NTNU – Trondheim
Norwegian University of
Science and Technology

Indoor climate in a zero energy building

An analysis of the thermal environment and
indoor air quality

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Master of Energy and Environmental Engineering
Submission date: June 2015
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MASTER THESIS

for

Student Odin Budal Søgnen

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Indoor climate in a zero energy building
Inneklima i en nullenergibygning

Background and objective

The research programme Zero Emission Buildings (ZEB) includes so-called pilot buildings as a part of the research. Powerhouse Kjørbo is an older office building that has been renovated to become a zero emissions building. See http://www.powerhouse.no/prosjekter/kjorbo/ for more information.

The goal of the project work is to study how well the applied solutions for heating, ventilation and cooling can provide good thermal environment and indoor air quality.

During the specialization project the candidate studied temperature distribution and thermal comfort in three floors in one of the two blocks. This work indicates that a more in depth study is required. In addition, it is also necessary to study the air distribution, especially in the open office landscapes.

The objective is to study and determine if the chosen solutions at Kjørbo gives a satisfactory indoor thermal and atmospheric indoor climate. It should be discussed if the solutions in general are well suited for ZEB.

The following tasks could be considered:

1. Literature study relevant for the chosen heating, cooling and ventilation strategy
2. Plan and perform measurements
3. Evaluate if simulations are necessary for the evaluation of the measurements
4. Analyse and report

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☒ Field work

Department of Energy and Process Engineering, 28. January 2015

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Preface

This thesis is a result of the work carried out at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU), the spring semester of 2015. It is based on the project work carried out in the autumn of 2014 as a part of the final assignments for a degree in energy and environmental engineering.

It is a study of the indoor climate, with a focus on thermal environment and indoor air quality, in a energy-positive building called Powerhouse Kjørbo. Both fieldwork measurements for temperature and ventilation efficiency in addition to a survey regarding the indoor climate has been conducted in this thesis.

Odin Budal Søgnen

Trondheim, 29.06.2015

Acknowledgments

I would like to thank my supervisor, Hans Martin Mathisen, for all the guidance and help to get a better understanding of the assignment, and for helping me analyze and interpret my results. I would like to thank my co-supervisor, Maria Justo Alonso, who has helped me write a better thesis and also given me many useful tips and relevant literature for the thesis. Both of them also assisted me on my fieldwork, which I couldn't have done without. A big thanks also goes to Rasmus Z. Høseggen who was my co-supervisor during the project work, and helped me understand Powerhouse Kjørbo and the processes behind it.

I would like to thank my student associates, Thea Marie Danielsen and Ivar Nordang. They have been studying the same building, and they have been great discussion partners during the project work and the master thesis.

Additional thanks goes to Inge Håvard Rekstad, Per Egil Gullsvåg and Gyungen Cao for helping me with the preparations for the fieldwork, and Thomas Berker for an insight in the study of domestication of buildings and inspiration for further studies around the perceived indoor climate. And to Olav Rådståga, my inside man in Asplan Viak, who has been of great assistance considering the fieldwork, discussions and insightful information about the building.

I would like to thank my father, who has helped and inspired me through my master's degree since the beginning of my education. And my mother, who has supported me and taught me so many things I could not have done without when writing this report.

Abstract

Buildings are responsible for around 40 % of the world's energy use (Novakovic, 2007), hence also for huge amounts of climate gases, both directly and indirectly. The building industry needs to become a part of the solution of an energy efficient and environmentally friendly future.

Powerhouse Kjørbo is Norway's first energy-positive office building, and is now in its second year of operation. It is an old rehabilitated office building located in Sandvika, outside of Oslo. The goal of a so-called *Powerhouse* is to produce more energy than it uses for materials, production, operation, renovation and demolition during the whole of its lifetime. This has been done by the use of highly efficient technical equipment, recycling and reuse of materials and an energy efficient building envelope. Solar panels have been installed on the rooftops of the building and on top of a nearby parking complex. Calculations show that Powerhouse Kjørbo will reach its goal during the building's lifetime of 60 years.

The heating and cooling demand in the building is covered by a geothermal heat pump, with district heating as peak load when necessary. Motion, temperature and CO_2 sensors optimize the use of lighting, ventilation, heating and cooling. Displacement ventilation with a variable air volume for the open landscapes and meeting rooms is the ventilation strategy. Cell offices use constant air volume displacement ventilation.

The heating and cooling system of Powerhouse Kjørbo is built around a centered heating strategy by waterborne panel radiators at each floor and *free cooling* through the ventilation system. The heating strategy is dependent on heat distributing equally among the open area and other rooms in the building due to no dedicated heat sources outside the center of each floor.

The measured ventilation efficiency indicates that the strategy works more like mixing ventilation than displacement ventilation in terms of removing pollutants and air exchange. This is not a final conclusion and it is suggested that more work is put into analyzing these results and perform new measurements.

Temperature distribution in the open landscapes vary with the outdoor temperature, by being more evenly distributed during higher outdoor temperatures. The horizontal temperature differences on the same floor were up to 2.7 °C during the coldest day (-6.3 °C), and up to 1.7 °C during the warmest day (10.8 °C), both at midday. A cell office with closed door at all times shows a temperature drop of around 2.0 °C between the hallway outside the cell office and inside the cell office during the coldest day at midday. The same is expected, if not a higher temperature drop, in the case of corner meeting rooms if the doors are kept closed.

A survey about the perception of the indoor climate has been conducted for the employees at Powerhouse Kjørbo and an architecturally similar office building, which has been renovated at a lower standard. Results indicate that employees are generally more satisfied with both the thermal environment and indoor air quality at Powerhouse Kjørbo compared to the other building. Complaints about occasionally low temperatures in the building and poor air quality in meetings rooms have been reported, but apart from that the satisfaction of thermal environment and air quality is high.

Sammendrag

Bygninger står for rundt 40 % av verdens energibruk (Novakovic, 2007), og er da også med på å forårsake store mengder klimagasser, både direkte og indirekte. Det er ønskelig at byggenæringen blir en del av løsningen i en energieffektiv og miljøvennlig fremtid.

Powerhouse Kjørbo er Norges første energipositive næringsbygg, og det er nå i sitt andre driftsår. Det er et rehabilitert kontorbygg som ligger i Sandvika utenfor Oslo. Konstruksjonen er basert på konseptet *Powerhouse*; en bygning som i løpet av sin levetid skal produsere mer energi enn det som er brukt i materialer, konstruksjon, drift, vedlikehold og riving av bygget. Dette blir gjort ved bruk av svært energieffektivt utstyr, resirkulering og gjenbruk av materialer og en tett og godt isolert bygningskropp. Det som skiller et plusshus fra andre bygg er produksjon av energi. Solcellepaneler er plassert på taket til bygget og på toppen av et nærliggende parkeringshus. Utregninger viser at målet vil bli nådd innen bygningens livstid på 60 år.

Energibehovet for oppvarming og kjøling av bygget er dekket med fornybar energi fra en geotermisk varmepumpe, og med fjernvarme som topplast. Sensorer for bevegelse, temperatur og CO_2 optimaliserer bruken av belysning, ventilasjon, varme og kjøling. Behovstyrt fortrengningsventilasjon med variable luftmengder er brukt i møterom og de åpne områdene i hver etasje. Cellekontor tar i bruk fortregningsventilasjon med konstante luftmengder. Det har blitt gjennomført et feltarbeid for måling av ventilasjonseffektiviteten i de åpne landskapene.

Oppvarming skjer gjennom vannbåren varme i radiatorer og gjennom oppvarmet tilluft. Frikjøling fra den geotermiske varmepumpen sørger for nærmest gratis nedkjøling av bygget gjennom ventilasjonssystemet, sett i et driftsperspektiv. Radiatorene i hver etasje er plassert i kjernen av bygget, og det er ingen varmekilder i cellekontor eller langs bygningskroppen. Oppvarmingsstrategien er avhengig av at varmen fordeler seg likt utover det åpne området og inn til rom. Det har blitt gjennomført et feltarbeid som tok for seg temperaturfordelingen i de åpne landskapene og for cellekontorene.

Den målte ventilasjonseffektivitet angir at ventilasjonstrategien ligner mer på omrøringsventilasjonventilasjon enn fortrengningsventilasjon når det gjelder fjerning av forurensninger og luftutskifting. Dette er ikke en endelig konklusjon, og det er foreslått videre arbeid for å analy-

sere disse resultatene og utføre nye forsøk.

Temperaturfordelingen i de åpne landskapene synes å variere etter utetemperaturen, og er mer jevn ved høyere utetemperaturer. De horisontale temperaturforskjellene på en etasje var opp til 2.7 °C under den kaldeste dagen (-6,3 °C), og opp til 1.7 °C i løpet av den varmeste dagen /10.8 °C) (begge kl 12:00). Temperaturen i cellekontorer med konstant lukket dør viser at det er et temperaturfall på omtrent 2.0 °C mellom gangen utenfor og inne på cellekontoret på den kaldeste dagen. Lignende, om ikke høyere temperaturfall, er forventet når det gjelder hjørnemøterom.

Det har blitt gjennomført en undersøkelse om det opplevde inneklimaet for de ansatte i Powerhouse Kjørbo og et arkitektonisk likt kontorbygg som er renovert etter lavere standarder. Resultatene tyder på at de ansatte er generelt mer fornøyd med både termisk miljø og luftkvaliteten i Powerhouse Kjørbo. Tilbakemeldinger om opplevd lav temperatur i bygget og dårlig luft i møterom har blitt rapportert, men sett bort i fra dette, er tilfredsheten av opplevd termisk miljø og luftkvalitet høy.

Contents

Abbreviations

BAS	Building Automation System
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Methodology
CAV	Constant Air Volume
DCV	Demand-Controlled Ventilation
HVAC	Heating, ventilating and air-conditioning
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
ROB	Renovated office building
VAV	Variable Air Volume
PK	Powerhouse Kjørbo
VTG(S)	Vertical temperature gradient (sensors)

Nomenclature

Latin Letters

A_{curve}	ppm·minutes	The area under or over the curve in a graph
A_{tail}	ppm·minutes	The calculated tail of a graph
$A_{tail,weighted}$	ppm·minutes	The weighted calculated tail of a graph
$A_{weighted}$	ppm·minutes	The weighted area under or over the curve in a graph
C_b	ppm	The concentration of contaminants in the breathing zone (zone of occupancy)
C_e	ppm	The concentration of contaminants in the exhaust air
c_i	ppm	The concentration at time t(i) in a graph
C_ps	ppm	The concentration of contaminants at a given point
C_s	ppm	The concentration of contaminants in the supply air
E	kWh	Energy
n	-	Population of potential participants (e.g. survey)
P	kW	Electrical Power
$\hat{p}$	%	Percentage of population that participated (e.g. survey)
t_a	°C	The air temperature
t_i	minutes	The time at point t(i) in a graph
t_o	°C	The operative temperature
t_r	°C	The mean radiant temperature
T	°C	Temperature in degrees Celsius
ΔT	°C	Temperature difference in degrees celsius

U	W/m^2K	Thermal transmittance
V	m^3	Volume
$\dot{V}$	m^3/h	Volume flow of a given fluid
q_v	m^3/s	Air flow rate
$\hat{q}$	%	Percentage of population that did not participate (e.g. survey)
X	-	Number of participants (e.g. survey)
$z_{\alpha/2}$	-	Z-score (statistics)

Greek Letters

ε_p^a	%	Air change efficiency in a given point
λ	ppm/minute	The slope of a section in a concentration/time curve
σ	%	Standard deviation
τ_n	seconds	The nominal turnover time (theoretical)
$\overline{\tau}_p$	seconds	The local mean age of air in a given point
Φ	Watts	Heating power output of a given system

Chapter 1 | Introduction

During the 1980's in Norway it was developed a national campaign called ENØK (economical energy saving), which encouraged to save energy by means that are economically beneficial. Today the focus on saving energy is bigger than ever, being introduced into electric equipment, transportation, buildings and so on. The building sector makes up a substantial part of the world energy budget. It is estimated that it represents 40 % of the energy consumption, in addition to the claim of 40 % of the material resources and is responsible for 40 % of the waste produced worldwide . They need to become a part of the future of energy saving and environmentally friendly solutions. (Novakovic, 2007)

Powerhouse Kjørbo is a low-energy building, but also the first energy-positive office building in Norway, Sandvika. This means that in addition to being very energy efficient it also produces energy. It was initially built in 1979, and started operation in April 2014 after the renovation. Powerhouse Kjørbo has been a huge interest for the building industry with visitors from all over the world. It strives to set a new standard in the Norwegian building industry.

This report is partly a literature study that summarizes the Powerhouse concept and the forces behind it, in addition to a study of the building design and services with a focus on the ventilation and heating solutions at Powerhouse Kjørbo. It is also a study of the thermal environment and the indoor air quality in terms of heat distribution and ventilation efficiency presented with the necessary background theory. The perceived indoor climate has been analyzed through a survey with participants from Powerhouse Kjørbo and compared to a similar office building located nearby. A short uncertainty analysis has been conducted for the fieldwork and survey, and suggestions for future work are presented in the conclusion.

There is an agreement between the owner of Powerhouse Kjørbo, Entra, the Research Center on Zero Emission Building (ZEB) and NTNU/SINTEF concerning publication of research done at Powerhouse Kjørbo. The agreement, enclosed in Appendix E, states the following about publications from students:

"The student is responsible for any data and results from the project [Powerhouse Kjørbo] presented in this thesis. The results are not approved by the project owner of the building or the ZEB Board."

1.1 Background

Powerhouse Kjørbo consists of two blocks, named 4 and 5, which are connected to each other by a hallway. In this thesis, only block 4 will be considered while conducting the temperature and ventilation fieldwork.

The panel radiators at Powerhouse Kjørbo are located in the center of each floor, resulting in heat moving from the center and towards the external walls. This is the opposite of the situation in most buildings, and it will therefore be interesting to analyze this heat distribution.

Earlier fieldwork has been studying cell offices and the comparison between an open and a closed door in terms of temperature (Søgnen, 2015). There has also been conducted a simulation of the thermal environment by Midtbust (2014). Both the fieldwork and simulation concluded that it would be difficult to obtain thermal comfort without radiator heating in cell offices and meeting rooms with closed doors. Earlier measurements did not include sub-zero outdoor temperatures, and this is expected during the temperature fieldwork for this thesis.

