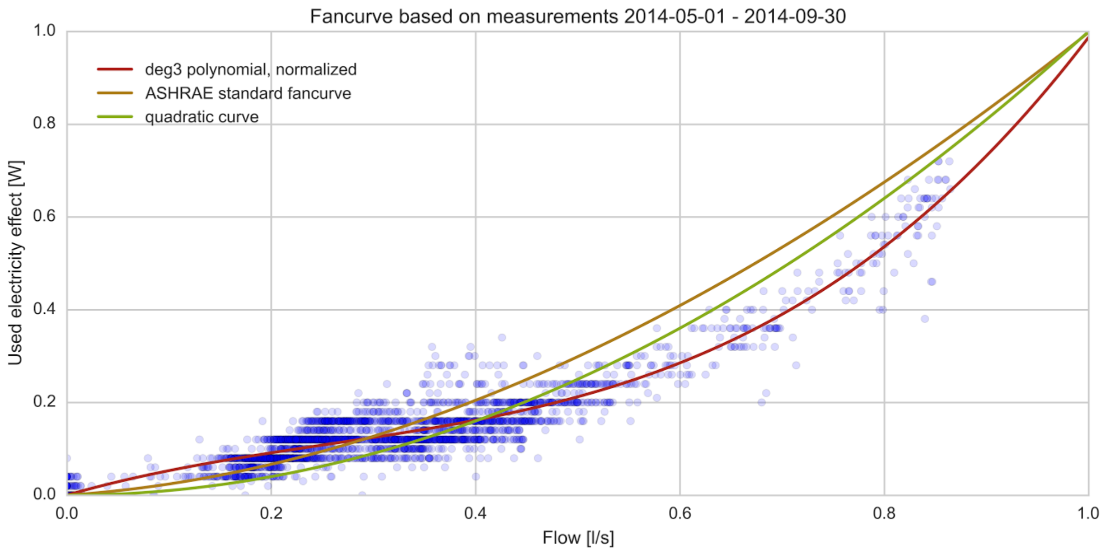


Figure 5: Relationship between airflow and used fan power.

The fan model was then tested by scheduling the airflow in IDA to exactly follow the measured airflow in the building. The electricity use in the IDA model for June 2014 was 2480 kWh, compared to 2478 kWh measured in the building.

5.3.3 Weather data

The weather files supported by IDA contain the following variables:

- air temperature [°C]
- relative humidity [%]
- wind direction [°]
- wind velocity [m/s]
- direct solar radiation [W/m^2, direct normal radiation]
- diffuse solar radiation [W/m^2, on horizontal surface]

A weather file containing data from Säve weather station was used as a base. The air temperature data was then exchanged to the measurements collected by the outdoor sensors in the studied building. An example of how the weather station temperatures differs from the measured can be seen in figure 6 below. As expected the temperature outside the city falls lower during the night. The difference is sometimes in the range of 4 degrees, and has a big impact on the night cooling potential. Since the relative humidity is affected by the temperature difference, the relative humidity was also exchanged to the values measured by the sensors on site.

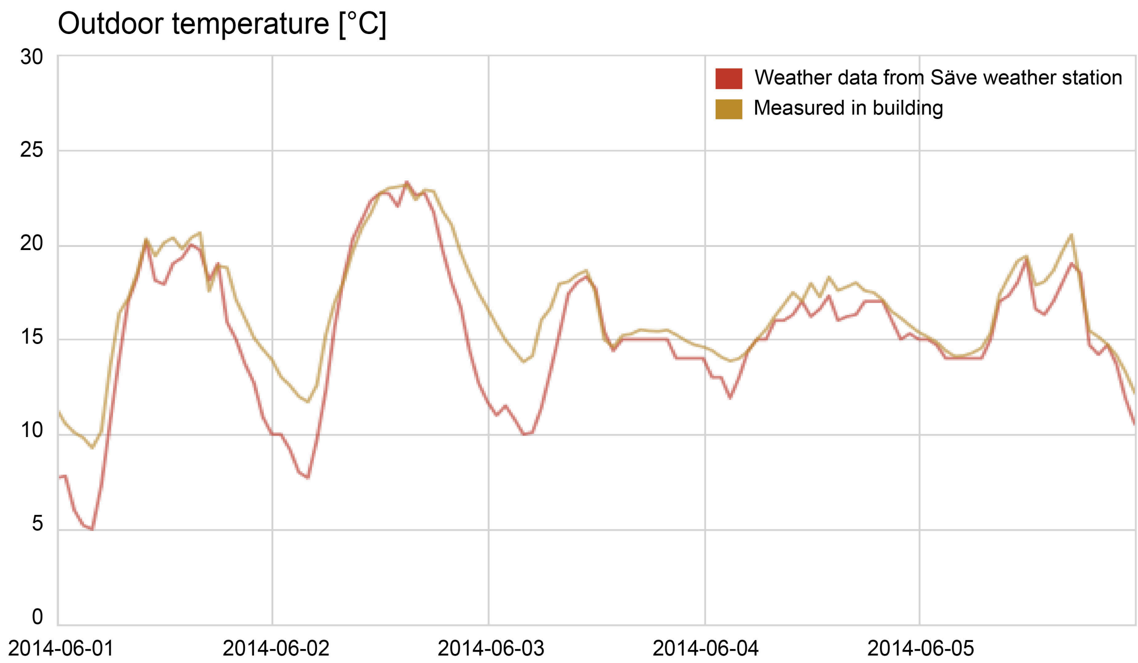


Figure 6: Outdoor temperature at the building site and Säve weather station

5.3.4 Occupancy and internal gains

The model for internal gains in IDA divide the gains into three categories; lighting, equipment and occupants.

Initially the assumption was made that 100% of the electricity used for lighting and appliances become internal gains. The data from the electricity meters, in kWh, were converted to power, in W, and exported as an in-data file to IDA. This assumption was later tested in the calibration process described in chapter 5.4.

There are several possible methods to model the occupancy. In the building there are presence sensors in both the VAV-equipment and the lighting equipment. However, the lighting has it's own technical system and is not logged or accessible. The VAV-system is much cruder with, for example, only a few sensors in an office landscape. In addition the VAV-equipment sensors are not logged for all rooms, but only for parts of the building. The building is used quite unevenly with some floors heavily occupied while others are used much less. As a result the decision was made to just model the occupants as present from 8-17 and assume 50 office spaces per representative floor and a 60% presence to account for less used areas such as the dining hall and that people are sometimes absent. This assumption was later tested in the calibration process.

5.3.5 Cooling machine energy

Unfortunately very little data is gathered about the performance of the cooling machines. The only data that is available is the use ratio, recorded as a current share of maximum power, and a few analog control signals. No internal temperatures are recorded, and the only available temperature data is outdoor temperature and the temperature of the treated supply air. The control of the cooling machines is in fact quite complex. Four different cooling machines supply cool media to four different coils in the cooling battery. Initially when the battery is started only one coil is active. When this coil reaches a 70% load another coil is activated and they share the load evenly, and so on.

In IDA it is possible to model a cooling machine in two ways. One is very simple, with unlimited performance and a fixed COP value including both sensible and latent cooling effect. The other method is quite complex, with a variable performance depending on condenser temperature, and current share of full load power. None of these models works well with the data available for the building.

Instead the choice was made to calculate the ratio of sensible cooling energy to electric energy used in the cooling machines. With this method all the cooling mechanisms available in the air handling unit (heat exchanger and cooling battery) were treated as a single mechanism with the function to provide air with the right dry bulb temperature. This ratio, denoted COP_{sens}, is calculated analogous to a COP value according to figure 7 and 8 and equation (1) and (2).

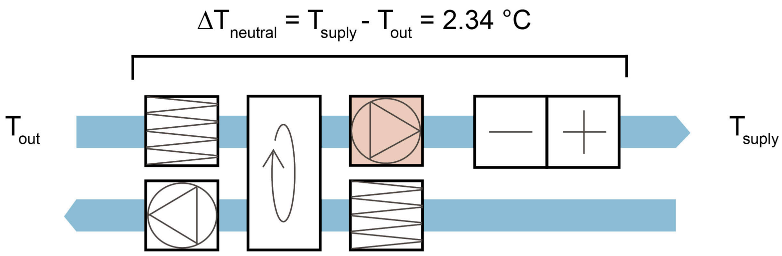


Figure 7: Temperature rise across AHU when heat exchanger and cooling battery is not active.

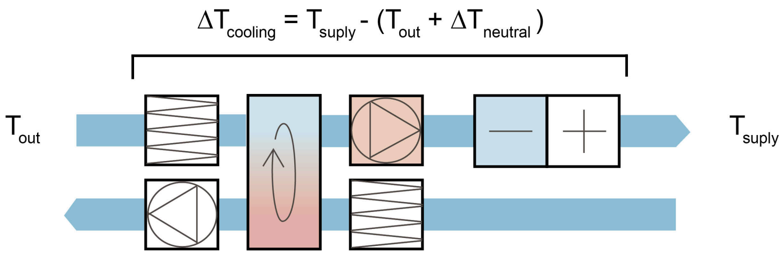


Figure 8: COP_{sens}

$$Q_{sens} = \int (\dot{V} \cdot \rho_{air} \cdot c_p \cdot \Delta T)dt \qquad (1)$$

$$COP_{sens} = \frac{-Q_{sens}}{Q_{el}} \qquad (2)$$

where

Q_{el}	Sensible heat transferred to supply air [kWh]
Q_{el}	Electric energy used in cooling machines [kWh]
$\dot{V}$	Volumetric supply air flow [m³/s]
c_p	Specific heat capacity [J/(kgK)]
t	time [h]
ρ_{air}	Density of air [kg/m³]

To determine COP_{sens} it is necessary to find the temperature raise in the system when no active cooling is applied. The supply air will be heated by fan motors and the surrounding environment in the equipment room, as described in figure 8. The sensor data for the period June - August 2014 were filtered to remove all occasions where cooling coils or heating coils had been active, or the heat exchanger have operated above 5% of its capacity. The later choice was made because the heat exchanger seldom seems to be turned off completely, for some reason. The average temperature difference between outdoor and supply temperature in these occasions were +2.34 °C. This number seems quite high and the distribution was studied using Pandas. The distribution as seen in figure 9 looks good, and the high number does not seem to be a result of outliers caused by for example AHU startup cycles.

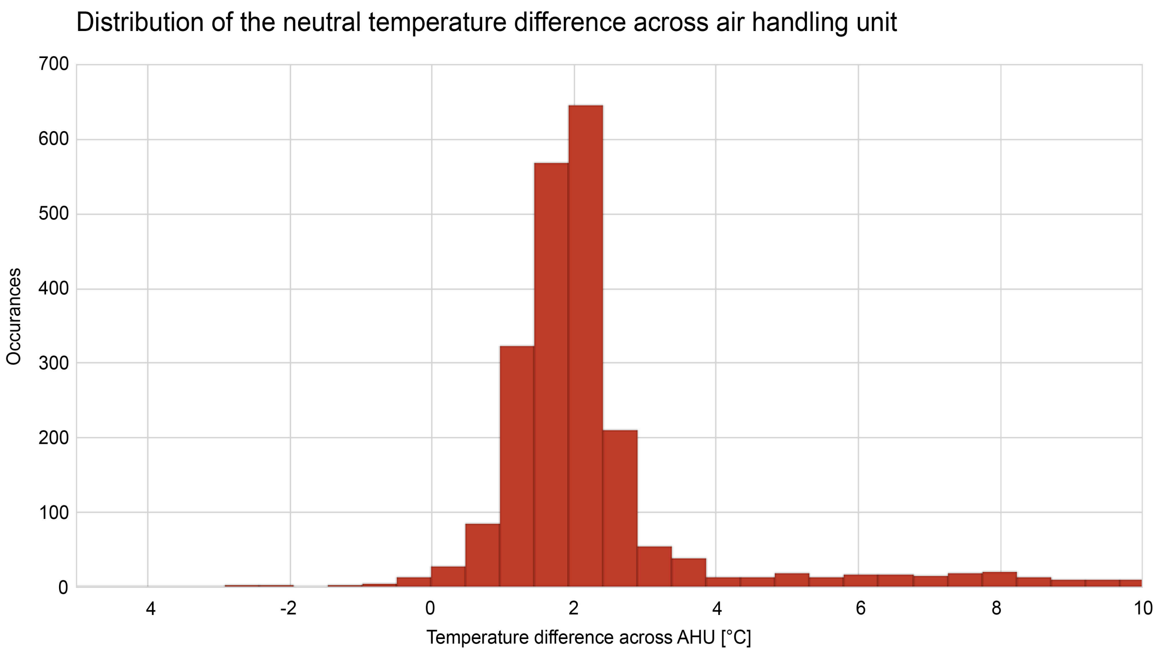


Figure 9: Distribution of neutral temperature difference across air handling unit

The COP_{sens} was calculated for the studied example month June, taking into account that the neutral temperature raise is +2.34 °C. The COP_{sens} was determined to be 2.95 kWh sensible cooling per kWh electric energy.

5.3.6 Solar shading

Even in a well shaded building like this one the sun has a significant impact on the cooling need. The shading external pillars of the building and the nearby structures were inserted as a geometry in IDA. The motorized external blinds were assumed to have a g-value of 0.1, a value based on measurements done by Bengt Dahlgren AB.

The shading control model in IDA operates on irradiance (W/m^2). The motorized external blinds in the building operates on illuminance (Lux) and have a separate control system, from which data could not be read. These circumstances made it difficult to choose the threshold when the blinds are drawn in the IDA-model. Instead of using the control systems data the choice was made to gather a few reference measurements to provide an initial assumption, and then include the irradiance threshold of the blinds as a parameter in the sensitivity analysis described in chapter 5.4.2. The reference measurements were done using a pyranometer in one cell office during five days. During these days irradiances of maximum 37 W/m^2 were recorded without causing the blinds to be drawn. However, the actual threshold is probably higher, since the clouds part quite quickly and causes much higher irradiance levels very fast. The limit was initially assumed to be 50 W/m^2.

5.3.7 Supply air temperature

In the studied building the supply air temperature set point is determined as a function of both return air temperature and outdoor temperature. The temperature curves can be adjusted in the control system, but it is uncertain how the settings were done during the studied period. The relationship between supply air temperature, return air temperature and outdoor temperature was investigated in Pandas. In the IDA model the control systems are fast and ideal, and the supply air in the IDA model always achieve the desired temperature. That is not the case in the real building.

As can be seen in figure 10 and 11 below, the relationship between supply air and return air temperature is not clear at all, while the outdoor compensation seems to have a very clear influence. A supply air curve only depending on the outdoor temperature was assumed for the IDA model. In figure 11 a somewhat linear relationship can also be seen, which is caused by the night cooling function. When the night cooling function is activated the supply air set point is changed to be equal to the outdoor temperature, plus a fixed offset value.

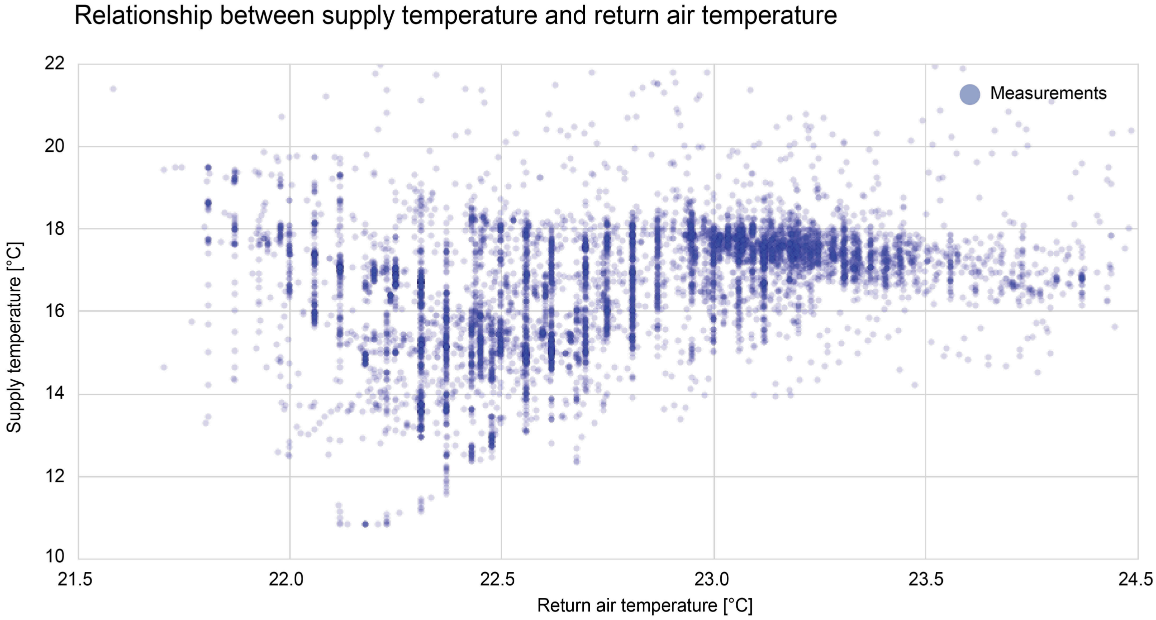


Figure 10: Relationship between supply air and return air temperature during May and June 2014.

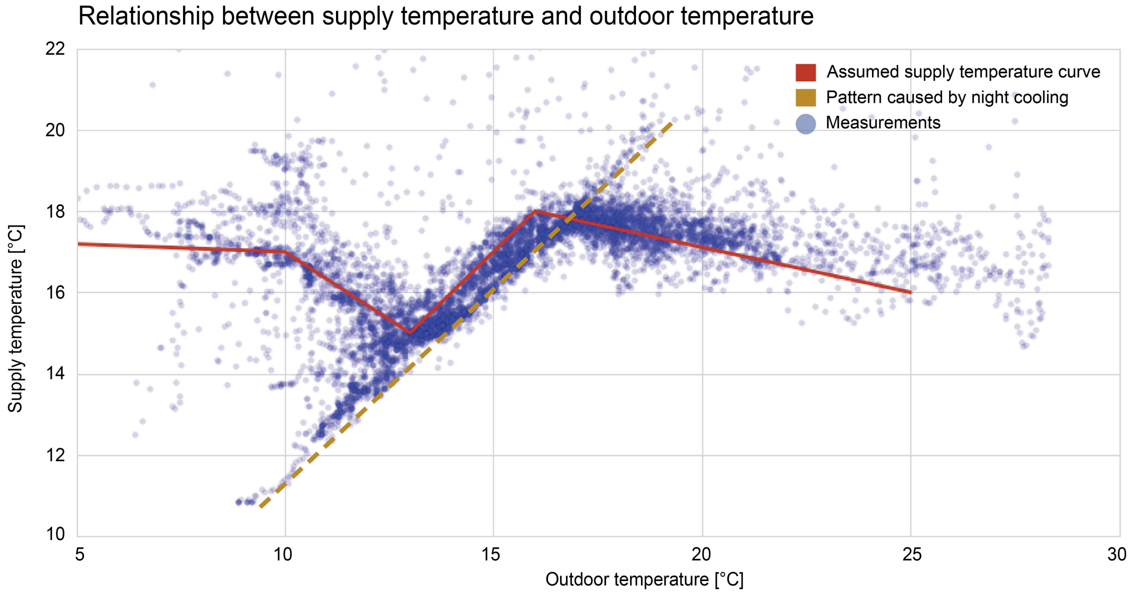


Figure 11: Relationship between supply air and outdoor air temperature during May and June 2014.

5.4 Calibrating an IDA model to the real measurements

A single zone IDA model of one office floor was used for this project. The model was developed in three steps, called phase 1, 2 and 3 in the chapters below. An initial base case for phase 1 was put together based on the analysis of the gathered data as described in chapter 5.3. Properties of walls and windows and building geometry were obtained from energy calculations originally performed for the building, and from construction drawings. A list of indata for the base cases in the different phases can be found in appendix A.

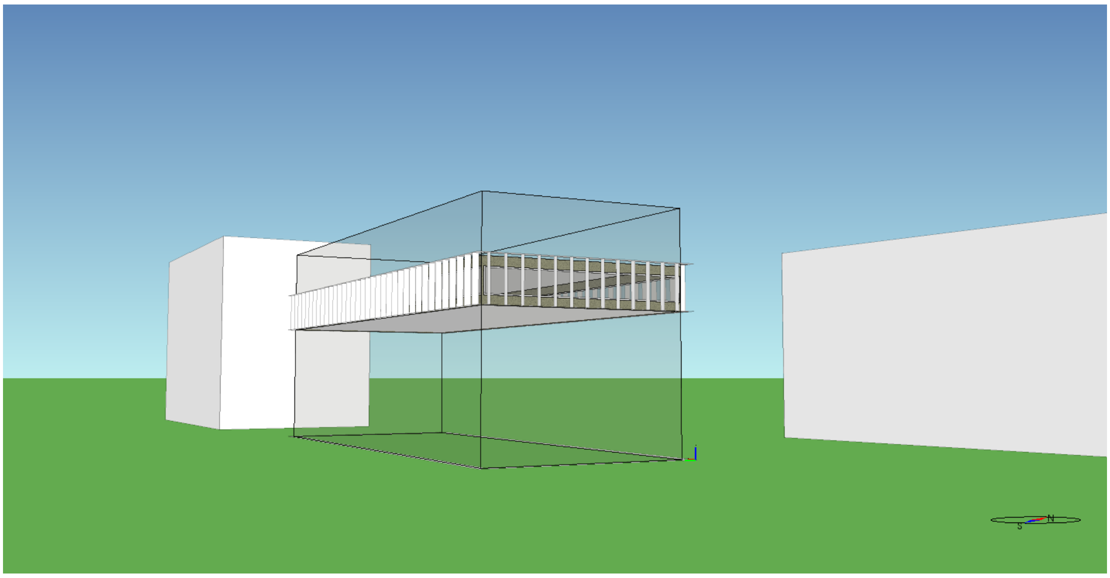


Figure 12: 3D view of IDA model

With this single zone setup a few important simplifications were made. The approximations were made that the entire building has a similar use pattern and that the air is completely mixed in an entire office floor. This setup for example ignores the fact that a few spaces has a different use, such as the dining hall and reception area on the first floor, and the technical rooms.

When calibrating the IDA model to the measurements two example days, the 3rd and 4th of June 2014, were chosen. They are two normal weekdays, a Tuesday and Wednesday, with no holidays. The mean outdoor temperature during these days were 16.06°C, which is very close to the monthly mean outdoor temperature measured in the building in June, 16.10°C. The monthly mean for June during the period 1961-1990 was 15°C, which indicates that the sample days and June 2014 were slightly hotter than usual. Even though only these two example days were studied for the calibration the simulation was run with 2014-05-01 as starting date, to remove any influence from initial temperatures in the IDA model.

5.4.1 Phase 1: Calibrating Mass

For phase 1 airflow and supply temperature were controlled in IDA to be exactly as measured, using time series input data files generated with Pandas. As a result only the building geometry and other parameters not related to the airflow can be the cause of any difference in indoor climate between the model and the gathered data. For this first step the effect of varying the exposed mass was studied. This parameter was assumed to be the only parameter affecting the speed of the thermal response of the building.

Internal thermal mass in IDA is taken into account based on the specifications given when placing walls and slabs in the 3D modeling environment. Extra mass can also be added into a zone by describing it as extra exposed wall area, thereby modeling internal geometry in a zone. In this case extra internal mass was modeled as exposed square meters of 26 mm gypsum boards.