The ventilation system is designed to deliver air with displacement ventilation and variable air volumes, controlled by CO_2 and temperature sensors in the open landscape and meeting rooms. Cell offices have constant air volume. With only one main exhaust point located at the top of a centered staircase (excluding smaller exhausts in technical and wet rooms), it will be interesting to measure the ventilation efficiency in order to analyze how well this solution works.

According to Office manager Eli Matheussen Delp during a conversation at Powerhouse Kjørbo, November 18th 2014, there have been some complaints about the atmospheric and thermal environment. It is also interesting to know how a low-energy building is received by its occupants. Therefore an indoor climate survey was developed.

1.2 Objectives

The main objectives of this master's thesis are to:

1. Describe the Powerhouse concept
2. Understand and present the general design and specifications of the building Powerhouse Kjørbo
3. Carry out a literature study of the heating and ventilation solutions at Powerhouse Kjørbo
4. Carry out a fieldwork studying the thermal environment in terms of air temperature and heat distribution
5. Carry out a fieldwork studying the ventilation efficiency
6. Carry out a survey to analyze the perceived indoor climate at Powerhouse Kjørbo

1.3 Limitations

Since the thesis was conducted during the winter, thus it has not been possible to analyze the cooling strategy in the same way as the heating strategy. It was concluded that this part of the given assignment would be left out of the report.

The building automation system provides operation data for Powerhouse Kjørbo such as temperatures, air supply etc. Data was not always available, and sometimes parts were missing. It took some time to gather everything that was needed. Some sensors in the automation system did work properly during the experiment and had to be left out of the results.

When measuring the ventilation efficiency, it would be ideal to have more days and more equipment to measure other areas in the building at the same time. This could not be done due to the lack of such additional equipment and the limited time such experiments can be preformed without disturbing the occupants of the building. Ideally, one should measure operative air temperature, but this would require equipment that was not available in the same quantity as the air temperature sensors. The results from the perceived indoor climate survey was not available before the end of the thesis. This made it difficult to do a more comprehensive analysis of the results as initially planned.

1.4 Approach

This master's thesis is conducted as a continuation of a project work from the fall semester of 2014. The work has consisted of gathering as much information as possible about the building through databases, visiting the building and talking to people involved in the building project. The problems studied in this thesis were chosen based on the findings from the project work, and as a continuation of another student's project work on the ventilation system at Powerhouse Kjørbo. In agreement with supervisor the question about if the chosen solutions [heating and ventilation] in general are well suited for ZEB buildings, has been modified to be a discussion of the performance and how good solution works. If the solutions are well suited for low-energy buildings or not would require an energy analysis of the heating and ventilation systems, which has not been conducted in this thesis.

The horizontal temperature distribution will be measured with temperature sensors through a time period of five weeks. The ventilation efficiency will be studied with a so-called *tracer gas*, and the changes of its concentration will be measured with a gas analyzer to evaluate the rate of air exchange in different areas of the building. This will be conducted during work hours and for two separate days. It was evaluated to not perform any simulations based on the measurements from the fieldwork. A simulation of the thermal environment has already been conducted by Midtbust (2014), and based on the amount of data it will be enough to only analyze the results from the fieldwork for now. As for a simulation of the air flow in the building it is recommended to solely analyze this in a different report, as there are many things to look into. The analysis of the experiments will be based on the findings in a literature study of relevant theory and state of the art studies.

Chapter 2 | Literature Study

When studying the heating, cooling and ventilation strategy at Powerhouse Kjørbo it has been essential to have access to the relevant project documents and people involved in the building process. A database website called Projectplace was used by the involved partners during the planning, construction and post documentation for Powerhouse Kjørbo. Chapter 4 is mostly based on this database. The database is not available to the public, thus also the referenced documents. Some of the description used in this report of Powerhouse Kjørbo was written during the project work.

Chapter 5 describes the background theory used in this thesis. The books "ENØK i bygninger" and "Acheiving the desired indoor climate" has been used to cover the basics of indoor climate and ventilation theory. REHVA (Federation of European Heating, Ventilation and Air Conditioning Association) guidebooks about the ventilation effectiveness (Mathisen et al., 2004) and displacement ventilation (Mundt et al., 2004) have been used to cover the theory behind ventilation and methodology behind the ventilation efficiency fieldwork. All of these sources have been very important for the understanding of the presented work in this thesis.

State of the art literature is presented in the discussion with the results of the fieldwork and indoor climate survey. The online bibliographic databases Scopus and Science Direct have been used to search for relevant research. Search words, and combinations of the following, such as "productivity", "thermal environment", "indoor air quality", "displacement ventilation", "ventilation efficiency", "low-energy building" and "heat distribution" was used when looking for relevant theory and state of the art studies. Filters were used to boil down to the most relevant articles.

Chapter 3 | The Powerhouse Concept

This chapter describes the powerhouse concept, the partners involved in the Powerhouse Alliance and other driving forces in the market for low-energy and energy-positive buildings. It also gives a short description of the building project Powerhouse Kjørbo. This is an updated chapter from the project work. The technical specifications of the building are presented in chapter 4.

3.1 What is a Powerhouse?

The definition of a Powerhouse may vary from country to country, but the Powerhouse Alliance in Norway has described it as Powerhouse Alliance (2012):

> *"A Powerhouse shall during its lifetime produce more energy than it uses for materials, production, operation, renovation and demolition."*

In other words, it must produce more energy than what is invested in production, construction, operation and disposal during the whole of its lifetime of 60 years (Powerhouse Alliance, 2012). This is seen in a *cradle-to-grave* perspective in figure 3.1. The powerhouse concept aims to develop climate neutral and energy-positive buildings. For Powerhouse Kjørbo the energy used to manufacture the equipment such as coffee machines, computers etc., is not included in the energy budget (Thyholt et al., 2013).

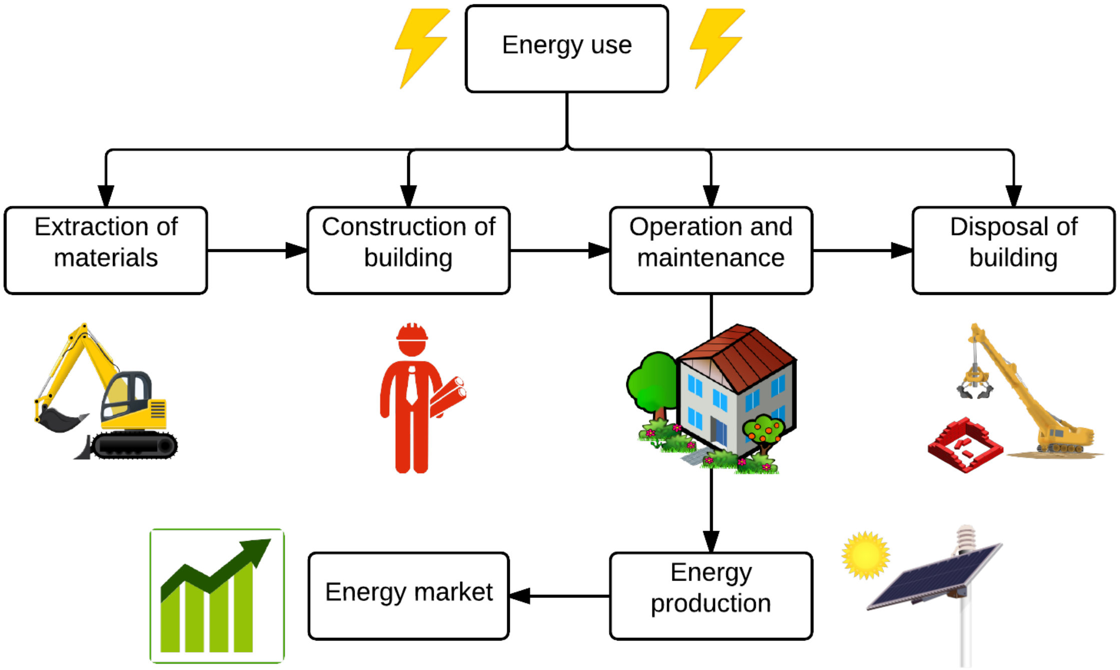


Figure 3.1: A powerhouse cradle-to-grave illustration. *Inspired by: Strømman (2010).*

To achieve this, the building specifications must meet most of the passive house standard described below, or better. The construction would need a *building envelope* with efficient insulation and low infiltration, more energy efficient technical installations (e.g. heat exchangers, heat pumps, automated building system) and local energy from renewable sources (e.g. solar heat, geothermal heat). There are many ways to design a building to achieve the goals set for the project, but in every case it comes down to the local climate and the surroundings when deciding which solutions to implement.

The powerhouse concept derives from the passive house concept, but it comes with the possibility to produce energy as well. It is common to do so with solar energy through the use of photovoltaic panels and solar thermal collectors. The passive house concept was first used in Germany in the 1990's and was partly developed by the Passive House Institute (2014), and they define it as follows:

> *"A Passive House is a building, for which thermal comfort can be achieved solely by post heating or post cooling of the fresh air mass, which is required to fulfill sufficient indoor air quality conditions - without a need for recirculated air."*

The requirements for a passive house in Norway is described in the standards NS3700 and NS3701. They are the criteria for passive houses and low-energy buildings for residential buildings and non-residential buildings, respectively. (Standard Norge, 2013)

3.2 The Powerhouse Alliance

The powerhouse concept is developed in Norway by a collaboration of companies, namely:

- Asplan Viak - Engineering consulting
- Entra – Real estates
- Hydro – Supplier of aluminum
- Sapa – Aluminum solutions
- Snøhetta - Architecture
- Skanska - Construction
- ZERO (Zero Emission Resource Organization) – Environmental organization

Together they are dedicated to design, develop and build energy-positive buildings that can provide us with the knowledge and expertise that we need for a more energy efficient and environmentally friendly future. They want to show that energy-positive buildings can also be profitable compared to ordinary buildings.

The Powerhouse Alliance is currently working on their second project at Brattøra in Trondheim, Norway, also known as Powerhouse One. It is a completely new office building with a planned project period of 2012-2016 (NAL, 2014). Their first project, which is going to be discussed in this report, is Powerhouse Kjørbo. Entra is the owner of both buildings.

3.3 Powerhouse Kjørbo

Powerhouse Kjørbo, seen in figure 3.3, is a rehabilitated office building from 1979 which has been transformed into a modern and functional office space. Powerhouse Kjørbo consists of two building blocks, 4 and 5, and is part of a building complex of nine blocks in total as seen in figure 3.2. In front of the building is Sandviksbukta, a sea bay with islands separating the ocean from the main land. It was Asplan Viak who signed a lease with Entra to use Powerhouse Kjørbo as their new office building. The rehabilitation project was ongoing from 2012-2014 and the final construction has been in use since April 2014. (NAL, 2015)

Figure 3.2: Bird's eye view of the two rehabilitated buildings block 4 (right) and block 5 (left) in Sandvika, with solar panels on the roof. At the lower left corner is a parking complex which partly has been used for solar panels as well. *Photo: Kartverket.*

Enova, a Norwegian public enterprise promoting more efficient energy consumption and increased production of renewable energy, gave the Powerhouse Kjørbo project 2.9 million NOK in support to the passive house rehabilitation, and 13 million NOK in support to the use of new technology. The building project aims to achieve the passive house standard described in NS3701. (NAL, 2015)

Figure 3.3: Powerhouse Kjørbo from the outside. Left is Block 5 and right is Block 4. *Photo: Powerhouse Alliance.*

3.4 The ZEB Definition

Powerhouse Kjørbo is a pilot project for FutureBuilt, a ten-year program for creating carbon-neutral urban areas and high-quality architecture. FutureBuilt has set a goal to reduce the greenhouse gas emissions from transport, energy and material consumption by at least 50 % (Futurebuilt, 2015). Powerhouse Kjørbo is also a pilot project for The Research Centre for Zero Emission Buildings (ZEB). ZEB, on the other hand, has a goal to create buildings where the greenhouse gas emissions are eliminated. This includes the construction, operation and demolition of the building as seen in table 3.1 (ZEB, 2014).

Table 3.1: The description of the levels of ambition set by ZEB. *(ZEB, 2014)*

Abbreviation	Description
ZEHB	**Zero Energy Heating Building** - The energy standard of the construction and technical installations should at least satisfy the energy goals as defined in the passive house standard NS 3700/NS3701, if special circumstances argue against it. The entire energy supply for space and DHW heating should be based on renewable energy sources with zero net emissions of climate gases during the building operation.
ZEB-O	**Operation** - The energy standard of the construction and technical installations should be at least as good as for ZEHB. The entire energy supply for building operation should be based on renewable energy sources with zero net emissions of climate gases during the building operation.
ZEB-O-EQ	**Operation ÷ Equipment** - Same as ZEB-O, but where the energy post for equipment is not taken into account in the zero emission balance calculation.
ZEB-O&M	**Operation & Materials** - The energy standard of the construction and technical installations should be at least as good as for ZEB-O. The entire energy supply for building operation should be based on renewable energy sources with zero net emissions of climate gases during the building operation. In addition, the building should produce a sufficient amount of excess renewable energy to compensate for the embodied energy and relate climate gas emissions for production of all the materials and technical installations in the building.
ZEB-O&M-EQ	**Operation & Materials ÷ Equipment** - Same as ZEB-O&M, but where the energy post for equipment is not taken into account in the zero emission balance calculation.

Futurebuilt and ZEB are not the same as the powerhouse concept. The ZEB definition and FutureBuilt are shaped around greenhouse gas emissions, whereas the powerhouse concept is shaped around energy. The level of ambition for Powerhouse Kjørbo according to the ZEB definition is ZEB-O&M-EQ (ZEB, 2014). This matches the powerhouse definition in terms of energy, but not emissions, even though Powerhouse Kjørbo aims for an environmental friendly construction.

3.5 BREEAM-NOR

BREEAM is an environmental assessment method and rating system for buildings, first launched by the "Building Research Establishment" (BRE) in 1990. It is an abbreviation for Building Research Establishment Environmental Assessment Methodology, and is the most widely used method for certification of the sustainability of buildings in the world. (BREEAM, 2014)

BREEAM-NOR is the Norwegian adaptation of BREEAM, first launched in 2011. The certification is managed by The Norwegian Green Building Council (NGBC). They aim to raise awareness of the benefits of buildings with a reduced impact on the environment to the owners, users, operators and designer of the building. The method covers ten categories in sustainability for buildings (NGBC, 2012). The categories with their respected number of achievable points and the weighting of these points is shown in table 3.2.