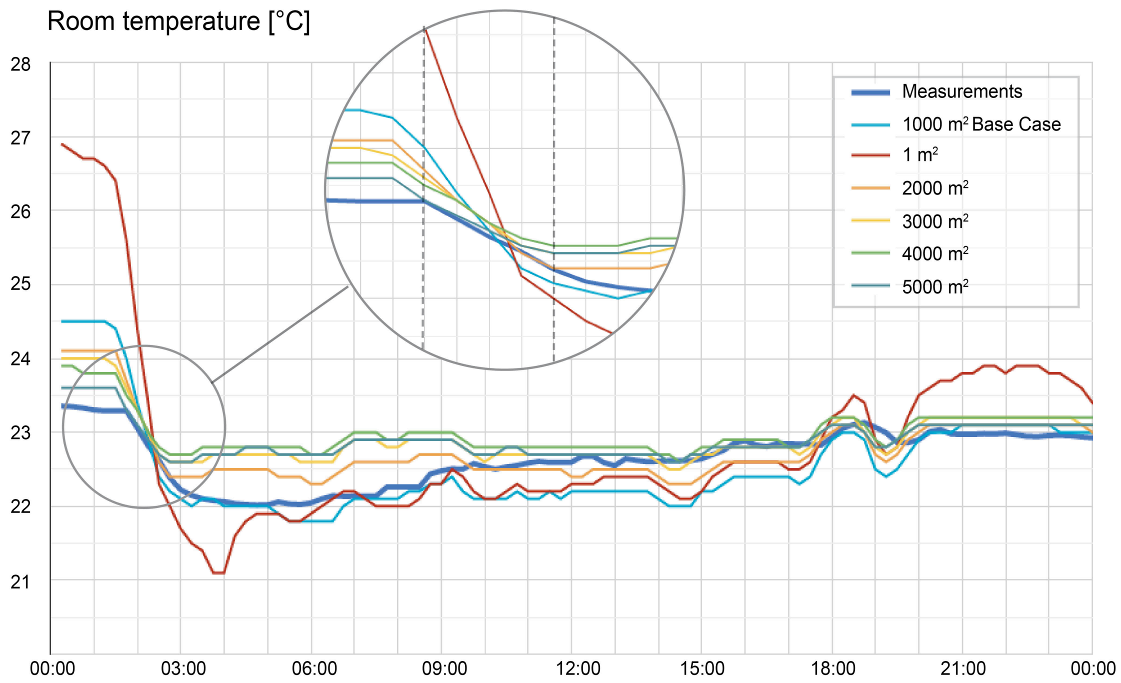


Figure 13: Indoor temperature during sample days.

Table 6: Temperature difference during initial phase of night cooling 3014-06-03

	Measurements	1 m2	1000 m2	2000 m2	3000 m3	4000 m2	5000 m2
ΔT	0.91°C	3.6°C	1.8°C	1.3°C	1.0°C	0.8°C	0.7°C

Studying table 5 and figure 13 it can be seen that the initial assumption for the mass, based on a very crude approximation of the amount of internal walls, looks way too low. A reason for this could be that all floors and ceilings were assumed to be insulated due to suspended ceiling and carpet flooring. In fact some parts of the floors are not covered in carpet, and possibly the large amount of furniture and other objects also contribute. An exposed wall area of 3000 m^2 was chosen as a new base case when proceeding with the calibrations in phase 2.

5.4.2 Phase 2: Calibrating gains

For phase 2 internal gains and solar shading were examined through a sensitivity analysis on a few parameters that were regarded as very important or where the uncertainty was large. In phase 2, as well as phase 1, airflow and supply temperature were controlled in IDA to be exactly as measured. The chosen parameters to study where the g-value of the solar shading, the threshold irradiance where the solar shading is drawn, the number of occupants in weekdays, and a scaling factor for the internal gains from lighting and appliances.

Lighting and appliances have dedicated electricity meters in the building and the measured effects during the studied period were used as indata in IDA, as described in chapter 5.3.4. A scale factor was then applied to these measurements for the sensitivity analysis. The use of a scale factor not equal to one could be used if needed since it's possible that all the electricity does not become internal gains and that the electricity sub meters are not very accurate.

Since the effect on the thermal balance of the building of all the studied parameters in phase 2 are quite similar it is difficult to know exactly which one of them to change to adjust for a possible difference between the base case and the measurements. However, for this thesis the exact source of the thermal gains in the building is not relevant, as long as the sum is correct enough.

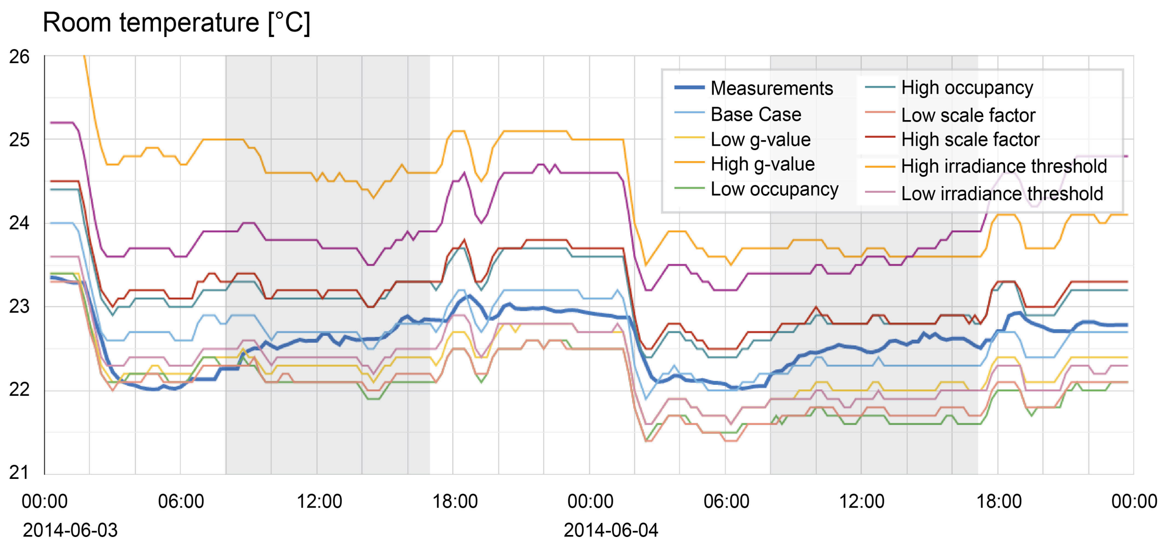


Figure 14: Indoor temperature during sample days

Table 7: Parameters tested in sensitivity analysis

	g-value of blinds	Threshold irradiance	Occupancy	Internal gain scale factor
High	0.2	100 W/m2	15 people	0.75
Base Case	0.1	50 W/m2	50 people	1
Low	0.08	20 W/m2	80 people	0.25

Studying the indoor mean temperature for the different studied cases it can be seen that the base case looks like the best alternative. The choice was made to keep the base case from phase 2 as a base case also in phase 3.

5.4.3 Phase 3: Calibrating control systems model

This far the supply temperature and the supply air flow in IDA have been controlled by an indata file to be exactly as measured in the building. Since the aim of this thesis is to examine the effect of varying the control systems settings the control system also have to be modeled to work like it does in the studied building.

IDAs default night cooling control mechanism was used as a starting point and was then modified to work as close to the settings in the real building as possible. Compared to the cooling control in the existing building, shown in figure 15, a few functions are different due to the available modeling options in IDA.

One main difference is that the night cooling function built in IDA is not applying a new supply temperature set point, but instead turns the cooler, heat exchanger and heater off. This gives the same result, provided that active cooling is not used at all during the nights in the studied building. However, this happens quite often with the current setup. For that reason the possibility to model the use of active cooling also at night was added as an extra function in IDA. In addition the choice was made to simplify the room temperature set points. In the building they are dependent on both schedule and presence sensors, but in the model they are set to be dependent only on schedule. The result is that presence is assumed from 8 to 5 on weekdays. The effects of starting the daytime ventilation manually, outside office hours, are also neglected since this cannot be modeled in a good way in IDA.

The control model was developed in 4 steps, case 1-4 in the figure below. As a first step the maximum and minimum airflow was adjusted. The next step was to adjust for the fact that the supply temperature during night cooling is a bit higher than expected. After that one last adjustment was made to account for the fact that the indoor temperature generally does not seem to increase to 23°C during daytime, as specified in the room temperature settings. The daytime upper limit was instead lowered to 22.7, which causes the airflow to increase and better fit to the measured values.

Case 4 is chosen as a base case for the further studies. However some differences in flow pattern during the workday remains, where the measurements show an increased airflow quite early, and the model waits until the afternoon to increase the flow. This is probably a result of the fact that the model only have one zone. In reality, the VAV-system may request large airflows in small offices and meeting rooms even when the building as a whole only would need minimum airflow if lumped together in one zone.

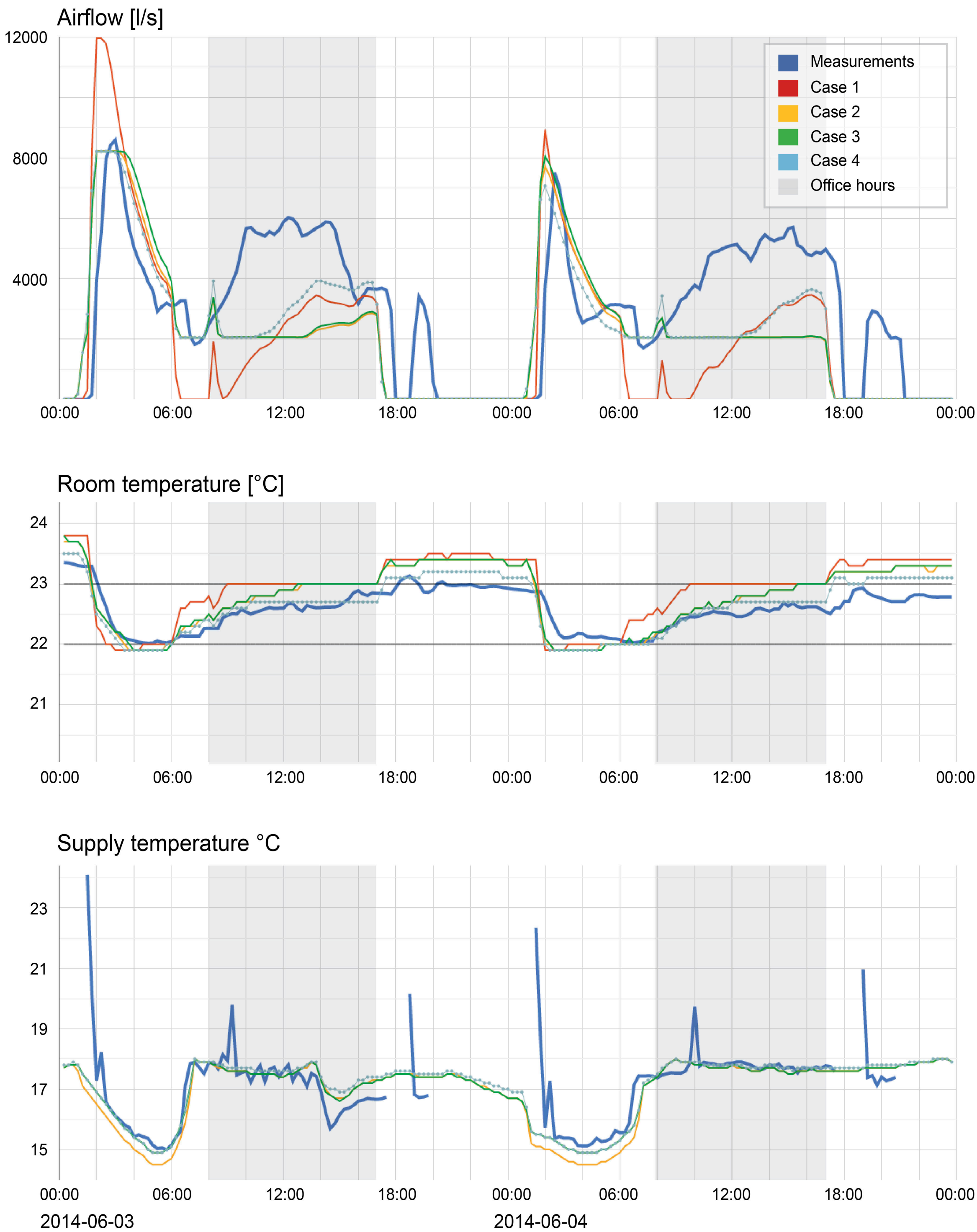


Figure 15: Supply temperature, room temperature and airflow for the tested cases.