Table 3.2: The categories of BREEAM-NOR which are evaluated with their respected points and weighting

Categories	**Obtainable points**	**Weighting**
Management	17	12 %
Health & Wellbeing	19	15 %
Energy	23	19 %
Transport	9	10 %
Water	9	5 %
Materials	12	13,50 %
Waste	6	7,50 %
Land Use and Ecology	10	10 %
Pollution	12	8 %
Innovation	10	10 %
SUM	127	100 %

Like the original BREEAM rating system, buildings can be rated as "Acceptable", "Pass", "Good", "Very good", "Excellent" or "Outstanding", in rising order. The BREEAM-NOR certification for Powerhouse Kjørbo has been completed by Marit Tyholt at SKANSKA, and according to her, in an electronic correspondence on the May 21th 2015, the final score is 85.2 %. This gives the grade "Outstanding", which was the goal of the project. Marit Thyholt also reports that the score could have been higher, but it would require more documentation and was left out of the report since the goal of "Outstanding" was already reached.

3.6 Similar Concepts

There are many low-energy office building concepts around the world. The highest rated building the BRE has ever certified is the new energy-positive office building "The Edge" in Amsterdam, The Netherlands (figure 3.4). It has been named the world's most sustainable office building with a BREEAM score of 98.36 %. It was created by OVG real estate, Deloitte and AKD, and started operation in 2014. There are not much technical details available, but some of the key features of the building are (OVG, 2014):

Figure 3.4: The world's most sustainable office building The Edge seen from inside. *Photo: Ronald Tilleman*

- Usable office floor area of 40 000 m^2
- Energy consumption of 40.7 kWh/m^2 per year
- 4100 m^2 of solar panels
- Aquifer thermal energy storage for heating and cooling
- User controlled temperature and lighting through smartphone user interfaces
- Re-use of rainwater and greywater

Chapter 4 | Building Design and Services at Powerhouse Kjørbo

This chapter is an overview of the building design and services in general. The background theory for the heating and the ventilation system is discussed in detail in chapter 5. Most of the information in this chapter is gathered from the database Projectplace. It is an updated version from the earlier project work.

The ground floor is referred to as the 1st floor, the one above is referred to as the 2nd floor and so on according to Norwegian terms. From now on Powerhouse Kjørbo is referred to as PK. Block 4 and 5 of PK have four and three floors respectively. Block 5 also has a basement, which consists of a wardrobe, showers and an emergency shelter. The two blocks are connected by a hallway between the three first floors.

4.1 Building Envelope and Specifications

The building envelope is the physical separators between the conditioned and unconditioned environment. It is a weather barrier, an air barrier and a thermal barrier. The building envelope consists of the foundation, frame structure, external walls, roof, windows and doors. In this case it is the thermal barrier which stands out from other ordinary buildings.

The reuse and recycling of the old materials have been of high importance. The external walls are built around the old concrete framework, which reduces the amount of embodied energy in the new structure, making it more environmental friendly. The exterior layer of the wall is burnt wood, also known as "Japanese burnt wood cladding". This type of cladding needs no further treatment during its estimated lifetime of 60 years.

The U-value for the windows is 0.8 W/m^2, including the window frame. They are around 40 % of the facade of the building, and it was chosen to have few, but large windows to reduce the length of the window frame per area of glass (Powerhouse Alliance, 2012). It is normal to place heat sources such as radiators or convectors below windows to compensate for the cold draft developed alongside the glazing of the windows. There are no heat sources under the windows since the need for such a compensation is greatly reduced with the low U-value. There is a mechanical, exterior window shading that is controlled automatically, or manually if needed.

The heated usable gross floor area (BRA) and heated air volume of PK are shown in table 4.1.

Table 4.1: Heated area and volume at PK. *(Thyholt, 2014a)*

Heated BRA [m^2]	5180
Heated air volume [m^3]	15 696

In table 4.2 one can observe the different specifications for the building envelope, technical equipment and the simulated energy use for the building throughout a year. These are the most recent values used in an energy simulation done by Bjørn Jensen at Skanska and published by Marit Thyholt at Skanska in her BREEAM-NOR report about energy efficiency. Block 4 and block 5 was simulated as individual buildings for a more detailed analysis. The simulation program used was SIMIEN.

The values in this table are an average of the values from block 4 and block 5, including the staircase located between the two blocks. The values of block 4 are included in brackets beside the average value whenever they differ from the average.

The values for PK is compared to the Norwegian regulation on technical requirements for buildings (TEK10) and the requirements found in the passive house standard for non-residential buildings NS3701. The U-values are calculated from NS-EN 6946 by Skanska. (Powerhouse Alliance, 2012)

Table 4.2: Comparison of TEK10, NS3701 and specifications of Powerhouse Kjørbo based on values from Thyholt (2014a).

Requirements in terms of	TEK10	NS 3701	Powerhouse Kjørbo
Total net energy use [kWh/m^2 year]	≤ 150	≤ 95	59.3 (58)
Net energy need for heating [kWh/m^2 year]	-	≤ 20.1	15 (12.1)
Net energy need for cooling [kWh/m^2 year]	-	≤ 9.4	3.9
U-values			
Windows and doors [W/(m^2 K)]	≤ 1.20	≤ 0.80	0.80
External walls [W/(m^2 K)]	≤ 0.18	≤ 0.10-0.12 [1]	0.13
Roof [W/(m^2 K)]	≤ 0.13	≤ 0.08-0.09 [1]	0.08
Floor [W/(m^2 K)]	≤ 0.15	≤ 0.08	0.20 (0.16)
Normalized thermal bridge, Ψ [W/mK]	≤ 0.06	≤ 0.03	0.025 (0.02)
Technical equipment			
Efficiency For Heat Exchanger [%]	≥ 80 %	≥ 80 %	87 %
SFP-factor for ventilation [kW/(m^3/s)]	≤ 2.00	≤ 1.50	0.70
Leakage number at 50 Pa [h^{-1}]	≤ 1.50	≤ 0.60	0.24 (0.23)
Average airflow in operating time [m^3/(m^2 h)]	≥ 2.5 + 26[2]	≥ 6	7
Average airflow outside operating time [m^3/(m^2 h)]	≥ 0.70	≥ 1	2 / 0
Average power demand for lighting when operating [W/m^2]	≥ 8 [3]	≥ 4	3.1

---

[1] Typical values for Passive houses (BoligENØK, 2015)

[2] Additional m^3/h per person in the room

[3] Value from NS3031

4.2 Technical Installations

The major technical installations at PK discussed in this report are the lighting, the energy supply and energy production, the heating and cooling system and the ventilation system. The two latter will be discussed in detail later on. The major technical installation that is excluded from this chapter is hot water supply.

4.2.1 Building Automation System (BAS), Sensors and Division of Zones

At PK, the heating, cooling and ventilation systems are controlled by a building automation system (BAS). It monitors and collects data from the different sensors around the building, and is the heart of the demand-controlled ventilation system which will be described in chapter 5, section 5.3.2.

The BAS uses motion sensors, temperature sensors and CO_2 sensors to control the indoor climate. The heat supplied by radiators is controlled by temperature set point, and the air supply volume is controlled by both temperature and CO_2 concentration set points (more of this later on). Each floor in block 4 and 5 is divided into several zones to make sure that the requirements for thermal environment and indoor air quality is met in terms of temperature and CO_2 concentrations. Figure 4.7 on page 22 shows the permanent PK sensors on the 2nd floor, block 4.

4.2.2 Lighting

The lighting is controlled by motion sensors, which are divided into zones on each floor. The luminous intensity is varied in the different zones to save energy, and the work stations are located near the facades, increasing the amount of daylight and thus decreasing the need for artificial lighting. The low-energy light fixtures uses LED where possible, and it is estimated that the energy use for lighting is 3 kWh/m^2 per year. (Thyholt, 2014b)

4.2.3 Energy Supply and Production

The energy supply of PK consists of a geothermal heat pump, district heating, electricity from the electrical grid, and when possible electricity from its own energy production. The energy production is provided by a solar panel system, also known as a PV (photovoltaic) system. The surplus energy produced is supplied to the electrical grid. The energy supply and production system is illustrated in figure 4.1.

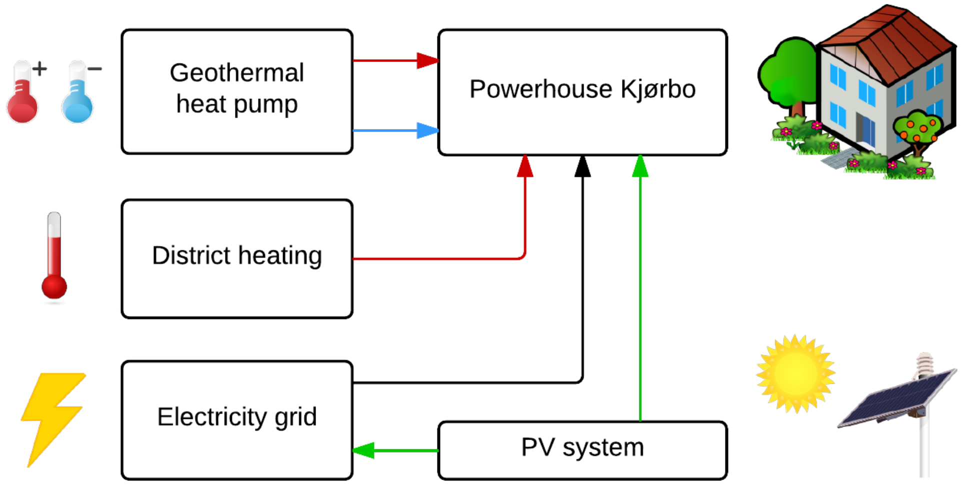


Figure 4.1: Illustration of the energy supply and production for Powerhouse Kjørbo

Geothermal Heat Pump and District Heating

The energy supply for heating and cooling is delivered through the geothermal water-to-water heat pump. There are ten 200 meter deep wells from where the heat is extracted. The system is also connected to the district heating terminal if the heat pump cannot cover the energy need for heating. The heat pump system is dimensioned to cover around 95 % of the heating demand. This information was discussed in a meeting with HVAC engineer Olav Rådstoga at October 22nd 2014 at PK.

PV System

The energy production is done by solar panels located on the roof of block 4 and 5, and also partly on the rooftop of a nearby parking complex as shown in figure 3.2 on page 9. The supplier of the PV System, Direct Energy, has estimated an average production of 229.342 kWh/year. For the whole building of 5180 m^2 BRA this corresponds to 44.3 kWh/m^2. (Thyholt, 2014b)

The produced electricity will mainly be used directly by PK. The surplus energy will be exported to nearby buildings or the electricity grid during periods with more energy production than energy need. This surplus energy is subtracted from the yearly energy need of the building.

4.3 Ventilation

The ventilation strategy at PK is one of the two main focuses in this thesis. The following sections will discuss the distribution and exhaust, and the ventilation units. The heating and cooling delivered from the ventilation system will be discussed in section 4.4.

4.3.1 Distribution and Exhaust

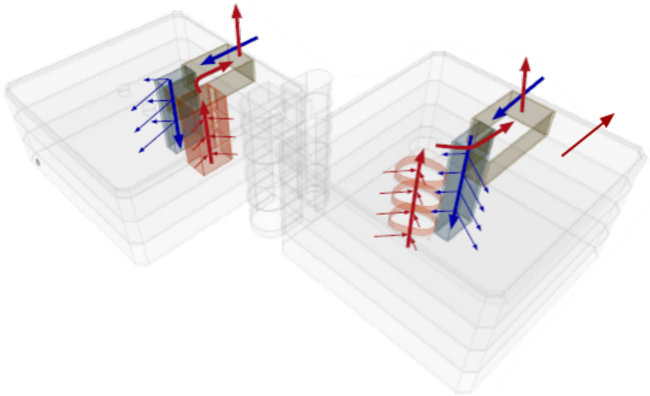


Figure 4.2: 3D-model of the ventilation distribution and exhaust. The blue lines are air supply and the red lines are air exhaust. Block 5 is to the left and block 4 to the right. *Illustration: Powerhouse Alliance (2012)*

The ventilation strategy is displacement ventilation with air distributed at floor level.The open landscape and larger meeting rooms utilize demand-controlled VAV (variable air volume), and cell offices and smaller meetings rooms utilize CAV (constant air volume). The diffusers in the open landscape are integrated with the internal walls at each floor, which is connected to the main air supply duct in the center of each building block as seen in figure 4.2.

Figure 4.3: Displacement diffuser found at cell offices and meeting rooms at Powerhouse Kjørbo. *Photo: Fläkt Woods*

The dedicated displacement diffuser in the cell offices and meeting rooms can be seen in figure 4.3. Some of the meeting rooms have custom designed, wall-integrated diffusers similar to those in the open landscape. There is a possibility for hybrid ventilation by opening hatches above the central staircase and windows on the top floors of the two blocks (Danielsen, 2014).

The ventilation system has an very low pressure drop through the components and ducts, giving air the possibility to be supplied at a very low velocity. This means lower energy use for fans and less noise from the ventilation system overall. Most of the air is withdrawn through outlets via the central stairwell in block 5 and the spiral staircase in block 4 as seen in figure 4.2. There is also an air exhaust at the 4th floor of block 4. The system is designed so that the overflow from cell offices goes to landscape, and on to secondary functions such as wet rooms. It is possible to open the windows at each workstation allowing some self-controlled ventilation if necessary (Powerhouse Alliance, 2012).

Temperature and CO_2 Set Point

The ventilation rate is controlled by the indoor temperature and the CO_2 level to compensate for excess heat and/or high levels of CO_2. The supply air temperature is controlled by an exhaust compensation curve during the heating season, in other words from the exhaust air temperature. The compensation curve is seen in figure 4.4.

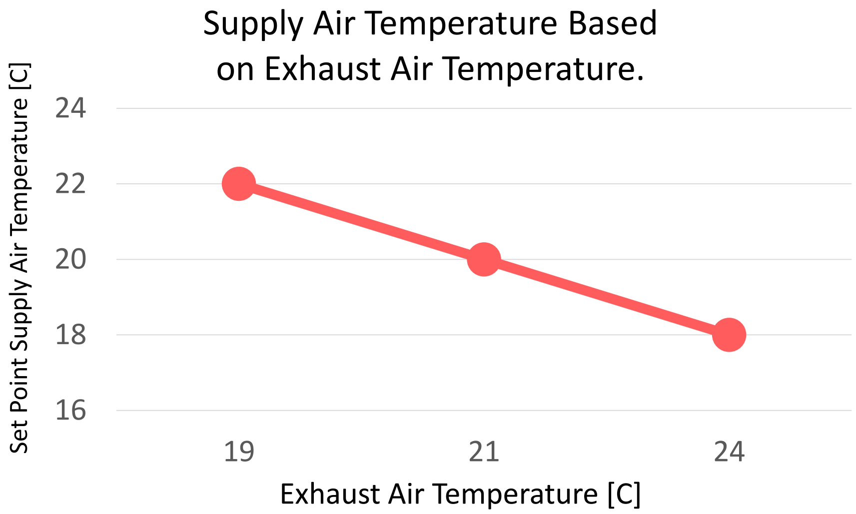


Figure 4.4: Compensation curve for inlet and outlet temperature. *(Rådstoga, 2014)*

The set point value of the indoor CO_2 level at PK is according to the building automation system 650 ppm for the open landscape and 550 ppm for meeting rooms. It is lower for meeting rooms in order to response more quickly to sudden changes, which would be the case for larger meetings. The air supply will begin to adjust at the set point, and will be at maximum capacity when the CO_2 concentration is 200 ppm over the set point. This is according Olav Rådståga from an electronic correspondence June 25th.

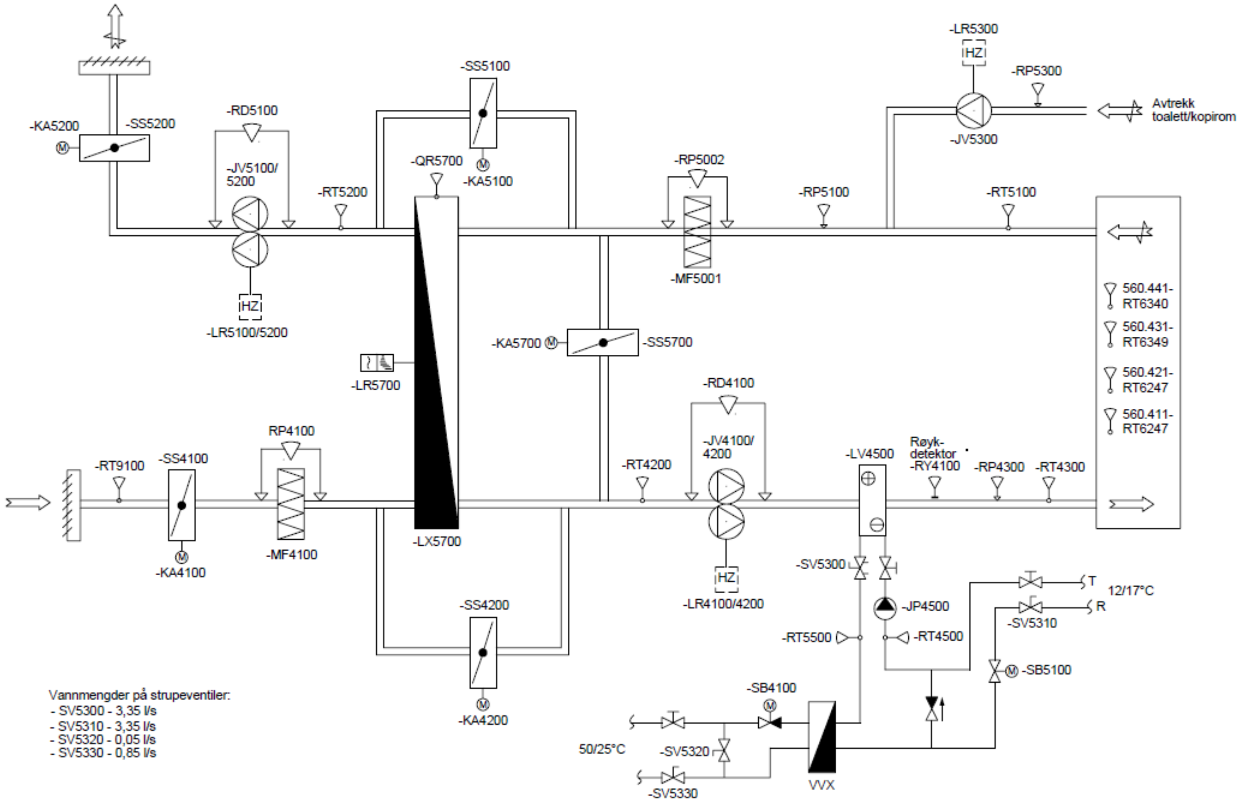
4.3.2 Ventilation Units

There are three ventilation units in block 4 and 5 combined as described in table 4.3. The components of the ventilation units can be seen in figure 4.5, and the major ones are as follows:

- Two frequency controlled fans for supply and exhaust
- Regenerative rotary heat exchanger
- Combined heating and cooling coil

Table 4.3: Overview of the ventilation units at Powerhouse Kjørbo. *(Systemair, 2013)*

Ventilation unit	**360.405**	**360.506**	**360.501**
Max. delivered air volume [m^3/h]	25 000	25 000	4 000
Distribution area	Entire block 4	1^{st}, 2^{nd} and 3^{rd} floor of block 5	Basement of block 5 (emergency shelter, wardrobe and showers)



Vannmengder på strupeventiler:
- SV5300 - 3,35 l/s
- SV5310 - 3,35 l/s
- SV5320 - 0,05 l/s
- SV5330 - 0,85 l/s

Figure 4.5: A technical drawing of the ventilation units as built at Powerhouse Kjørbo. *(Source: Projectplace)*

The units are equipped with a bypass function. If there is no need to recover heat from the indoor air, then the exhaust air will not run through the exchanger, but directly out of the building. The unit is also equipped with an option of recycling the air through a connection between the supply and exhaust duct. This is seen to the right of the heat exchanger in figure 4.5. The heating and cooling from the combined coil is discussed in section 4.4.2.

4.4 The Heating and Cooling System

PK has a very low-energy budget for heating and cooling due to the well-insulated building envelope and *free cooling* from the heat pump. Heat is delivered to the building through the ventilation system and the panel radiators. Cooling is delivered through the ventilation system as well. The supply and demand of the heating and cooling system is illustrated in figure 4.6. The heat pump makes sure that the building gets hot water, space heating through radiators and preheated or cooled (free cooling) air supply when needed. Additional heat is covered by district heating when necessary.

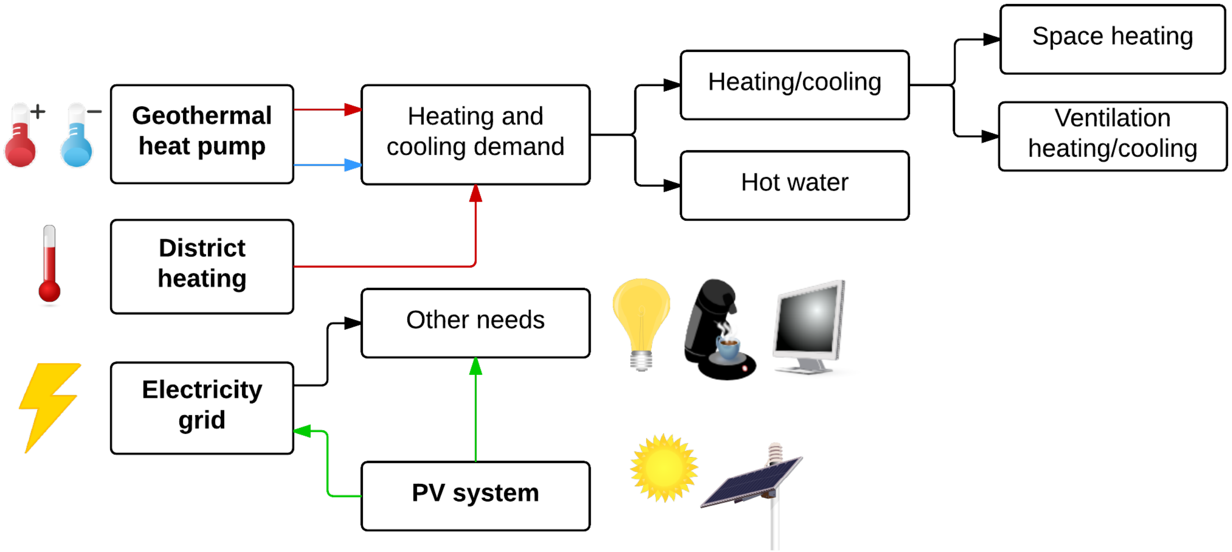


Figure 4.6: Illustration of the heating and cooling system at Powerhouse Kjørbo including the energy demand and production of electricity. *Inspired by Standard NS3031.*

4.4.1 Heating and Cooling Solution

The heating solution is built around a low-temperature waterborne system with a few, large panel radiators placed around the center of each floor as seen in figure 4.7. Air diffusers are supplying air to the open area, the corner office in the upper left of the figure, and to the cell offices and meeting rooms located alongside the external wall. There are no dedicated heat sources in the meeting rooms and cell offices.

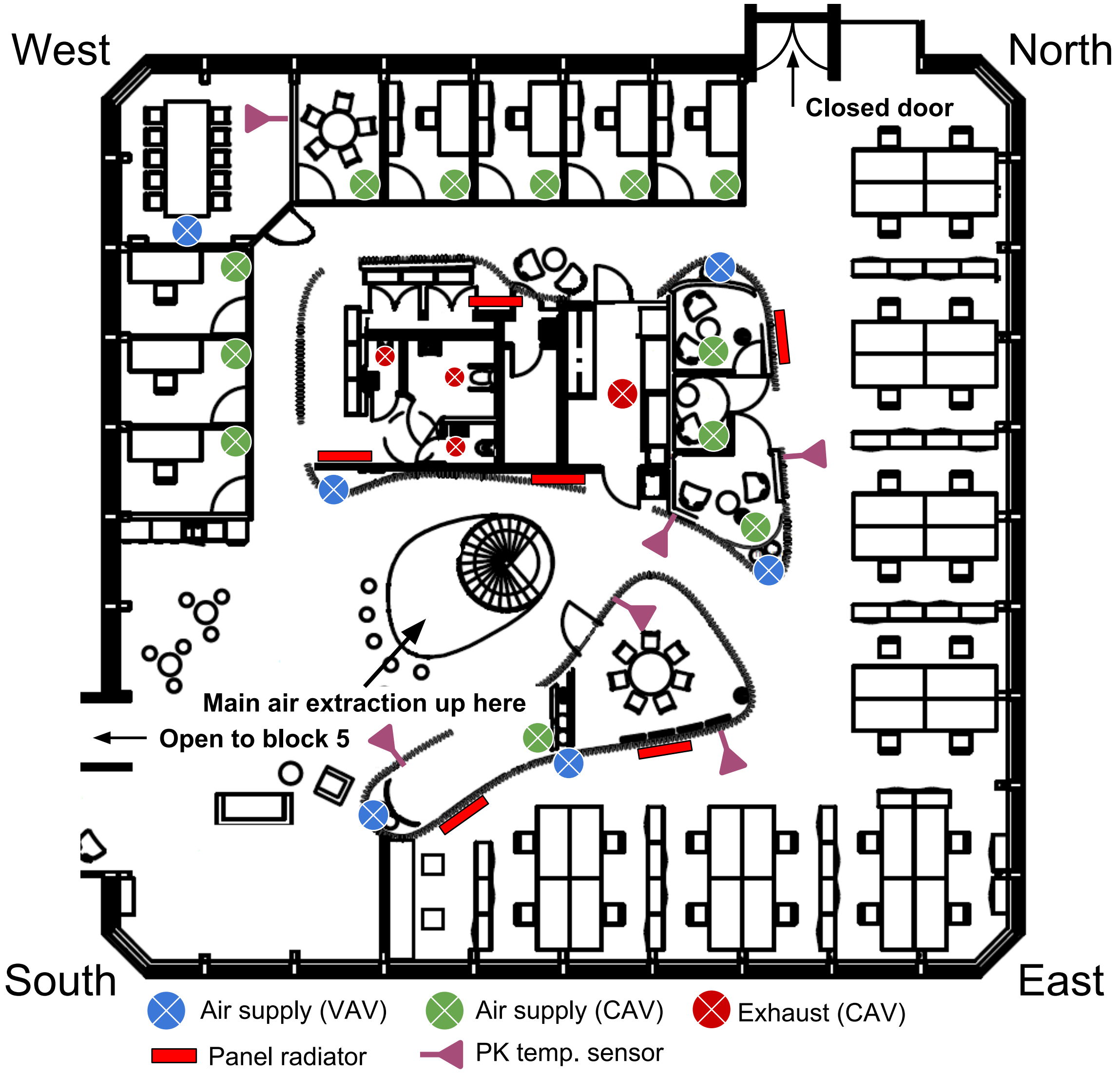


Figure 4.7: Building plan of the 2nd floor in block 4. It illustrates the placement of the permanent temperature sensors, the air diffusers and ventilation strategy and the radiators. *Technical drawing: Entra.*

4.4.2 Heating and Cooling by Ventilation

For heat regulation and conservation the ventilation units are equipped with a rotary heat exchanger, and a combined heating and cooling coil with waterborne heating and cooling supplied by the heat pump. Heat will be added to the coil when the heat exchanger cannot deliver enough heat to the air supply. This happens when the indoor temperature is below 20.5 °C, and it will continue to ad heat until it has reached 22.5 °C. Preheating of the supply air is allowed when the outdoor air temperature is below -7.5 °C. Cooling will commence when the indoor air temperature is too high. This is when the indoor temperature surpasses 23 °C , and it will stop when it reaches the set point of 20.5 °C. Free cooling is allowed as long as the outdoor temperature is over 12 °C . (Rådstoga, 2014)

4.4.3 Heating by Vertical Panel Radiators

Each floor at PK has between six and eight low-temperature waterborne panel radiators, which in total is 52. The details are shown in table 4.4. This low number means less use of pipes and henceforth a more efficient system. The radiators supplying heat to the indoor space air are the Thema Vertikal Plan radiators by the German company HM Heizkörper and is shown in figure 4.8. Thema Vertikal is a waterborne vertically aligned panel radiator with a flat front panel, and has a bottom input and output middle connection to the pressurized waterborne heating system. Each radiator was delivered with a custom paint that matches with the color of the wall it is attached to, making them more discrete. This is seen in figure 4.9. The heating capacity of the radiators is described in chapter 5 on page 36.