Case nr 4 is proceeded with as a base case when trying new control settings, and the assumption is made that a night cooling strategy that shows an improvement in the IDA model, compared to this base case, also would be an improvement in the real building. Possible ways to develop the method in this respect are discussed in the discussion section 8.5.

5.5 Designing and testing new operation cases

Different operation cases were tested and compared to the base case formulated in chapter 5.4. The test cases were divided into 5 case groups.

As a first stage, in case group 1, different extremes were tested, such as removing the night cooling function altogether, or letting it run totally unlimited. As a second stage, in case group 2-4, different control parameters were varied individually in a sensitivity analysis. As a third stage, in case group 5, the strategies that looked promising in the sensitivity analysis were combined and studied in a few different operation cases.

Table 8: Case group 1, initial investigations

Case number and name	Description
Case 1.1 No night cooling	The night cooling function is completely turned off.
Case 1.2 Unrestricted night cooling	Night cooling can run from 17:00 to 07:00, regardless of outdoor temperature and benefit limit, as long as indoor temperature remains within requirements during office hours.
Case 1.3 No night cooling in weekends	Night cooling function disabled during weekends in the time schedule.
Case 1.4 Larger temperature span during night cooling	Room temperatures at night are set to go down to 21°C when the night cooling is activated, instead of 22°C in the current setup.
Case 1.5 Maximize current ideas	The current ideas with the night cooling function is to let the temperatures be as low as possible during night, while still remain within the temperature requirements during office hours, and avoid the use of cooling machines during night. This case is a variation of case 1.4, but where the cooling machines are also disabled at night.

Table 9: Case group 2, cooling machine at night

Case number and name	Description
Case 2.1 More cooling machine at night	The cooling machine provides a ΔT of -2°C.
Case 2.2 Less cooling machine at night	The cooling machine provides a ΔT of -1°C.
Case 2.3 No cooling machine at night	The cooling machine is completely turned off during nights.

Table 10: Case group 3, benefit limit

Case number and name	Description
Case 3.1 0°C	Benefit limit set to 0°C
Case 3.2 3°C	Benefit limit set to 3°C
Case 3.3 7°C	Benefit limit set to 7°C
Case 3.4 10°C	Benefit limit set to 10°C

Table 11: Case group 4, flow limit

Case number and name	Description
Case 4.1 4100 l/s	Airflow limited in AHU to 4100 l/s
Case 4.2 6200 l/s	Airflow limited in AHU to 6200 l/s
Case 4.3 12000 l/s	Airflow limited in AHU to 12000 l/s

Table 12: Case group 5, combination cases

Case number and name	Description
Case 5.1 4.1+2.4	A combination of case 4.1 and 2.4
Case 5.2 4.2+2.4	A combination of case 4.2 and 2.4
Case 5.3 4.1+2.4+lower demands	A combination of case 4.1 and 2.4, with room temperatures up to 24°C allowed during office hours.
Case 5.4 4.2+2.4+lower demands	A combination of case 4.2 and 2.4, with room temperatures up to 24°C allowed during office hours.
Case 5.5 4.3+2.4+lower demands	A combination of case 4.3 and 2.4, with room temperatures up to 24°C allowed during office hours.

6 RESULT

The result is described in figure 16, 17 and 18 below. The cases that don’t live up to the current comfort demands, a room temperature between 22°C and 23°C during office hours, are marked with red but kept in the results for discussion.

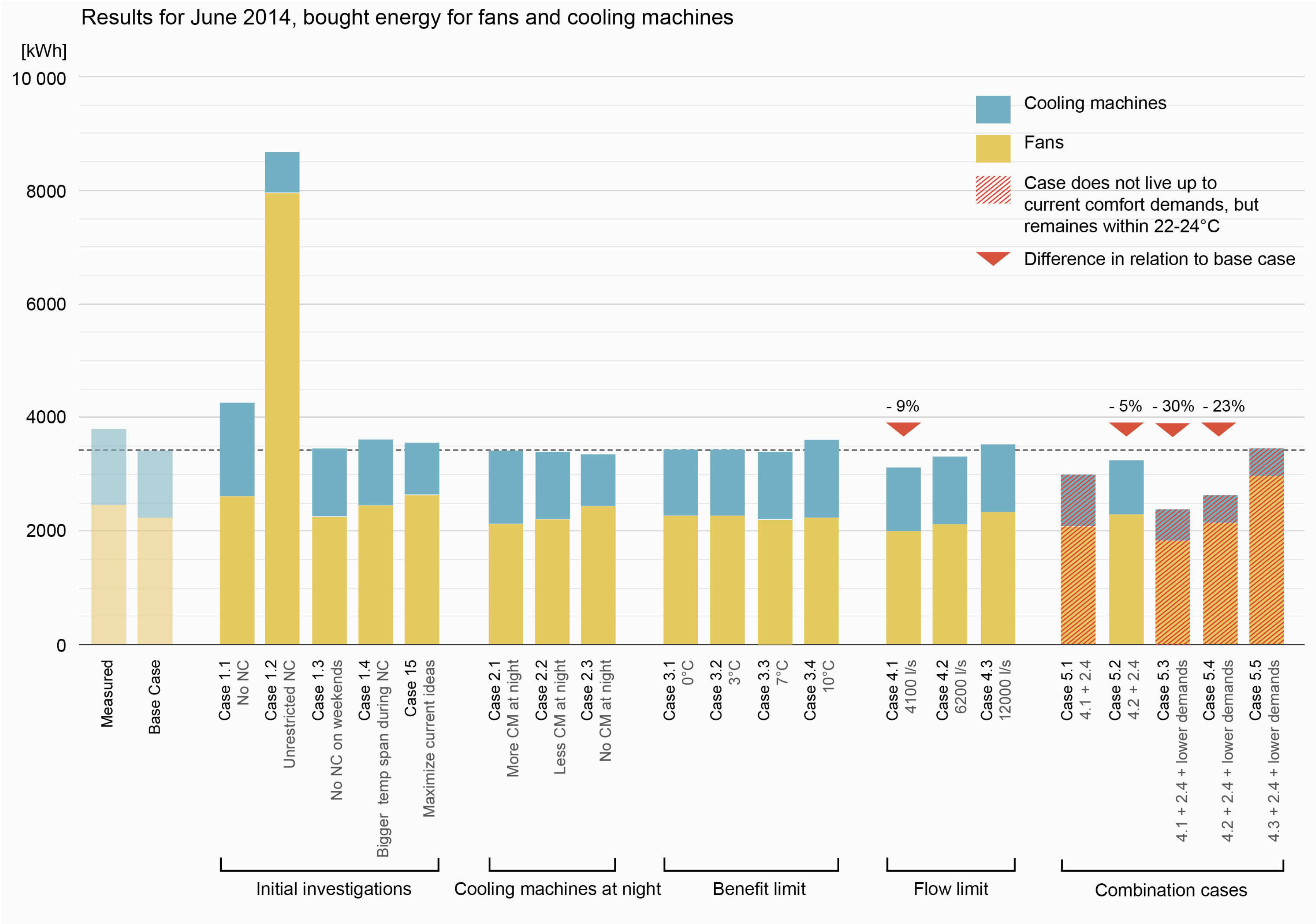


Figure 16: Case results for the indicator bought energy.

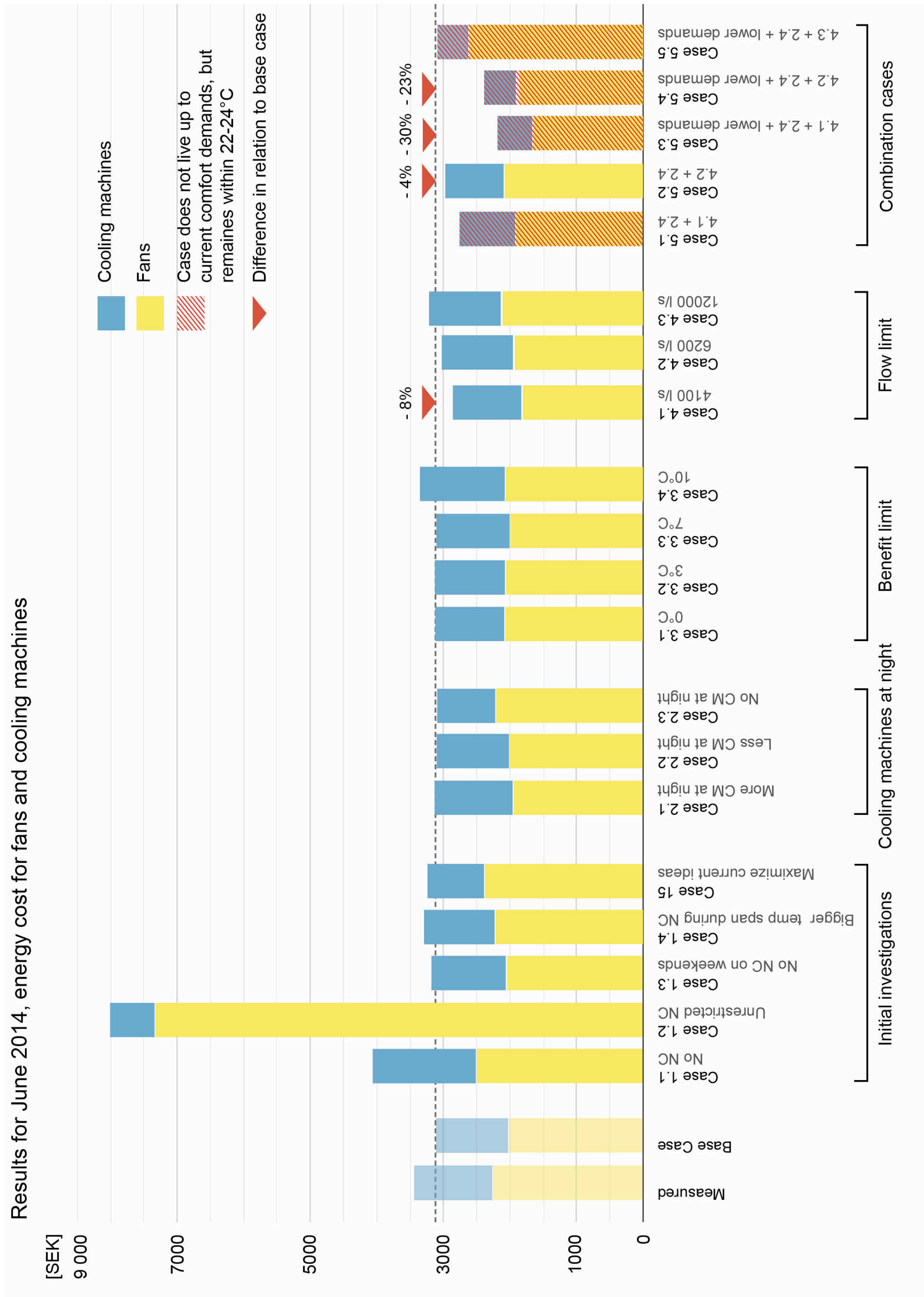


Figure 17: Case results for the indicator electricity cost.