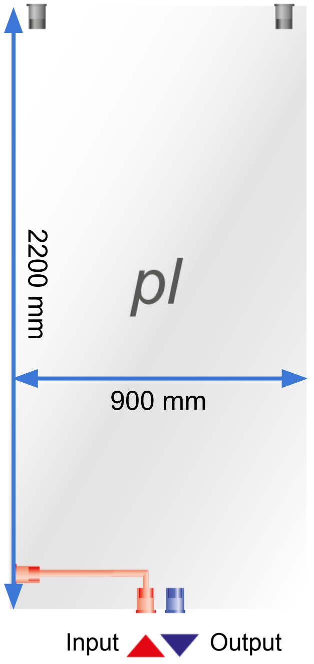


Figure 4.8: Thema Vertikal Plan radiator seen from the front with the input/output placed at the bottom of the frame, and the chosen dimensions for Powerhouse Kjørbo. *Figure: Heizkörper (2015).*

Table 4.4: The number of radiators at each floor in block 4 and block 5 at Powerhouse Kjørbo. *Source: Projectplace, Technical drawings*

Block 4	Number of radiators	Block 5	Number of radiators
1st floor	6	Basement	6
2nd floor	6	1st floor	6
3rd floor	6	2nd floor	6
4th floor	8	3rd floor	8
Total	**26**	**Total**	**26**

Due to the low U-value of the windows, cold draft is not considered a problem, and therefore there are no radiators placed under any windows. Each radiator has a width of 900 mm and a height of 2200 mm. There are two exceptions in block 5 with a width of 600 mm and a height of 2000 mm. The two extra radiators at each top floor is due to the larger area of the building envelope facing the surroundings, increasing the need to compensate for the heat loss.

According to HVAC engineer Olav Rådstoga during a meeting at PK, 28.11.14, it has earlier been discussed to install extra electrical panel heaters in specific rooms (e.g. rooms in corners and/or with closed doors). In November 2014 it was installed one electrical panel heater in office 4104 and one in meeting room 4106 (both on the ground floor in block 4). Due to limited access, these rooms are always closed, thus only relying on heat transfer through conduction from the surrounding surfaces, and heated air from the air diffuser and two air vents above the door. The installed heating effect for each of the rooms is 600 W.

Figure 4.9: A painted vertical panel radiator at Powerhouse Kjørbo hidden behind acoustic absorbers. *Photo: Odin Søgnen*

There is one main reason, according Olav Rådstoga, for why the radiators are aligned vertically instead of horizontally. The answer is simply the lack of usable surfaces. A low-temperature waterborne heating system requires a larger distribution area for the heating, thus it necessary to increase the size of the radiators. As seen in figure 4.7 on page 22, the radiators are placed on internal walls around the center of each floor. The design of the walls has round corners making it hard to place horizontally lined radiators with a size that could match the vertical alternative. Therefore the radiators have been placed vertically instead of horizontally. It is no secret that the aesthetic look had something to do with this solution as well.

Chapter 5 | Theory

This chapter presents the background theory regarding indoor climate, specifically the thermal environment and indoor air quality, and principles for how it is measured and perceived by the occupants. This chapter also deals with the theory behind the heating and ventilation strategies used at PK, with comparisons of other strategies. Finally, the methodology behind the analysis methods used for ventilation efficiency are presented.

5.1 Indoor Climate

The building design and technical equipment strongly influence the indoor environment, which consist of seven parameters illustrated in figure 5.1 (Hanssen, 2007). Both the measurable and perceived indoor climate will be presented in this chapter in terms of thermal environment and indoor air quality.

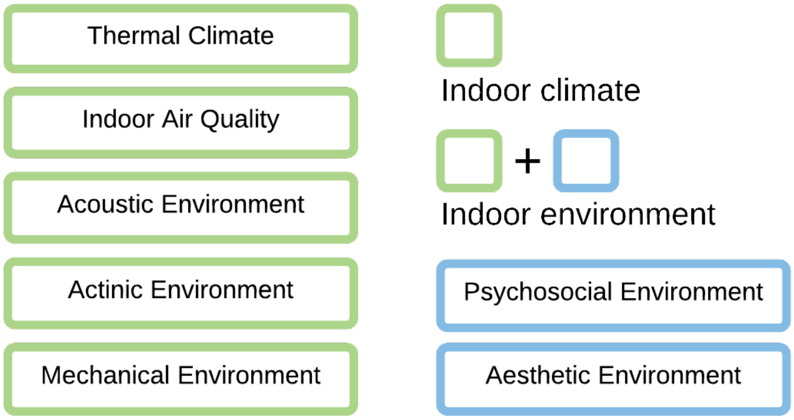


Figure 5.1: The parameters that make up the indoor climate and the indoor environment. *(Hanssen, 2007)*

5.1.1 Thermal Environment

The thermal climate is often seen as a matter of temperature adjustment, but there are several other parameters that affects how the thermal climate is measured. The perception of this environment is affected by the following factors (Gunnarsen, 2003):

- Air temperature, t_a [°C]
- Mean radiant temperature of surrounding surfaces, t_r [°C]
- Relative air velocity $[m/s]$
- Water vapour pressure in ambient air $[Pa]$
- Activity level $[met]$
- Clothing $[clo]$

All of these parameters can be measured physically with suitable instruments, except for the activity level and clothing, where values can be found in the standard NS-EN ISO 7730 (Standard Norge, 2006).

It is common to use the *operative temperature* when analyzing the thermal environment. The operative temperature, t_o, is approximately the average of the mean radiant temperature and the air temperature, as seen in equation 5.1 (Hanssen, 2007).

$$t_o \approx \frac{t_a + t_r}{2} \tag{5.1}$$

When acceptable thermal environment is achieved, one has reached *thermal comfort.* NS-EN ISO 7730 describes thermal comfort as:

> *“The condition of mind which expresses satisfaction with the thermal environment.”*

The temperature that ensures thermal comfort varies among persons, but the standard set point temperature of an office building is 21 °C during operation and 19 °C when not operated according to standard NS3031 (Standard Norge, 2014).

Recommendations for the Thermal Environment

The acceptable indoor temperatures for open landscapes and cell offices are given in "*Byggdetaljer 421.505 Krav til innemiljøet i yrkes- og servicebygninger*" (Byggforsk, 2000).

They are divided into three categories, 1, 2 and 3, based on the level of ambition, category 1 being the most ambitious, then 2 and so 3. Category 2 is the normal ambition used in new and rehabilitated buildings such as PK, and it will be the reference in this thesis. All the categories are included in table 5.1.

Table 5.1: Recommended values for the thermal environment at an office building (both open landscape and cell offices). *(Byggforsk, 2000)*

Cell office and open landscape (met =1.2)	**When**	**Category**		
		1	**2**	**3**
Operative temperature [°C]	Winter (1.0 clo)	22.0 ± 1.0	**22.0 ± 2.0**	22.0 ± 3.0
	Summer (0.5 clo)	24.5 ± 1.0	**24.5 ± 1.5**	24.5 ± 2.5
Air velocity [m/s]	Winter (1.0 clo)	0.15	**0.18**	0.21
	Summer (0.5 clo)	0.18	**0.22**	0.25
Vertical temperature difference [K]	All year	< 2	**< 3**	< 4

The American standard ASHRAE 55 defines the maximum allowed temperature change over a period of time in table 5.2. If the temperature changes at a quicker rate it is possible that the air will be perceived as not thermally comfortable.

Table 5.2: The maximum allowed temperature change over time. (ASHRAE, 2004)

Time period [hours]	**0.25**	**0.5**	**1**	**2**	**4**
Max. allowed temperature change [°C]	1.1	1.7	2.2	2.8	3.3

5.1.2 Indoor Air Quality

The concept of indoor air quality depicts the "cleanliness" of indoor air. This can be perceived by humans, or be a study of how the pollutants may affect human health, products (e.g. materials, technical equipment etc.) and/or processes indoors. The severity of a pollutant in terms of its effect on comfort, health or both depends on concentration and exposure time (Ekberg and Fanger, 2003). An airborne pollutant might be (Abel, 2003):

- generated by people (e.g. CO_2)
- emitted from building structure, materials, furniture and/or technical equipment

- brought in from the outdoor with air supplied by the ventilation system and/or through the building envelope

Examples of sources of pollutants is illustrated in figure 5.2 below.

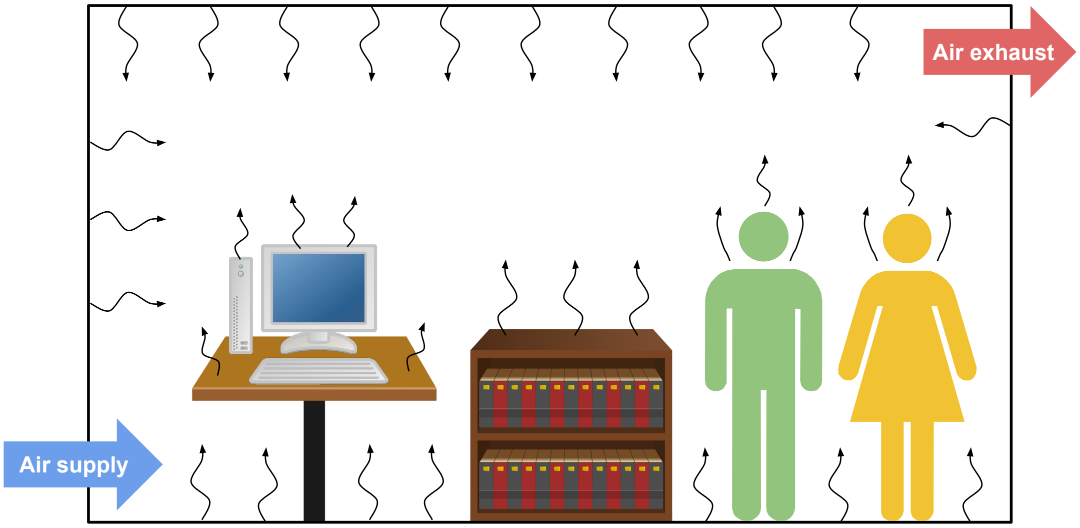


Figure 5.2: Some examples of sources of pollutants in a room. Pollutants from the air supply are not illustrated here. *Inspired by: Abel (2003).*

One can control the indoor quality by eliminating or reducing sources of pollution, by ventilating and frequently cleaning the room, and by shaping it in a matter to increase the efficiency of the ventilation strategy and avoid dust and dirt accumulation.

Recommendations for the Indoor Air Quality

The Norwegian regulations on technical requirements for buildings (TEK10) states that

> *"The air quality in a building shall be satisfactory with regard to odours and pollution. Indoor air shall not contain harmful concentrations of pollutants that pose health hazards or cause irritation."*

The standard NS-EN 15251 gives the recommended CO_2 concentrations above the outdoor concentration when using a ventilation strategy controlled by the level of CO_2. It is given in table 5.3. The same ambition categories are used here as for the recommended temperature values discussed earlier.

Table 5.3: Recommended CO_2 concentrations aboce outdoor concentrations sorted by the ambition category of the building. *(Standard Norge, 2007)*.

Category	**Indoor CO_2 Level Above Outdoor [ppm]**	**Actual Setpoint [ppm] (Outdoor = 400 ppm)**
1	350	750
2	**500**	**900**
3	800	1200

5.1.3 Human Perception of Indoor Climate

The beauty of the human mind and body is that we all experience things differently, and indoor climate is no different. The physical values are one thing, but the perception may differ. It is important to take into account both the physical and the mental well-being of building occupants when studying indoor climate. The World Health Organization (1991)(WHO) has defined health in the following way:

> *"Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity."*

A literature study on how different factors influence human comfort in indoor environments by Frontczak and Wargocki (2011) shows the following results:

- Creating a comfortable thermal environment is often considered to be the most important factor in achieving a good indoor climate.
- Personal control of the indoor environment (controllability) can improve thermal comfort and overall satisfaction with indoor climate.
- It is suggested, but cannot be confirmed that the thermal comfort is influenced by the relationship with superiors and colleagues, level of education of building users, and time pressure, and not significantly influenced by room interior or by color of light.
- It is suggested, but cannot be confirmed that the perception of air quality is affected by the psychosocial atmosphere at work and by job stress.

Thermal Environment

According to Gunnarsen (2003), the human perception of thermal comfort is satisfactory when three conditions are met:

1. The heat loss of the body should be balanced by the heat generation.
2. The skin temperatures and sweat secretion should be within the narrow limits which promote thermal neutrality (thermoneutral zone).
3. The person should not experience unwanted heating or cooling of a particular part of the body.

Gunnarsen (2003) states that the most common cause of thermal discomfort is draft, and also asymmetric radiation heat from surfaces with high or low temperatures. Humans are in general more sensitive to asymmetric radiation from above and below than from horizontal surrounding sides. Stratification of air (vertical layers of air) can give an uneven vertical temperature distribution. In addition to the factors discussed above, also time of residence, furniture, thermal properties of building materials, age, gender, satiety and state of mind can have an effect on how the thermal environment is perceived.

The thermal sensation of a human being can be calculated with the predicated mean vote (PMV), which is needed to calculate the predicted percentage dissatisfied (PPD). The PPD gives an indication of how many people will be dissatisfied with a given thermal environment. This can either be calculated for one specific condition, or for a period of time. To do this one would need the operative temperature, clo, met, and relative air velocity.

According to Gunnarsen (2003) it is not possible to satisfy more than 95 % with one optimal thermal environment due to interpersonal variations. It is also a risk that the users of a building will exaggerate their perceptions in order to influence the actions taken to improve the indoor climate in the future. It also states that it is normal to expect the PPD to have more than 10 % dissatisfied users 95 % of the time. This is with a 1.2 met (normal office work), and 1.0 clo in the winter and 0.5 clo in the summer.