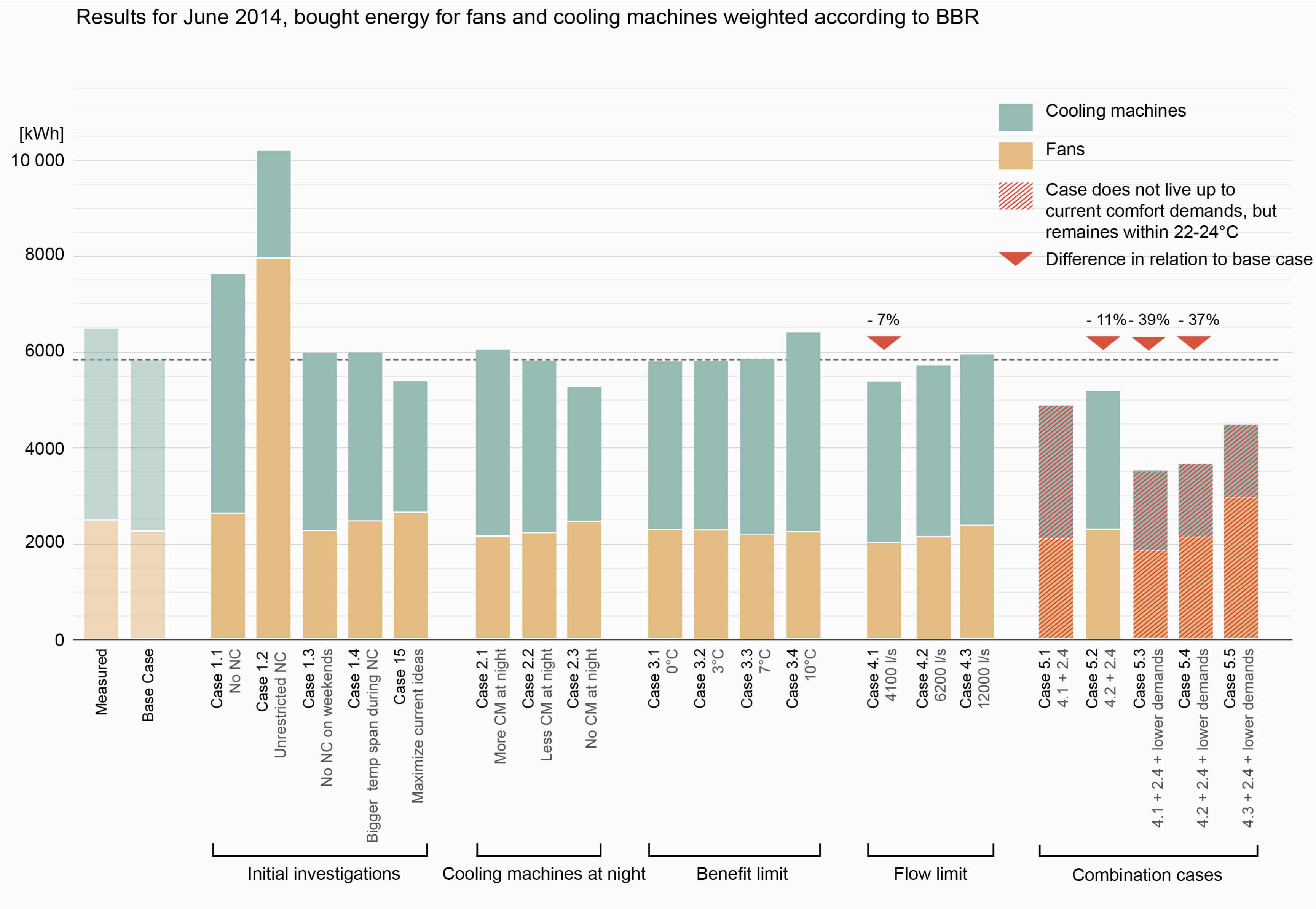


Figure 18: Case results for the indicator bought energy weighted according to BBR.

7 CONCLUSIONS

7.1 Conclusion regarding the case study results

Case group 1

By comparing the base case to case 1.1 it can be concluded that night cooling is a favorable strategy that lowers both energy use, energy cost and Specific Energy Use according to BBR.

In case 1.2 it could also be concluded that running the night cooling function unlimited, regardless of the surrounding conditions is not a good idea. This shows that at least some thought have to go into the process when using night cooling as a strategy, and that applying it in the wrong way can cause an increased energy use.

Case 1.3, where the schedule allows no night cooling during weekends, very little change is seen. The idea behind this case was that maybe there are not a lot of gains in the weekends and that applying the night cooling during that time could be a waste of fan power. As it turned out the temperature in the weekends climb quite high without the night cooling, and the energy demand on Monday morning becomes really high instead. The result in case 1.3 led to the decision to not study the effects of varying the time schedule further. The allowed timespan for night cooling seems large enough for the room temperatures to reach the desired set point and the flow requested by the VAV system to decrease as a consequence of that. If the timespan is larger than needed that doesn't really matter.

In case 1.4 and 1.5 the idea to let the temperature go lower during the nights was tested, and the indoor temperature was allowed to go as low as possible without compromising with indoor temperature requirements in the morning. In case 1.5 the cooling machines were turned off during night as well, taking full advantage of the free outdoor air. These cases showed no improvement compared to the base case, except case 1.5 that shows improvement when it comes to specific energy use BBR. Since that strategy led to a lower electricity use for the cooling machines, compared to the base case, this becomes important when the cooling electricity is counted with a factor 3.

Case group 2-4

In case group 2 the extent to which the cooling machines are used at night is varied. Varying this parameter has very little impact on the cost or overall use of energy. There is a small tendency towards a lower energy use when the cooling machines are used less, but mostly the benefit from turning the cooling machines off at night seem to be balanced out by the fact that the fans have to be used more. However, shifting energy use from cooling machines to fans is beneficial when looking at specific energy use according to BBR as indicator to compare.

In case group 3 the benefit limit was varied. Setting the benefit limit very high would of course lead to a result identical to 1.1, with no night cooling at all. Varying the benefit limit within reasonable limits, however, had very little effect. It turns out that the benefit limit is seldom the determining parameter to decide whether the night cooling runs or not. If the indoor temperature is high enough at the end of the day, indicating that it's cooling season, it is rarely a problem in Sweden that the outdoor temperature at night is high enough to be anywhere close to the indoor temperature. This parameter is probably more relevant in a hotter climate.

Case group 4, investigating the impact of limiting the maximum air flow in the AHUs, had a little more effect on the result. As a general trend it can be seen that running the night cooling at lower flows , avoiding the initial peak when the night cooling function activates, is beneficial for all indicators.

Case group 5

In case group 5 different promising strategies were combined. In case 5.1 it can be seen that both limiting the airflow very heavily and limiting the use of cooling machines at night provides too little cooling power. Even though the strategies work individually the temperature rises above 23°C during the afternoons if they are combined. Case 5.2 which allows a bit more airflow worked well.

In cases 5.3 to 5.5 the allowed temperature span was a bit wider. Case 5.3 shows a significant improvement and is the most beneficial test case for all indicators. This is of course partly because allowing a higher temperature reduces the need for cooling in general, but also because it allows for a more efficient use of night cooling. By letting the temperatures rise a bit higher in the afternoon the cooling need is "saved for later" and can instead be taken care of using the free outdoor air instead of the cooling machines.

7.2 Conclusions regarding indicator differences

The outcome varied very little between the price indicator or the energy indicator. The fact that energy is cheaper during night did not have any noticeable effect and these two indicators showed the same tendencies throughout the study. Comparing the cases fulfilling the current comfort requirements, case 4.1 is the most favorable one for both these indicators.

The indicator for specific energy use according to BBR, where cooling machine energy is counted with a factor 3, showed somewhat different results. Not surprising, this indicator showed more favorable results for test cases where the use of cooling machines is minimized during nights. Comparing the cases fulfilling the current comfort requirements, case 5.2 is the most favorable one.

However, the airflows during daytime is a parameter that shows some difference between the measured values and the closest model in IDA. As discussed in chapter 5.4.3, this is probably a consequence of the use of a single zone model, and it may not be possible to put the limit that low in reality without losing comfort. If the cases where the flow is limited to the lowest value, case 4.1 and 5.1, are regarded as unsafe, the next best alternative is case 5.2. This alternative then becomes the preferable one for all indicators.

7.3 Proposed changes in Kängurun 18

The combined strategies of making sure that the cooling machines are turned off at night and capping the maximum flow of the fan could be tried in the real building. As discussed in chapter 7.2 it may not be possible to limit the flow as low as in case 4.1 and 5.1 without losing comfort. But the strategy should still be valid, and it should be possible to use case 5.2. Case 5.2 has a flow limit of 6200 l/s, which is above the measured daytime flows and still shows a 5% lower energy use for cooling. It can also be seen in this study that somewhat less strict requirements on comfort could be very beneficial if the tenants of the building find that acceptable.

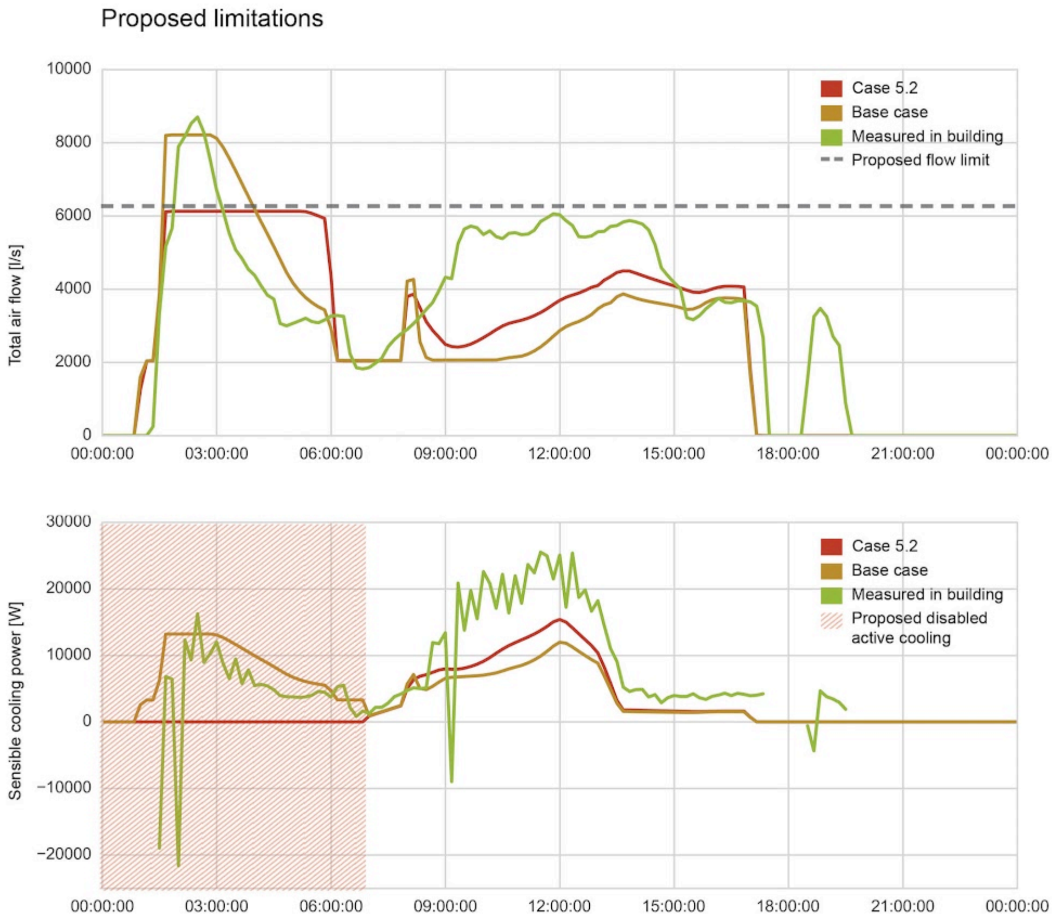


Figure 19: Airflow and cooling machine activity during example day 2014-06-03. Proposed limitations indicated in figure.

If the proposed changes are to be implemented in the real building there are also other issues to take into account. An important aspect when limiting the maximum flow or pressure provided by the AHUs is to make sure that fire safety is not affected. The building is designed for the fans to be active in case of a fire event, and the proposed cap on AHU air flows should not remain if the ventilation system is used for smoke evacuation. How the control system deals with fire alarms should therefore be investigated before applying limits to the flow.