Indoor Air Quality

According to Ekberg and Fanger (2003) the human being has three senses that perceive air quality, all found in the nasal cavity. Together they form a perception of the air quality as if the air is fresh, stale, irritating or "old and heavy".

1. The thermal sense
   - Detects temperature difference between the air and the body.
2. The general chemical sense
   - Sensitive to more than a hundred thousand chemicals (irritants).
3. The olfactory sense
   - Sensitive to around half a million chemical compounds.

Professor P. Ole Fanger defined the sensory pollution generated by a standard person as one "olf", which stems from Latin olfactus meaning the olfactory sense. The standard person is an average adult, sedentary in a non-industrial workplace, and in thermal comfort with a hygienic level of 0.7 baths per day. Olf is used to define the sensory strength of a pollutant, and the ventilation rate can designed to handle the total sensory load so that it does not bother the occupants. There are no instruments to measure this value today, but it can be estimated by the percentage of people dissatisfied with the air quality. (Ekberg and Fanger, 2003)

5.1.4 The Effects of Indoor Climate

The indoor climate affects certain factors in human beings, and it has been shown to influence the comfort, health and productivity. *Health* is mostly connected to the air quality, but also temperature, noise, light and psychosocial factors play a role. The *productivity* is defined as the ability to perform various tasks, and studies show connections between the thermal, acoustic and atmospheric (air quality) environment. (Ekberg, 2003)

There are several models developed from different studies about temperature and productivity. Seppänen et al. (2003) have collected some of them in addition to their own model in figure 5.3.

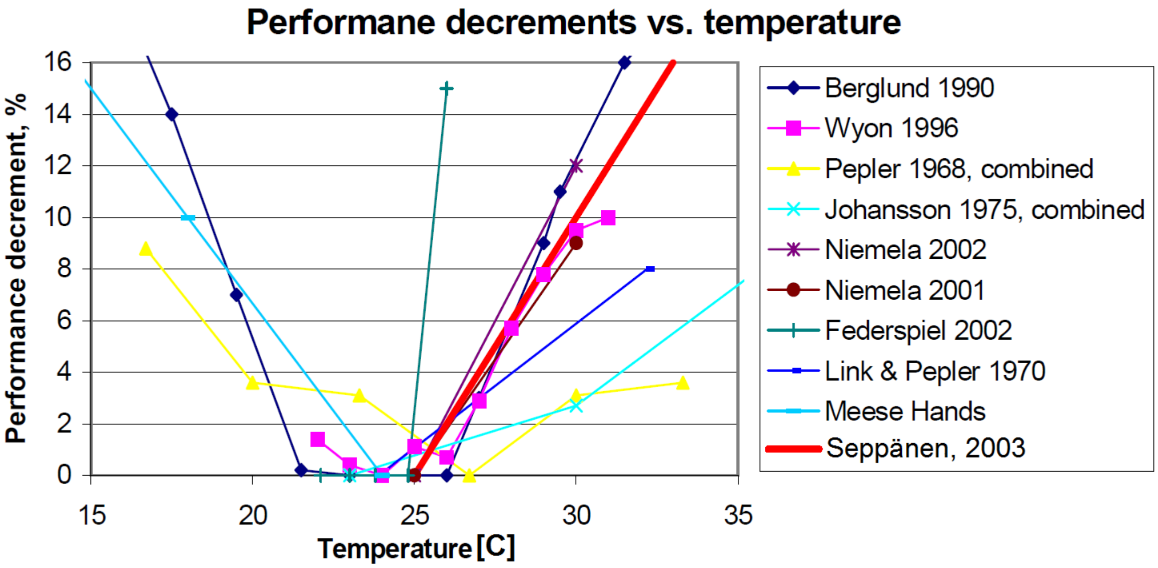


Figure 5.3: The relationship between temperature and performance in office work. (Seppänen et al., 2003)

A study by Wargocki et al. (2000) shows the productivity of office work as a function of sensory pollution load (olf) and ventilation rate in figure 5.4. It states that higher ventilation rates and/or lower pollution loads could increase the productivity of the occupants.

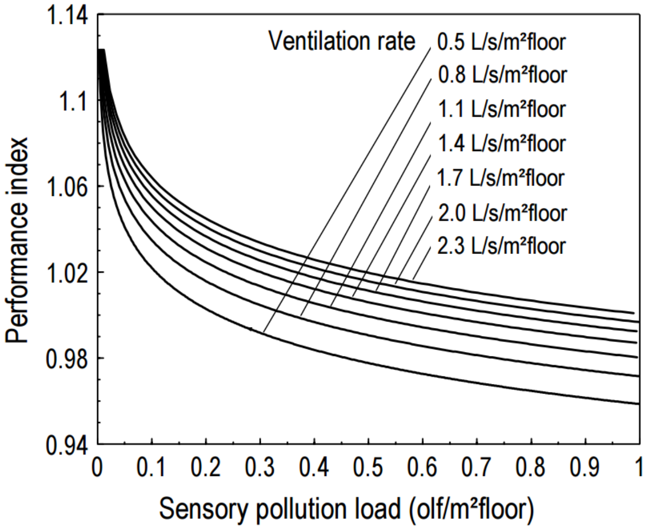


Figure 5.4: The relationship between ventilation and performance in office work. Wargocki et al. (2000)

5.2 Heat Sources and Distribution

In addition to delivered heat from ventilation and radiatiors, there are internal and external heat sources. The internal heat sources are defined by standard NS3031 as heat from lighting, people, technical equipment (computers, coffee machines etc.) and fans in the ventilation system. External heat is defined as heat from the sun. (Standard Norge, 2014)

The waterborne radiator distributes heat through convection and radiation. The proportion depends on the temperature difference between the radiator and the surrounding air. This is illustrated in figure 5.5. The radiative heat distribution is always larger than the convective heat distribution, but closes in for temperature differences over 10 °C. (Zijdemans, 2012)

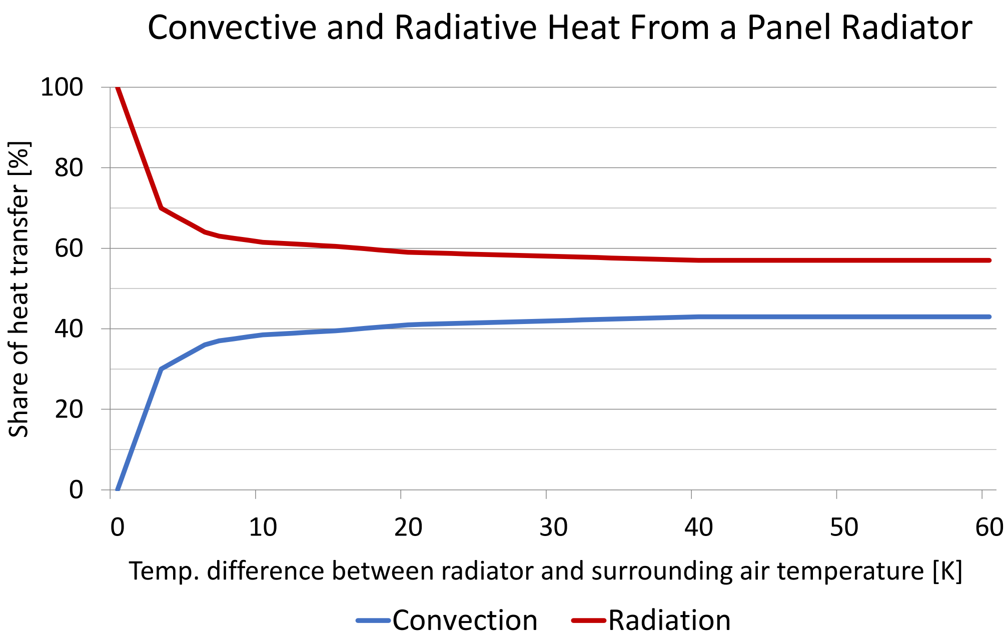


Figure 5.5: The relationship between radiative heating and convective heating distribution for a one panel radiator. *Inspired by (Zijdemans, 2012).*

Convection can be distributed in two ways: forced convection and free convection (also known as natural convection). Forced convection originates from an external forcing condition, e.g. from a fan or a pump that pushes the fluid. Free convection is caused by buoyancy forces due to the combined presence of a fluid density gradient and a body force that is proportional to density. Free convection is generally much smaller than forced convection. (Incropera et al.,

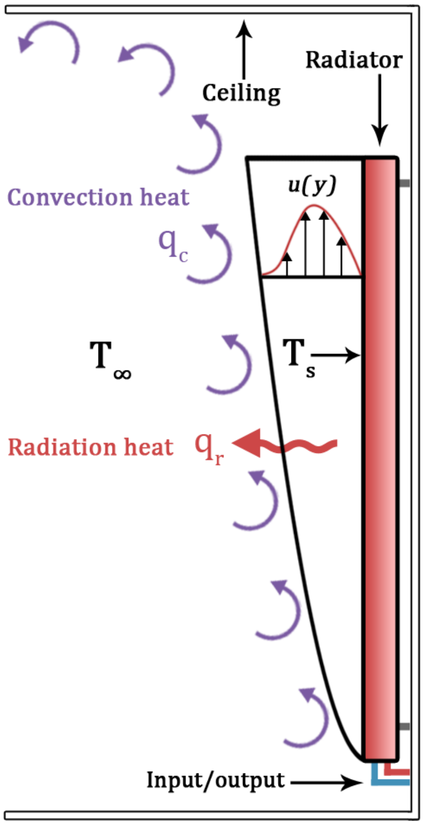


Figure 5.6: Illustration of the radiative and convective heat distribution from the vertical panel radiator. The boundary layer development continues above the radiator despite what is illustrated. *Inspired by Incropera et al. (2007).*

2007)

Radiators, which are not located close to any external forces that could cause forced convection, would rely on free convection. In an advanced model such as a room with heat sources, ventilation inlets and outlets, openings to the outdoors and so on, there will be a combination of both free convection and forced convection. At Kjørbo the heating system relies on the heat being distributed equally around each floor. This has to be done by radiators and the ventilation system.

Figure 5.6 depicts the vertical radiator installed at Powerhouse Kjørbo. The radiator distributes radiative heat, q_r, and convective heat, q_c. T_s is the surface temperature of the radiator and T_∞ is the surrounding temperature. The thermal environment is usually perceived as better when the mean radiant temperature is higher than the air temperature (Zijdemans, 2012).

Free convection is developed by buoyancy forces, and most commonly these are due to temperature gradients. A temperature gradient describes in which direction and at which rate the temperature changes. In this situation a temperature gradient will occur when $T_s < T_\infty$, thus developing free convection. This is illustrated in front of the radiator where one can observe the development of a buoyancy-driven free boundary layer on the heated surface of the radiator. The velocity of the free convection is expressed by *u(y)*. The velocity of the buoyancy varies with the distance from the radiator surface within the boundary layer (Incropera et al., 2007).

5.2.1 The Vertical Temperature Gradient

The vertical temperature gradient (VTG) describes the operative temperature between floor and ceiling. The desired operative temperature is most often measured at the height of 1.8 meters above the floor. Figure 5.7 illustrates the ideal vertical temperature gradient from the bottom of the floor to 2.4 m above the floor. It varies from almost 23 °C at the bottom to around 17 °C at the top, with around 19 °C at 1.8 m above the floor (Zijdemans, 2012).

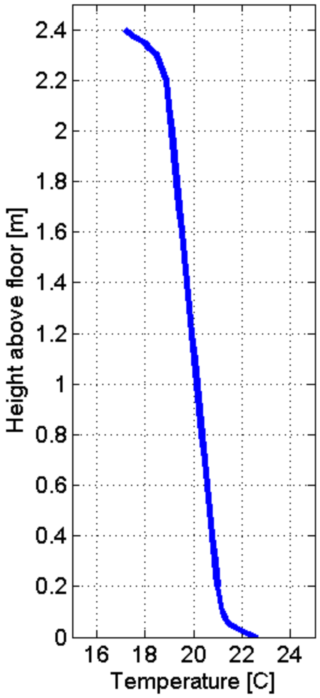


Figure 5.7: The ideal vertical temperature gradient in a room of occupancy. (Zijdemans, 2012).

5.2.2 Delivered Heat

The supply temperature for the radiators is adjusted by the outdoor air temperature, shown in table 5.4. The amount of delivered heat by the radiators is found in the product data sheet provided by Heizkörper (2015). The return temperature is assumed to be around 10 °C below the input temperature. The first three calculations of the heating power outputs are delivered by HM Heizkörper, but the three below them in table 5.5 are calculated from equation 5.3 and equation 5.2 (Zijdemans, 2012). The total heat output is for the whole heating system of 52 waterborne panel radiators.

Table 5.4: The temperature of the water supplied to the radiators after specific outdoor temperatures. *(Rådstoga, 2013)*

Outdoor Air Temperature	**Input Water Temperature**
+10 °C	+30 °C
0 °C	+40 °C
÷20 °C	+50 °C

Table 5.5: The heating power output for the vertical radiator at specific input/output temperatures with the set point air temperature of an office building during operation, 21 °C (Appendix A.3 in NS3031)

Input/output temperature (°C)	**Heating power output (W)**	**Total heating output (W)**
75/65	2 519[1]	130 988
70/55	2 021[1]	105 092
55/45	1 285[1]	66 820
50/40	999[2]	51 951
40/30	488 [2]	25 367
30/20	92 [2]	4 794

$$\Phi = \Phi_{CAT} + (\frac{\Delta T}{\Delta T_{CAT}})^{1.33} \tag{5.2}$$

$$\Delta T = \frac{T_{input} + T_{output}}{2} - T_{room} \tag{5.3}$$

Φ : The heating power output of the given system.

Φ_{CAT} : The heating power output specified by the supplier (in this case HM Heizkörper).

ΔT : Temperature difference between the average temperature of the radiator and the room temperature.

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[1] From Heizkörper (2015)

[2] Calculated with equation (5.2) and equation (5.3)

5.3 Ventilation

To keep the air quality at an acceptable level it is necessary to ventilate the building. This can be done by relying on natural forces or by using mechanical ventilation units with fans. Ventilation does not only remove pollutants (e.g. CO_2), but also excessive heat, and helps regulate the thermal environment in terms of temperature and sometimes humidity. There are different types of ventilation strategies and methods which will be discussed further on.

5.3.1 CAV and VAV

There are two main methods to regulate the air supplied to a room:

- Constant air volume (CAV)
- Variable air volume (VAV)

CAV systems have constant airflow, but the temperature is regulated in response to heat surplus/deficit. VAV systems have generally constant supply air temperature, whereas the airflow rate is regulated in response to the heat load and/or the concentration of CO_2 (Jagemar, 2003). The air supply temperature is variable at PK, but the airflow rate is adjusted after the indoor temperature and CO_2 concentration. The regulation of VAV is described in the next section.

5.3.2 Demand Controlled Ventilation

Demand controlled ventilation (DCV) is defined by Norges Byggforskningsinstitutt (2005) as a control principle where fresh air supply is regulated in relation to pollution concentrations (e.g. CO_2), presence of people, relative humidity and/or indoor air temperature. In many modern buildings, DCV is regulated automatically by appropriate sensors, but manual control is also common. Other buildings might either have no mechanical ventilation system or have a constant air volume flow not regulated by the mentioned factors. DCV is a way of controlling VAV systems.

Provided that the loads of CO_2 and/or temperature (depending on what the system regulates) varies over time, one can assume a reduction in energy use by utilizing a DCV system (Mathisen, 2007).

The difference between a CAV, VAV and DCV system is illustrated in figure 5.8. It shows roughly how the VAV and DCV saves energy by regulating the airflow in a room. Only DCV can adjust the ventilation rate following temperature and contamination concentration since it responds to data from sensors. The load of the airflow is not necessarily at maximum for all ventilation units. In this example it is only used as a reference.

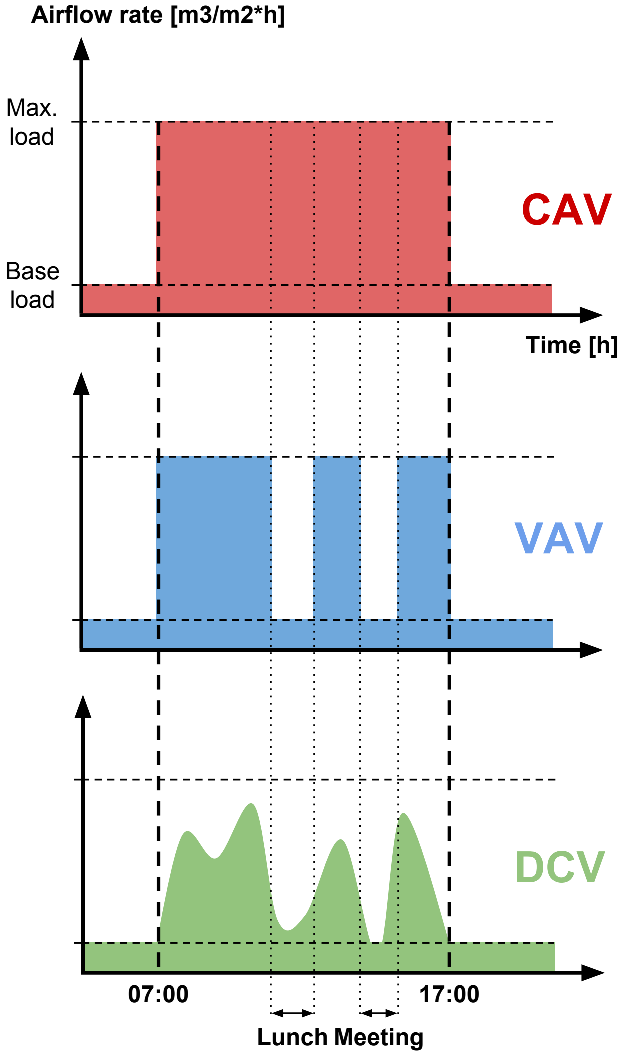

Figure 5.8: A simple example of how CAV, VAV and DCV affects the airflow in a room at an office building. *Inspired by Exhausto (2015).*

5.3.3 Ventilation Strategy

A ventilation strategy regulates how the air is supplied to the room and how it is extracted. There are two main methods of mechanical ventilation strategies used today: Mixing ventilation and displacement ventilation. Displacement is the chosen strategy at Powerhouse Kjørbo, and will be discussed more throughly. A third strategy is called piston flow, which is mostly used in industrial buildings, and will not be discussed in this report.

In the upcoming models one can observe the following variables:

C_s : The concentration of contaminants in the *supply air*

C_e : The concentration of contaminants in the *exhaust air*

C_b : The concentration of contaminants in the *breathing zone (zone of occupancy)*

C_p : The concentration of contaminants *at a given point in the room*

The following important terms are also used:

- **The adjacent zone** is defined as the area around the air diffuser where draft occurs (Mundt et al., 2004). Draft is experiences when the supply air has not reached a satisfactory velocity and/or temperature. This velocity is usually below 0.2 m/s (Mundt et al., 2004). The adjacent zone is shown in figure 5.9 and 5.10.
- **Zone of occupancy** is the space in which persons normally reside and where the requirements of the indoor environment shall be satisfied. The default area in standard NS 12792 is 0.5 meters away from internal and external walls, 1 meter away from external windows, doors and radiators, and from 0.1 meters to 1.8 meters above the floor (European Committee for Standardization, 2003). This is seen in figure 5.9 and 5.10.
- **Thermal plume** is an air current rising from a hot object (body, technical equipment etc.) (Mundt et al., 2004).
- **Thermal stratification level** is the layering of air within a space due to density differences caused by different temperatures. The thermal stratification layer is a simplified level differentiating the "cold" zone and the "hot" zone (Mundt et al., 2004).
- **Short circuiting** is when supply air from an inlet is extracted from the room before passing the occupied zone. (Mathisen et al., 2004)

Mixing Ventilation

Mixing ventilation is achieved by supplying air to the room at a high velocity. The room air will be entrained by the air stream and launch a circulation of air to create a uniform mix of the concentration of contaminants. The air is most often supplied at ceiling level outside of the zone of occupancy to avoid the feeling of draught (Mathisen, 2007). A very simplified model of the mixing ventilation concept is shown in figure 5.9. In this model the concentration of contaminants, originated from the person, is mixed so that a uniform concentration of contaminants is made throughout the room. A perfectly mixed room would have $C_s = C_b = C_e$.

Mixing ventilation is most suited where (Mundt et al., 2004):

- Contaminants are colder or denser than the surrounding air
- Ceiling heights are below 2.4 meters

- Disturbances to room air flow are strong
- Surplus heat is the critical factor, and not air quality (cooling load is high)

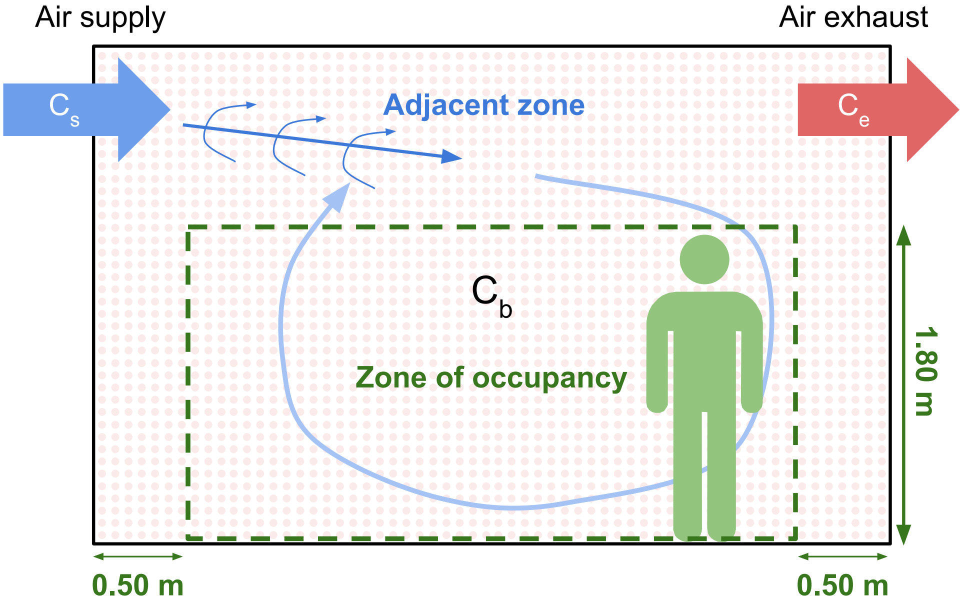

Figure 5.9: A one-zone model of the mixing ventilation strategy. The concentration of contaminants (red dots) is mixed uniformly throughout the room. The arrows represent air flow. *Illustration inspired by (Nielsen, 2003)*

Displacement Ventilation

Displacement ventilation takes advantage of the buoyancy forces in the room by supplying cool air (1-8 °C below the room temperature) with a low velocity at floor level. The low temperature is to make sure that the supplied air does not rise up before it has reached all of the occupied zone. If it is warmer than the surrounding air there will be a risk of short circuiting of air between the supply and exhaust vent. Free convection from heat sources will drive the cooler air upwards, thus creating a vertical air movement which drags along contaminants and excess heat up to the extraction point located by the ceiling. (Mundt et al., 2004) Due to the low air supply velocity one needs a high cross sectional area for the diffuser in order to supply enough air. Displacement ventilation is well suited for variable air supply (VAV), as the system is not affected by impulses from the supply air rate (Norges Byggforskningsinstitutt, 2005).

The principle of displacement ventilation is based on air stratification, which makes it natural to divide the space into layers, or a simplified two-zone model. The model consists of an upper, heated and polluted zone, and a lower, cooler and cleaner zone. This is shown in figure 5.10.

The lower zone should cover at least the zone of occupancy to meet the requirements of indoor air quality.

Displacement ventilation is most suited where (Mundt et al., 2004):

- Contaminants are warmer and/or lighter than the surrounding air
- Ceiling heights are above 3.0 meters
- Lower noise from the air diffusers is desired
- Large airflows shall be supplied in small rooms
- Supply air is colder than the ambient air

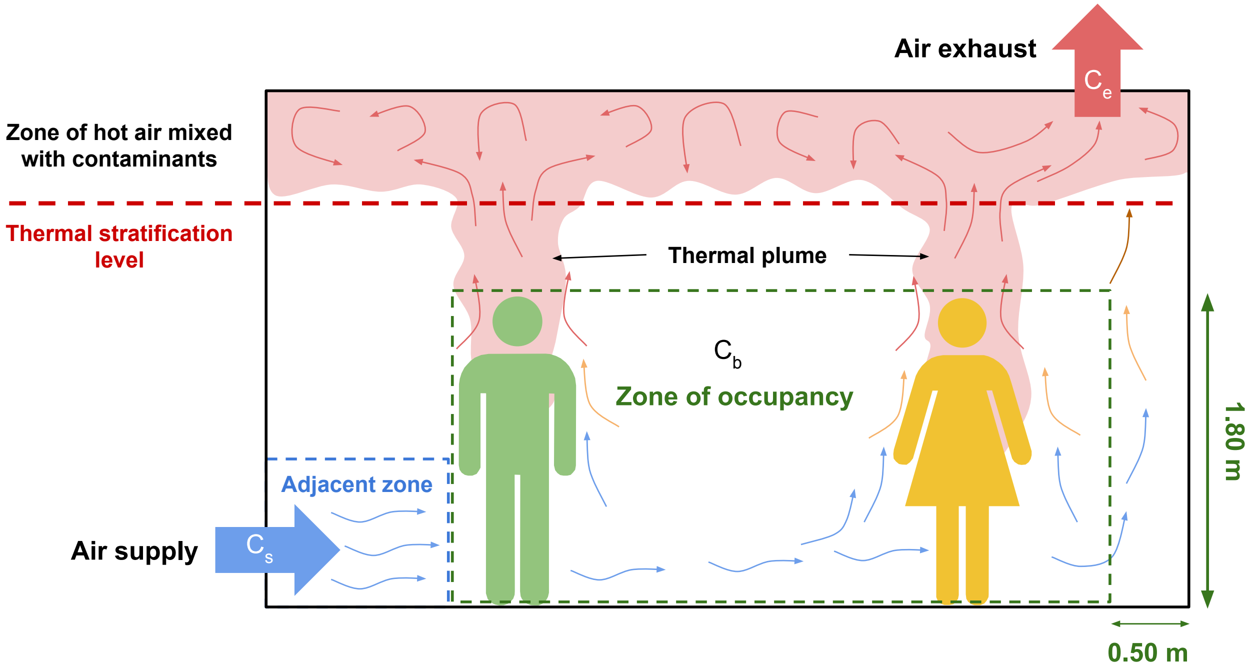

Figure 5.10: An illustration of how displacement ventilation works. This is a two-zone model: a lower zone with cold, fresh air and an upper zone with heated and contaminated air. *Illustration inspired by (Nielsen, 2003).*

The Measured Adjacent Zone

A measurement done by HVAC engineer Olav Rådstoga at PK showed that a displacement diffuser (1.15 m^2) in the open landscape had the following air velocities at full airflow (800 m^3/h):

Table 5.6: Air velocity from displacement diffuser in open landscape at maximum load (800 m^3/h).

Distance from diffuser [m]	Air Velocity [m/s]
0	0.50 - 0.55
0.50	0.20 - 0.40
1.00	0.20 - 0.30

5.3.4 Ventilation Efficiency

The main objective of ventilation is to ensure good indoor air quality, and the efficiency varies among the ventilation strategies. One way to measure the ventilation efficiency is with the air exchange efficiency, ε^a. High efficiency would mean less air required to ensure the same air exchange compared to a lower efficiency. ε^a can vary between 0 % (no air exchange at all) to 100 % (ideal air exchange). Mathisen et al. (2004) states that mixing ventilation has an efficiency of up to 50 %. It is achieved a fully mixed room with equally distributed pollutant concentration when the efficiency is 50 % . Displacement flow has a higher efficiency with 50 % $\leq \varepsilon^a \leq$ 100 %. If the efficiency is somewhat below 50 % it could indicate a short circuit between the air supply and the exhaust, which is not preferable. According to supervisor Hans Martin Mathisen, the efficiency of displacement flow is usually 55-60 %.

There are many ways of measuring ventilation efficiency. The method used in this thesis is described in the following sections and is based on the REHVA Guidebook for "Ventilation effectiveness" written by Mathisen et al. (2004). The appropriate equipment used for this method is presented in Appendix A. The execution of the fieldwork is presented in chapter 6.