8 DISCUSSION

8.1 Reflections regarding the result

The result is very specific for this building and the result itself is probably not transferrable to other situations. The studied building is not typical, and a larger allowed temperature span, a lighter building or less efficient solar shading could, for example, lead to a different optimal solution. However, the method developed in this thesis could be reused as a tool to investigate and improve systems control. Night cooling is one example, but the method could also be used in other areas.

The proposed case to apply in the real building shows a 5% lower cooling energy need in the simulations, compared to the base case. This figure should be regarded as an approximation and not as a prediction of the exact improvement. The calculations are not done for the entire cooling season but only for one month and there is not a total compliance between the measurements and the base case.

The studied building was constructed with a very high aim and is one of the more energy efficient offices in Sweden. This study shows that it may be possible to reduce energy use even more, using this method. The improvement is not very big, but on the other hand the building is already managed by a skilled and experienced building technician. Technicians with extensive experience and high skill level when it comes to managing systems in complex buildings are not always available, and this study shows that it is possible to arrive at quite similar conclusions with less experience but more tools in modeling and numerical analysis.

Regarding the use of indicators it can be seen that it did not matter much for this building. For the application in this study it can be concluded that the difference between electricity prices during day and night is not large enough to make it interesting to take varying price into account when managing a building. One of the ideas behind providing an hourly price and a free electricity market is to shift electricity use to times when it’s easier to produce or the demand is lower. In the discussion around smart grids there is a hope that buildings will be a part of this shift, but the incentive is still too low to make that interesting for the kind of applications studied in this thesis.

8.2 Detailed data or detailed building modelling?

Generally, when making energy calculations for buildings, there is a tendency to focus on the model of the physical building such as multiple zones, building geometry, wall properties etc. When it comes to other indata there is a tendency to rely on rule of thumb and general purpose approximations. In this study the method was the opposite; using a very simple model but studying the conditions and indata patterns of the specific building closely. Of course these two methods are not really in opposition, but when time is limited a choice have to be made regarding where to place the effort.

There are pros and cons with both methods. The data driven approach used for this study is of course not possible for all projects. The building has to be built already, and the data has to be gathered and available. But if that is the case, and energy efficiency measures are compared, the data driven method may see a different set of potential solutions that otherwise will be overlooked. In this study the difference between the actual building and the standard assumptions was sometimes quite large. The fact that the cooling machines are running at night would probably have been overlooked without the use of gathered data, and this turned out to be one of the two major suggested improvements.

One big risk regarding use of actual measurements in energy analysis is that the gathered datasets may not be representative. However, this is a risk also when using standard values and averages as indata. As an example SMHI (Swedish Metrological and Hydrological Institute) recently changed the standard for normal year correction of energy statistics due to current trends towards a hotter climate. In fact many of the commonly used climate files that are based on averages of older data may be outdated due to climate change. Another important aspect of using actual measurements in energy analysis is taking care when mixing gathered data with standard assumptions. For example, drawing conclusions from a model that uses time series data from cooling machines for an extraordinary hot summer but normal year corrected weather data could easily lead to pitfalls.

How applicable the data driven approach is, compared to other available methods, largely depends on the availability and quality of the data. If the data is easily accessible and fairly well structured, and the post processing tools are good, it could probably be in the same range as other methods when it comes to required working hours for analyzing a building. But if there are large problems with the datasets and collection methods it can easily become very time consuming.

When it comes to post processing and analysis of data a large number of tools, both building industry specific and general purpose tools, were investigated in the prestudy phase of this thesis. The chosen tool, Python and Pandas, worked very well. The rich amount of documentation and online discussion makes problem solving very time efficient, provided that the user has a little programming experience.

8.3 Possible improvements in data collection in Kängurun 18

As discussed in the previous chapter structured, documented and available data is key to make this method possible and reasonably fast. Quite a few problems occurred in this study, and some of them seem unnecessary when taking into account that money and effort is spent on making this building a modern test case. Below are three main points that would make data driven analysis methods smoother:

- Have one data storage and gather all the relevant data that is intended to be stored in one place. To make it easily accessible, make it available over internet by using a service with well documented APIs. The Azure table storage used in this building is a good example in that aspect, but has little to no advantage over the previously used systems if it’s not implemented all the way.

- If the data is intended to be used by someone else than the person who set the system up it has to be documented. The data gathered in this building is intended to be used in research and is also meant to follow the building if it's sold. The current level of documentation is not enough to be able to do that in a good way, and there is a large risk that a lot of knowledge will be lost if a few responsible people for some reason are no longer available. There is always a knowledge loss if important people leave, but it should not be on a level that renders fairly large investments useless. In fact a former employee had to be contacted during the work with this study and the fact that this thesis could be completed relies completely on that he was kind enough to take time to help. When it comes to documentation many of the customs followed in modern IT development could probably be implemented in the building industry with good results.

- A couple of problems that occurred had to do with malfunctions and lack of documentation when it comes to equipment where product manufacturers and entrepreneurs are responsible. This is probably not an issue that concerns this building in particular, but rather the building industry as a whole. It may seem unreasonable to invest a lot of money in systems and equipment and not be able to find out exactly what they do, but this is sometimes the case. The impression from working with this thesis is that the building industry accepts a much lower standard when it comes to access and documentation than consumers of other technology.

8.4 The future of data driven analysis of technical systems in buildings

The method developed in this study is usable as it is, and is probably interesting to use for some types of projects. But for applications like the one in this thesis where the building already functions well the economical benefit in terms of energy savings would not make it worth it. Even if no extra investments are needed there is still a cost involved in terms of consultancy hours. On the other hand projects where there are comfort problems or a larger energy savings potential the method may be more economically interesting.

The fact that these improvements could be found even in this very energy efficient building indicates that the potential to decrease energy use in the building stock by improved systems control could be very large. The residential sector typically lack these systems, but most offices, schools, hospitals and other public buildings have some kind of automation in place. With an increased focus on energy and climate issues and a growing possibility and interest for data collection there is a big potential for development in this area. To what extent that potential is used at the moment depends, among other things, on the energy prices and the availability of skilled and experienced technicians. Data driven analysis could contribute, and will probably be an increasing part of the work with energy efficiency.

In the future it is possible that the external cloud based control services will have a larger role. Calibrated zone models and control parameter optimization could be dealt with systematically in these services. That way an optimization method or algorithm could be applied on several buildings at once. If that happens it would be in line with general trends in the IT sector, where cloud services selling the same replicated analysis to multiple consumers are common. For that development to take off there are however a few barriers in the building industry that need to be overcome, such as the hesitant attitude to open data access among entrepreneurs and systems manufacturers.

8.5 Recommendations for further studies

To further develop this method it could be interesting to see how it behaves when analyzing a building with a less favorable point of departure. In some ways it has been a challenge that the test case building in this thesis was already working very well, but on the other hand a different set of challenges come when a building has for example large comfort problems, regulatory instability of very insufficient solar shading.

Another possible way to develop the method in this thesis is to try it with multiple zones. As indicated in this study one zone may not be enough. For this building in particular a way forward could be to try two zones, one that represents the heavily used office areas and another zone to represent less used areas such as the dining hall. In buildings with more influence from the sun there may be a need for zones in all directions.

9 References

Boverket (2015): *Boverkets byggregler, BFS 2011:6 med ändringar t.o.m. BFS 2015:3,* (Boverket´s Building regulations, BFS 2011:6 with amendments up to version 2015:3. In Swedish), Boverket, Sweden

Eriksson E. et al (2013): *Prismodeller för egenproduktion av el, Elforsk rapport 13:40* (Price models for own production of electricity, Elforsk report 13:40. In Swedish), Elforsk, Stockholm, 2013, Sweden, 26 pp.

Coakely D. et al (2012): *Calibration of whole building energy simulation models*, First Building Simulation and Optimization Conference, Loughborough, UK, September 2012

Kajl S. et al (2005):*Optimization of HVAC Control System Strategy Using Two-Objective Genetic Algorithm*, HVAC and Research, No. 3, July 2005

Lain M. and Hensen J. (2006): *The optimization of the mechanical night cooling system in the office building,* 6th International Conference on Compressors and Coolants, Casta Papiernicka, Slovakia, September 2006, 8 pp.

APPENDIX A: IDA SIMULATION INDATA

Building property	**Base Case** Phase 1	**Base Case** Phase 2 and 3	**Base Case** Chapter 5.5
Geometry and construction			
Atemp	4114 m^2	4114 m^2	4114 m^2
U-value wall	0.17 W/ m^2K	0.17 W/ m^2K	0.17 W/ m^2K
Exposed thermal mass	1000 m^2 of 26 mm gypsum	3000 m^2 of 26 mm gypsum	3000 m^2 of 26 mm gypsum
Infiltration	neglected	neglected	neglected
Thermal bridges	neglected	neglected	neglected
Window and shading properties			
g-value, windows	0.55	0.55	0.55
U-value, windows	0.72	0.72	0.72
g-multiplier, external blinds	0.1	0.1	0.1
Radiation limit where blinds are drawn	50 W/m^2	50 W/m^2	50 W/m^2
Zone set points			
Temperature span, weekdays daytime (8:00-17:00)	-	-	22°C - 22.7°C
Temperature set point, night cooling active	-	-	22°C
Temperature span, other times	-	-	19°C - 26°C
Max CO2 levels	1000 ppm	1000 ppm	1000 ppm
Max airflow	2.91 l/s m^2	2.91 l/s m^2	2.0 l/s m^2
Air handling unit			
Maximum fan power (incl return air fans)	50 kW	50 kW	50 kW
Maximum supply air flow	12 000 l/s	12 000 l/s	12 000 l/s
Return air flow	assumed balanced	assumed balanced	assumed balanced
Neutral temp raise across AHU	-	-	2.34 °C

Supply air, daytime ventilation			
Schedule	Scheduled to measured values	Scheduled to measured values	Weekdays: 07:00-17:00 Sat: - Sun: -
	Scheduled to measured values	Scheduled to measured values	Requested to comply with temp. requirements in zone
Supply air temperature	Scheduled to measured values	Scheduled to measured values	Outdoor temperature dependent according to curve in figure 11
Supply air, night cooling ventilation			
Schedule	Scheduled to measured values	Scheduled according to measured values	Weekdays: 01:00-7:00 Sat: 03:00-7:00 Sun: 02:00-7:00
Supply air flow	Scheduled to measured values	Scheduled to measured values	Requested in IDA to comply with temp. requirements in zone
Supply air temperature	Scheduled to measured values	Scheduled to measured values	Outdoor air temperature +1°C
Cooling machines			
COP sensible	electricity use not calculated	electricity use not calculated	2.91
Occupancy			
Occupants per office floor (08:00-17:00)	50	50	50
Presence	60%	60%	60%
Light and appliances			
Scale factor (applied on source file based on data from electricity meters)	1	1	1

APPENDIX B: SOFTWARE AND EQUIPMENT

Programming languages and software versions

Application	Version	Comment
IDA ICE	4.6.2	Building energy simulation software
SQLite3	3.8.5	SQL database engine
Python	2.7.9	Main programming language used for post processing of data in this thesis
Anaconda	2.1.0	Python distribution containing commonly used libraries for scientific computing. The ones of major importance are included in this list.
NumPy	1.9.1	Numerical methods python library
SciPy	0.15.1	Scientific computing python library
Pandas	0.15.2	Dataset and time series analysis python library
Matplotlib	1.4.0	Graphical plotting python library
Seaborn	0.5.1	Statistical data visualization python library
IPython	2.3.1	Command shell
IPython notebook	2.3.1	Browser based computational environment for IPython

Equipment and model

Equipment	Model
Pyranometer	Kipp & Zonen CMP 3

APPENDIX C: EXAMPLE OF CODE

Script that:

- Calculates COPsensibel and total sensible cooling energy for a measured time series in an SQLite database
- Loads IDAprn result files
- Calculates COPsensibel and total sensible cooling energy in IDA result
- Calculates energy price (from hourly Spot price, no utility company fees included)

Written by Anna Larsson, April 2015

In [2]:

```
# Load libraries
import pandas as pd
import sqlite3
import matplotlib.pyplot as plt
import numpy as np
%matplotlib inline

# Graphic settings
import seaborn as sns
sns.set(style="whitegrid")
sns.set_palette(sns.hls_palette(10, l=.4, s=.7))
plt.rcParams['figure.figsize'] = (15, 7)
plt.rc('xtick', labelsize=13)
plt.rc('ytick', labelsize=13)

#Versions
%load_ext version_information
%version_information numpy, scipy, matplotlib, sympy
```

```
The version_information extension is already loaded. To reload it, us
e:
  %reload_ext version_information
```

Out[2]:

Software	Version
Python	2.7.9 64bit [GCC 4.2.1 (Apple Inc. build 5577)]
IPython	2.3.1
OS	Darwin 14.1.0 x86_64 i386 64bit
numpy	1.9.1
scipy	0.15.1
matplotlib	1.4.0
sympy	0.7.5
Wed May 20 17:40:44 2015 CEST	

LOAD DATA

In [3]:
```
# Load measurements and base case as time series from database

# Database connections
con = sqlite3.connect("/Skola/2015_Thesis/Databehandling/Databas/BestO
fBDAB5min")
conEl = sqlite3.connect("/Skola/2015_Thesis/Databehandling/Databas/ElM
atareBETA")
conIDA = sqlite3.connect("/Skola/2015_Thesis/Databehandling/Databas/Be
stOfIDA")

# Electricity for lumped AHUs (UTC+2 during summers) (10 min instant v
alues, said to represent coming interval)
# Fan power, electric [W]
df_BDAB_P_FANS = pd.read_sql("SELECT * from BDAB_P_FANS AS INT", conE
l)
# Heatpump power, electric [W]
df_BDAB_P_HEATPUMPS = pd.read_sql("SELECT * from BDAB_P_HEATPUMPS AS I
NT", conEl)
# Fan energy, electric [kWh]
df_BDAB_EL_FANS = pd.read_sql("SELECT * from BDAB_EL_FANS AS INT", con
El)
# Heat pump energy, electric [kWh]
df_BDAB_EL_HEATPUMPS = pd.read_sql("SELECT * from BDAB_EL_HEATPUMPS AS
INT", conEl)

# Electricity price
df_SE3 = pd.read_sql('SELECT * from SE3 AS INT', conEl)
df_SE3['SE3'] = df_SE3['SE3'].convert_objects(convert_numeric=True)

# Lumped AHUs (UTC) (5min, mean value of coming interval)
# Supply air flow [l/s]
df_BDAB_FL_GF11 = pd.read_sql("SELECT * from BDAB_FL_GF11", con)
# Supply air temperature [degC]
df_BDAB_GT11 = pd.read_sql('SELECT * from BDAB_GT11', con)
# Outdoor temperature [degC]
df_BDAB_UTE_GT31_PV = pd.read_sql('SELECT * from BDAB_UTE_GT31_PV', co
n)
df_BDAB_P_IN_COP = pd.read_sql("SELECT * from BDAB_P_IN_COP", con)
# Average temperature in centrally placed sensors [degC]
df_BDAB_CENT_AVG_GT = pd.read_sql("SELECT * from BDAB_CENT_AVG_GT", co
n)

# IDA base case
df_IDA_BC = pd.read_sql("SELECT * from IDA_BC", conIDA)
```

In [4]:
```
# Gather datasets from measurments
allDf=[df_BDAB_P_FANS,
       df_BDAB_P_HEATPUMPS,
       df_BDAB_EL_FANS,
       df_BDAB_EL_HEATPUMPS,
       df_BDAB_FL_GF11,
       df_BDAB_P_IN_COP,
       df_BDAB_GT11,
       df_BDAB_UTE_GT31_PV,
       df_BDAB_CENT_AVG_GT]


allID=['BDAB_P_FANS',
       'BDAB_P_HEATPUMPS',
       'BDAB_EL_FANS',
       'BDAB_EL_HEATPUMPS',
       'BDAB_FL_GF11',
       'BDAB_P_IN_COP',
       'BDAB_GT11',
       'BDAB_UTE_GT31_PV',
       'BDAB_CENT_AVG_GT']
```

ANALYSIS ON SCADA DATA FROM THE BUILDING

In [5]:
```
# Make datetime index
for x in allDf:
    x.set_index(pd.DatetimeIndex(x['TIMESTAMP']),drop=False,inplace=Tr
ue)

df_SE3.set_index(pd.DatetimeIndex(df_SE3['TIMESTAMP']),drop=False,inpl
ace=True)

# Move SCADA data to UTC+2
df_BDAB_P_IN_COP.index = df_BDAB_P_IN_COP.index + pd.offsets.Hour(2)
df_BDAB_FL_GF11.index = df_BDAB_FL_GF11.index + pd.offsets.Hour(2)
df_BDAB_GT11.index = df_BDAB_GT11.index + pd.offsets.Hour(2)
df_BDAB_UTE_GT31_PV.index = df_BDAB_UTE_GT31_PV.index + pd.offsets.Hou
r(2)
df_BDAB_CENT_AVG_GT.index = df_BDAB_CENT_AVG_GT.index + pd.offsets.Hou
r(2)

# Resample SCADA data and price data to 10 min intervals
df_BDAB_P_IN_COP = df_BDAB_P_IN_COP.resample('10Min')
df_BDAB_FL_GF11 = df_BDAB_FL_GF11.resample('10Min')
df_BDAB_GT11 = df_BDAB_GT11.resample('10Min')
df_BDAB_UTE_GT31_PV = df_BDAB_UTE_GT31_PV.resample('10Min')
df_BDAB_CENT_AVG_GT = df_BDAB_CENT_AVG_GT.resample('10Min')

df_SE3 = df_SE3.resample('10Min')
df_SE3['SE3']=df_SE3['SE3'].fillna(method='ffill')

# Gather data in one dataframe
df_BDAB= pd.DataFrame() #empty dataframe
count=0
for x in allDf:
    df_BDAB[allID[count]]=x[allID[count]]
    count=count+1
```

In [6]:
```
# Choose time interval
daysLow = '2014-06-01 00:00'
daysHigh = '2014-06-30 23:59'

for x in allDf:
    x=x[daysLow:daysHigh]

df_BDAB = df_BDAB[daysLow:daysHigh]
df_SE3 = df_SE3[daysLow:daysHigh]

# Append price to gathered dataframe, convert to price per kwh
df_BDAB['SE3']=df_SE3['SE3']/1000
```

In [7]:
```
#Calculate COPsensible for SCADA data

#Columns for sensible cooling power in AHU, excl. neutral dT
df_BDAB['BDAB_DT_IN_COP'] = df_BDAB['BDAB_GT11']-(df_BDAB['BDAB_UTE_GT
31_PV']+2.34)
df_BDAB['BDAB_P_IN_COP'] = df_BDAB['BDAB_FL_GF11']*1.2*df_BDAB['BDAB_D
T_IN_COP']

#Integration to calculate cooling energy in AHU, in kWh
df_BDAB['BDAB_Q_IN']=df_BDAB['BDAB_P_IN_COP']*0.166667/1000 #kWh kylen
ergi

# Columns for electric energy applied in heat pumps and fans
df_BDAB['BDAB_EL_HEATPUMPS_DIFF'] = df_BDAB['BDAB_EL_HEATPUMPS'].shif
t(-1) - df_BDAB['BDAB_EL_HEATPUMPS'] #kWh värmepumpsel
df_BDAB['BDAB_EL_FANS_DIFF'] = df_BDAB['BDAB_EL_FANS'].shift(-1) - d
f_BDAB['BDAB_EL_FANS'] #kWh fläktel

#Result for chosen time span
Q_cool_el=df_BDAB.BDAB_EL_HEATPUMPS[-1]-df_BDAB.BDAB_EL_HEATPUMPS[0] #
Total used electricity, kWh
Q_cool_sens=-df_BDAB['BDAB_Q_IN'].sum() # Total added sensible coolin
g, kWh

COP_sens=Q_cool_sens/Q_cool_el

print('BDAB - sensible cooling:')
print(Q_cool_sens)
print('BDAB - cooling macine el:')
print(Q_cool_el)
print('COP sensible:')
print(COP_sens)
```

```
BDAB - sensible cooling:
3932.32111347
BDAB - cooling macine el:
1334.0
COP sensible:
2.94776695163
```

ANALYSIS ON IDA PRN FILE

In [8]:
```
#Load IDA-prn


#URI
URI_FLOWS = '/Skola/2015_Thesis/IDAresultat/Casegroup6/Case6-2/AHU_FLO
WS.prn'
URI_TEMPS = '/Skola/2015_Thesis/IDAresultat/Casegroup6/Case6-2/AHU_TEM
PERATURES.prn'
URI_ENERGY = '/Skola/2015_Thesis/IDAresultat/Casegroup6/Case6-2/AHU-EN
ERGY-DETAILS.prn'
URI_ZONETEMP = '/Skola/2015_Thesis/IDAresultat/Casegroup6/Case6-2/TEMP
ERATURES.prn'

URI_BC_ZONETEMP = '/Skola/2015_Thesis/IDAresultat/BaseCase/TEMPERATURE
S.prn'

#Fetch from database
df_IDA_AHU_FLOWS = pd.read_csv(URI_FLOWS, sep=r"\s*", engine='python')
df_IDA_AHU_TEMPS = pd.read_csv(URI_TEMPS, sep=r"\s*", engine='python')
df_IDA_AHU_ENERGY = pd.read_csv(URI_ENERGY, sep=r"\s*", engine='pytho
n')
df_IDA_ZONETEMP = pd.read_csv(URI_ZONETEMP, sep=r"\s*", engine='pytho
n')

df_IDA_BC_ZONETEMP = pd.read_csv(URI_BC_ZONETEMP, sep=r"\s*", engin
e='python')
```

In [9]:
```
# Make datetime index
day_start=pd.datetime(2014,06,01)
IDAtime_start = df_IDA_AHU_FLOWS.time[0]
df_IDA_AHU_FLOWS['TIMESTAMP'] = day_start
df_IDA_AHU_TEMPS['TIMESTAMP'] = day_start
df_IDA_AHU_ENERGY['TIMESTAMP'] = day_start

df_IDA_ZONETEMP['TIMESTAMP'] = day_start
df_IDA_BC_ZONETEMP['TIMESTAMP'] = day_start

for x in df_IDA_AHU_TEMPS.index:

    DT = df_IDA_AHU_TEMPS.time[x]-df_IDA_AHU_TEMPS.time[0]
    hours = int(df_IDA_AHU_TEMPS.time[x]-df_IDA_AHU_TEMPS.time[0])
    minutes = int(60*(DT-hours))
    df_IDA_AHU_TEMPS.TIMESTAMP[x]=df_IDA_AHU_TEMPS.TIMESTAMP[x] + pd.o
ffsets.Hour(hours) + pd.offsets.Minute(minutes)
```

In [10]:
```
# Gathered dataframe for IDA case
df_IDA = df_IDA_AHU_TEMPS.copy()
df_IDA['sf_volflow'] = df_IDA_AHU_FLOWS['sf_volflow']
df_IDA['sf_qsup'] = df_IDA_AHU_ENERGY['sf_qsup']
df_IDA['tairmean'] = df_IDA_ZONETEMP['tairmean']


# Set datetime index
df_IDA = df_IDA.set_index(pd.DatetimeIndex(df_IDA['TIMESTAMP']))
```

In [11]:
```
# Columns for sensible cooling power in AHU, excl. neutral dT
df_IDA['IDA_DT_IN_COP'] = df_IDA['tsupply']-(df_IDA['tute']+2.34)
df_IDA['IDA_P_IN_COP'] = df_IDA['sf_volflow']*1.2*df_IDA['IDA_DT_IN_CO
P'] #Watt

#Integration to calculate cooling energy in AHU, in kWh
df_IDA['IDA_Q_IN']=df_IDA['IDA_P_IN_COP']*0.166667/1000

#Column for cooling machine electricity (using calculated COPsens)
df_IDA['IDA_EL_HEATPUMPS_DIFF'] = -df_IDA['IDA_Q_IN']/COP_sens #kWh

#Column for fan electricity
df_IDA['IDA_EL_FANS_DIFF'] = df_IDA['sf_qsup']*0.166667/1000 #kWh

#Results
Q_cool_sens=-df_IDA['IDA_Q_IN'].sum()
Q_cool_el=Q_cool_sens/COP_sens
Q_fan=df_IDA['IDA_EL_FANS_DIFF'].sum()

print('IDA - sensible cooling:')
print(Q_cool_sens)
print('IDA - cooling macine el:')
print(Q_cool_el)
print('IDA - fan el:')
print(Q_fan)
```

```
IDA - sensible cooling:
2856.638348
IDA - cooling macine el:
969.085546745
IDA - fan el:
2295.84269776
```

PROCESS BASE CASE FOR COMPARISON IN GRAPH

In [12]:
```
df_BC_TAIRMEAN = df_IDA_AHU_TEMPS.copy()
df_BC_TAIRMEAN['tairmean']=df_IDA_BC_ZONETEMP['tairmean']
df_BC_TAIRMEAN = df_BC_TAIRMEAN.set_index(pd.DatetimeIndex(df_BC_TAIRM
EAN['TIMESTAMP']))
df_IDA_BC = df_IDA_BC.set_index(pd.DatetimeIndex(df_IDA_BC['TIMESTAM
P']))
```

ELECTRICITY COSTS

In [13]:
```
#Price, SCADA data


df_BDAB['BDAB_COST_HEATPUMPS']=df_BDAB['BDAB_EL_HEATPUMPS_DIFF']*df_BD
AB['SE3']
df_BDAB['BDAB_COST_FAN']=df_BDAB['BDAB_EL_FANS_DIFF']*df_BDAB['SE3']

HeatpumpsCostBDAB=df_BDAB['BDAB_COST_HEATPUMPS'].sum()
FansCostBDAB=df_BDAB['BDAB_COST_FAN'].sum()

print('BDAB SCADA - heatpump cost')
print(HeatpumpsCostBDAB)
print('BDAB SCADA - fan cost')
print(FansCostBDAB)
```

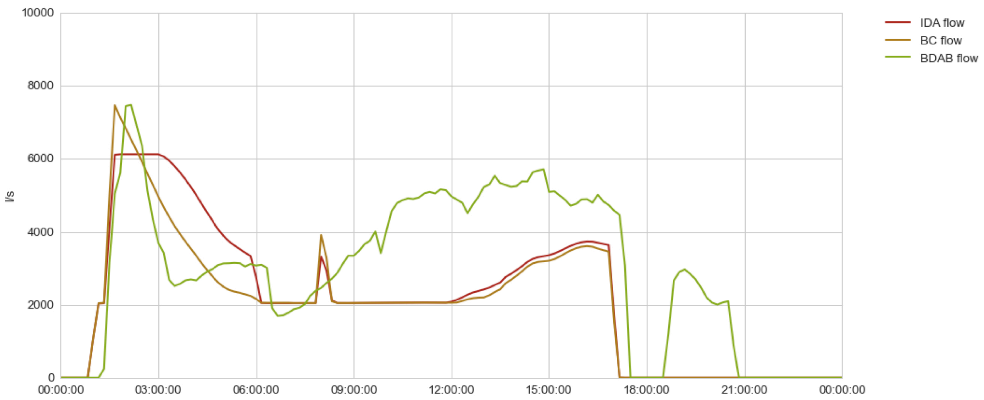
```
BDAB SCADA - heatpump cost
367.020485
BDAB SCADA - fan cost
708.741625
```

In [14]:
```
# Price, IDA case

df_IDA['IDA_COST_HEATPUMPS']=df_IDA['IDA_EL_HEATPUMPS_DIFF']*df_BDA
B['SE3']
df_IDA['IDA_COST_FAN']=df_IDA['IDA_EL_FANS_DIFF']*df_BDAB['SE3']

HeatpumpsCostIDA=df_IDA['IDA_COST_HEATPUMPS'].sum()
FansCostIDA=df_IDA['IDA_COST_FAN'].sum()

print('IDA - heatpump cost')
print(HeatpumpsCostIDA)
print('IDA - fan cost')
print(FansCostIDA)
```

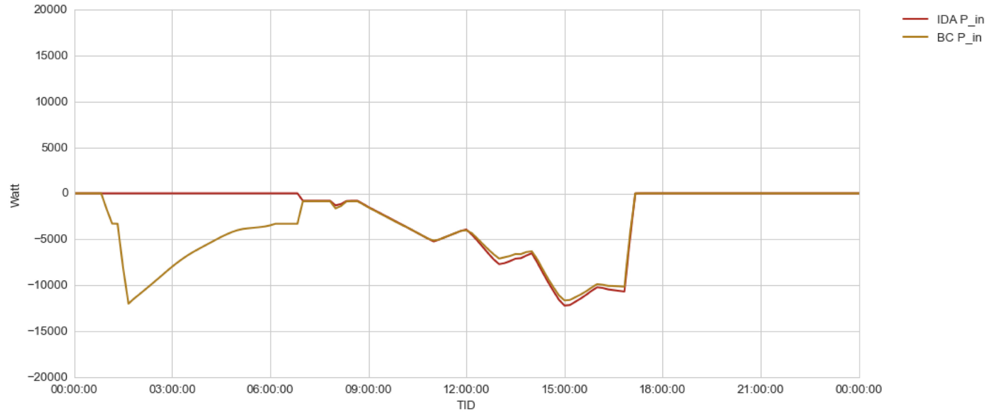
```
IDA - heatpump cost
306.490644924
IDA - fan cost
655.244523987
```

PLOT

```
In [16]: daysLow = '2014-06-04'
         daysHigh = '2014-06-05'

         #Flow
         fig1, ax1 = plt.subplots()

         ax1.plot(df_IDA.index,df_IDA['sf_volflow'], label="IDA flow", lw=2)
         ax1.plot(df_IDA_BC.index,df_IDA_BC['sf_volflow'], label="BC flow", l
         w=2)
         ax1.plot(df_BDAB_FL_GF11.index,df_BDAB_FL_GF11['BDAB_FL_GF11'], labe
         l="BDAB flow", lw=2)

         ax1.set_ylabel('l/s', fontsize=13)
         ax1.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0, prop={'si
         ze':13});

         ax1.set_xlim([daysLow,daysHigh])
         ax1.set_ylim([0,10000])

Out[16]: (0, 10000)
```

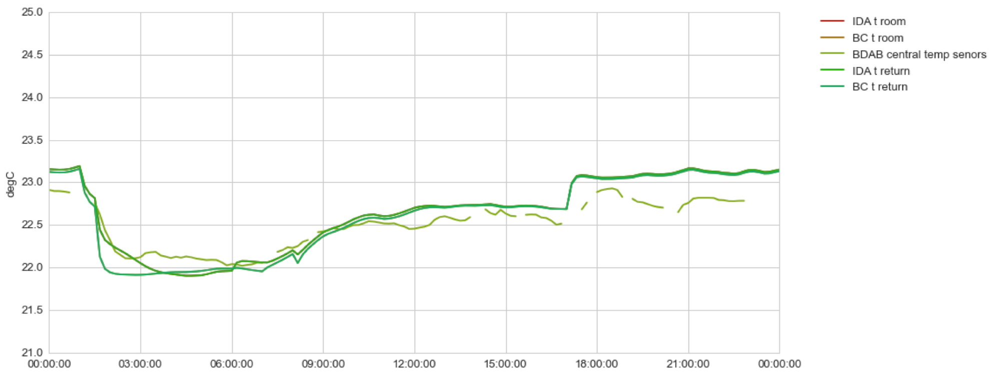


```
In [17]: #Sensible effect in AHU
fig2, ax2 = plt.subplots()

#P_in
ax2.plot(df_IDA.index,df_IDA['IDA_P_IN_COP'], label="IDA P_in", lw=2)
ax2.plot(df_IDA_BC.index,df_IDA_BC['IDA_P_IN_COP'], label="BC P_in", l
w=2)

ax2.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0, prop={'si
ze':13});
ax2.set_xlabel('TID', fontsize=13)
ax2.set_ylabel('Watt', fontsize=13)
ax2.set_xlim([daysLow,daysHigh])
ax2.set_ylim([-20000,20000])

Out[17]: (-20000, 20000)
```



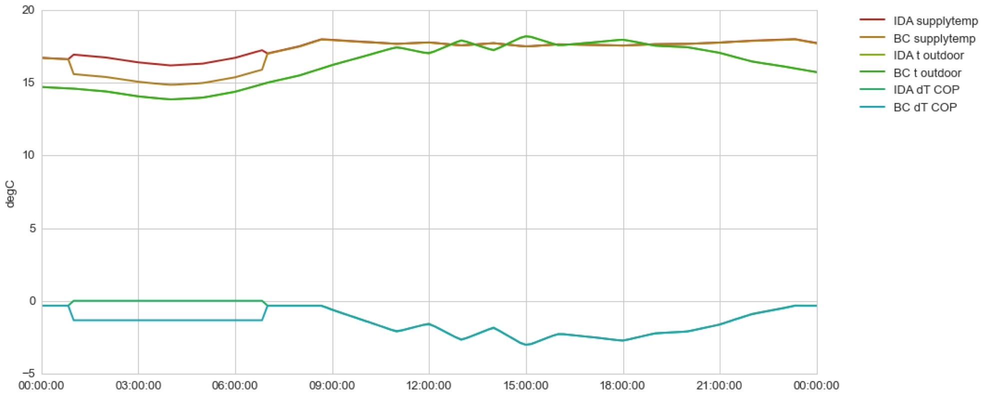
In [18]:
```
#Temperatures
fig3, ax3 = plt.subplots()

# Room temp
ax3.plot(df_IDA.index,df_IDA['tairmean'], label="IDA t room", lw=2)
ax3.plot(df_BC_TAIRMEAN.index,df_BC_TAIRMEAN['tairmean'], label="BC t
room", lw=2)
ax3.plot(df_BDAB_CENT_AVG_GT.index,df_BDAB_CENT_AVG_GT['BDAB_CENT_AV
G_GT'], label="BDAB central temp senors", lw=2)

#return air temp
ax3.plot(df_IDA.index,df_IDA['texhaust'], label="IDA t return", lw=2)
ax3.plot(df_IDA_BC.index,df_IDA_BC['texhaust'], label="BC t return", l
w=2)

ax3.set_ylabel('degC', fontsize=13)
ax3.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0, prop={'si
ze':13});
ax3.set_xlim([daysLow,daysHigh])
ax3.set_ylim([21,25])
```

Out[18]:
```
(21, 25)
```



In [19]:
```
fig4, ax4 = plt.subplots()

#tilluftstemp
ax4.plot(df_IDA.index,df_IDA['tsupply'], label="IDA supplytemp", lw=2)
ax4.plot(df_IDA_BC.index,df_IDA_BC['tsupply'], label="BC supplytemp",
lw=2)

#utetemp
ax4.plot(df_IDA.index,df_IDA['tute'], label="IDA t outdoor", lw=2)
ax4.plot(df_IDA_BC.index,df_IDA_BC['tute'], label="BC t outdoor", l
w=2)

#dt
ax4.plot(df_IDA.index,df_IDA['IDA_DT_IN_COP'], label="IDA dT COP", l
w=2)
ax4.plot(df_IDA_BC.index,df_IDA_BC['IDA_DT_IN_COP'], label="BC dT CO
P", lw=2)

ax4.set_ylabel('degC', fontsize=13)
ax4.legend(bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0, prop={'si
ze':13});
ax4.set_xlim([daysLow,daysHigh])

ax4.set_ylim([-5,20])
```

Out[19]: (-5, 20)



APPENDIX D: PHOTOS OF SENSORS AND CONTROL UNITS

Figure 20: Top left, supply temperature sensor. Top right, preassure sensor after fan. Bottom left, SAIA PLC. Bottom right, Swegon superwise (VAV control units)