Step-Change Response Method

The step-change response can both be measured as a step-up or a step-down response. The step-up method introduces a tracer gas to the indoor air, which is monitored until the concentration of the tracer gas reaches a steady state value. The step-down method is the opposite of the step-up method. When the tracer gas has reached a steady state value the gas supply is cut. The concentration is monitored as it decays with the exchange of indoor air. Thus these two methods can easily be done in the same setting. They are both illustrated in figure 5.11.

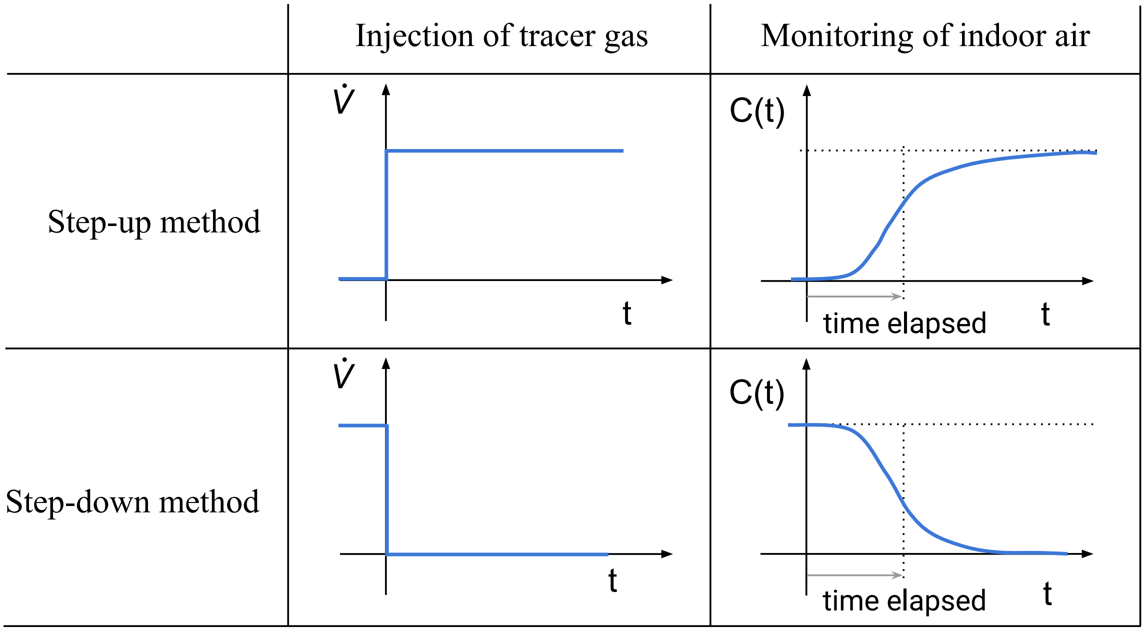

Figure 5.11: The two step-change response methods of measuring the ventilation efficiency and by tracer-gas concentrations. *Based on: (Han, 2012).*

The analysis for both the step-up and step-down method include finding the following variables (Mathisen et al., 2004)):

1. $\overline{\tau}_p$ - **Local mean age of air** is the mean time it takes for the supply air to reach a certain point in a room. With fully mixed air the mean age is the same throughout the room. The step-up method uses equation 5.5, and step-down method uses equation 5.4.
2. τ_n - **Nominal time constant** is the room volume divided by the ventilation flow rate as seen in equation 5.6.
3. ε_p^a - **Air change efficiency** at a given point is the measure of how fast the air is replaced in that point. See equation 5.7. This can also be measured for a whole room.

$$\overline{\tau}_p = \int_0^\infty \frac{c_p(t)}{c_e(0)} \cdot dt \tag{5.4}$$

$$\overline{\tau}_p = \int_0^\infty \left(1 - \frac{c_p(t)}{c_e(\infty)}\right) \cdot dt \tag{5.5}$$

$$\tau_n = \frac{V}{q_s} \tag{5.6}$$

$$\varepsilon_p^a = \frac{\tau_n}{2 \cdot \overline{\tau}_p} \cdot 100[\%] \tag{5.7}$$

Equation 5.7 shows that the mean age of air has to be larger than the nominal time constant in order to achieve more than 50 % ventilation efficiency.

Analysis of the Results - Methodology

To find the mean age, nominal time and ventilation efficiency one can use a computer spreadsheet program (e.g. Excel) to analyze the measured values. Mathisen et al. (2004) thoroughly demonstrates the methodology used in this master thesis. This regards both the step-up and step-down method, and it is based on the equations discussed above. The method is shortly explained in figure 5.12 combined with the following list of steps:

1. Set a point, $t(0)$ for where the gas was turned on/turned off. It is important to be specific.
2. Calculate the area over/under the curve as seen in figure 5.12. In excel this is done by using the approximation method with equation 5.8. The summation goes from $t(0)$ to $t(\text{tail})$. The tail area is calculated separately.
    (a) The step-up method must be turned upside-down. With larger rooms it can take quite some time before the tracer-gas concentration is equal to the supply concentration. Therefore, when the graph is turned the supply concentration, equal to $c(\infty)$, is used: $c^*(t) = c(\infty) - c(t)$. It should now look like the step-down graph with $c^*(t)$ as the new graph line.
3. The area above/below the curve is weighted with equation 5.9.
4. At the end of the measurement period the graph can become irregular. This part is called the tail, and the area is calculated by using the exponential trend function in excel to determine the slope, λ, which is marked in the figure. The normal and weighted tail is calculated by using equation 5.13 and 5.10.

5. The mean age of air is calculated using equation 5.11.
6. The nominal time constant is calculated using equation 5.12.
7. The air exchange efficiency is then calculated as described earlier in equation 5.7.

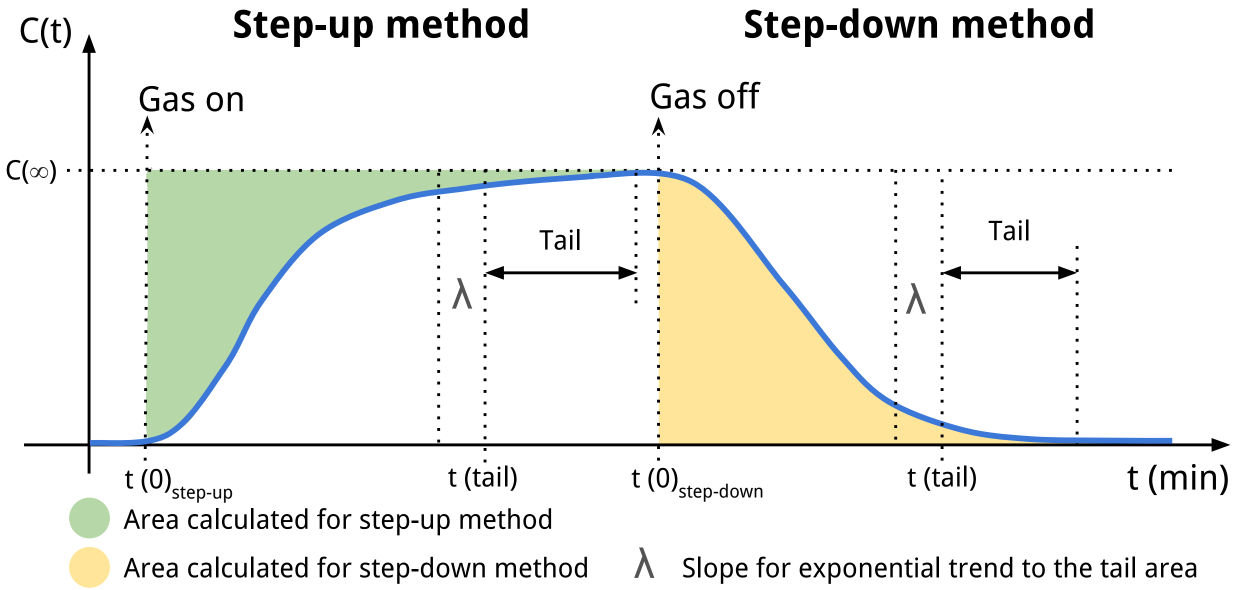

Figure 5.12: A graphical illustration of how the ventilation efficiency is calculated. *Based on: Mathisen et al. (2004).*

$$A_{curve} = A_{tail} + \sum_{i=1}^{n} \left(\frac{c_i + c_{i+1}}{2} \right) \cdot (t_{i+1} - t_i) \tag{5.8}$$

$$A_{weighted} = A_{tail,weighted} + \sum_{i=1}^{n} A_{curve,i} \cdot \left(\frac{t_{i+1} + t_i}{2} \right) \tag{5.9}$$

$$A_{tail,weighted} = A_{tail} \cdot \left(\frac{(-1)}{\lambda} + t(\text{tail}) \right) \tag{5.10}$$

$$\overline{\tau}_{p,graph} = \left(\frac{A_{weighted}}{A_{curve}} \right) \tag{5.11}$$

$$\tau_{n,graph} = \left(\frac{A_{curve}}{c(0)} \right) \tag{5.12}$$

$$A_{tail} = -\left(\frac{c(\text{tail})}{\lambda} \right) \tag{5.13}$$

When analyzing the curves for each measurements it is important to study both the linear and logarithmic scale. During decay one should observe a straight line in the logarithmic scale. This means that the decay is stable, but if this is not the case there might be irregularities, either external (e.g. unwanted air flow movements) or internal (e.g. errors in the equipment). (Mathisen et al., 2004)

Tracer Gases

A tracer gas is used to measure the ventilation efficiency. This gas should not be naturally present within the room. However, if this is the case then the concentration should be constant. The gas density of the tracer gas should be equal or close to that of the air so it mixes well. The gas should ideally also be chemically stable, behave more or less like air, be affordable, easy to obtain, easy to measure, non-flammable, non-toxic and environmentally friendly (Mathisen et al., 2004).

Of all the tracer gases recommended by Mathisen et al. (2004), Nitrous Oxide (N_2O) was concluded to be the most suitable when measuring the ventilation efficiency at PK. Its properties are discussed in Appendix A. Mathisen et al. (2004) describes the method for how to supply and measure a tracer gas during ventilation effectiveness experiments. The specific technical details on how it was done for this thesis is portrayed in Appendix C.

5.4 Analysis of Quantitative Surveys

This section is about the standard deviation used for the indoor climate survey presented in the results. It does not discuss how to analyze the results otherwise.

The survey conducted for this thesis is a quantitative study of the perceived indoor climate. In surveys there is a percentage of error in the results that can be calculated by finding the standard deviation. As an example, a question regarding the satisfaction of the temperature in a building is answered by giving a rating. As long as not all of the potential participants participates in the survey, one can not be sure that the results reflect the overall satisfaction for the temperature. The potential participants are called a *population*.

The average score has a standard deviation, which is given with a confidence interval. As an example, 25 of 100 people participates in a survey, and with a confidence interval of 95 %. One can be 95 % certain that if all of the population (100 people) participated in the survey, the results would be within the calculated standard deviation of ± 8.4 %. A confidence interval is given with a *"z-score"*, $\pm z_{\alpha/2}$, that is implemented in the final equation. The most used confidence interval is 95 %, and it gives a z-value: $\pm z_{\alpha/2} = 1.96$ (Johnson and Bhattacharyya, 2011).

The standard deviation for a population n, where X people participates is given by equation 5.14:

$$\sigma = \pm z_{\alpha/2} \cdot \sqrt{\frac{\hat{p} \cdot \hat{q}}{n}} \tag{5.14}$$

Where,

$$\hat{p} = \frac{X}{n} \qquad \text{and} \qquad \hat{q} = (1 - \hat{p})$$

Chapter 6 | Methodology - Fieldwork

This chapter explains the methodology behind the fieldwork conducted at PK. The goal is to analyze the thermal environment and indoor air quality. The measurable indoor climate has been analyzed with temperature and ventilation measurements, and the perceived indoor climate has been analyzed with a quantitative survey about the perception of the indoor climate.

The fieldwork was done in block 4, and mainly on the 2nd floor. The same floor was used during the project work fieldwork, and it was chosen on the basis of being a floor with a normal load of occupants and an "average floor" being between two similar floors, 1st and 3rd. The indoor climate survey, however, was conducted on both block 4 and 5 (which is PK), and block 9. Block 9 is a renovated office building with lower standards than PK, and was originally built at the same time and is architecturally similar. It will be used as a comparison regarding the perception of the indoor climate.

The room numbers at Powerhouse Kjørbo have four digits. Room numbers will be used in this report. A quick guide as to how these room numbers work, with an example room number, **4106**, is given in table 6.1.

Table 6.1: Example of how the room numbering at Powerhouse Kjørbo works.

4106	**4**	**1**	**06**
The unique room number	*The block*	*The floor*	*The room number at the 1st floor in block 4*

Remark: From now on the renovated office building, block 9, will be referred to as *ROB*.

6.1 The Measurable Indoor Climate

This section will describe the methodology behind the physical fieldwork regarding temperature and ventilation efficiency measurements. PK experienced its first winter in 2014/2015, and during November 2014 measurements from Søgnen (2015) indicated that a closed cell office might not be able to meet the recommended indoor temperatures during sub-zero outdoor temperatures. As a follow-up there will be a new experiment in the same closed cell office, in addition to a comprehensive temperature mapping of the 2nd floor in block 4. The goal is to study and determine if the rooms with closed doors and the overall floor can meet the recommendations in terms of temperature during the winter.

There has not been a physical study of the ventilation efficiency at PK before. The goal is to measure and evaluate the behavior and effectiveness of the ventilation strategy, which in theory is, and in practice should be, displacement ventilation.

The temperature fieldwork used the *iButton* temperature sensor in addition to the local permanent temperature sensors installed at PK. When measuring the ventilation efficiency, a *Multi-gas monitor - type 1302* and a *Multipoint sampler and doser - type 1303* was used to take samples of the indoor air and analyze it. Appendix A offers a detailed description of all the equipment used for both of the fieldworks.

6.1.1 Temperature Distribution

The following experiments measure the heat distribution within a building floor, and the temperature profile of a cell office with a closed door. The temperature experiments took place between February 4th 2015 and March 13th 2015, lasting approximately five weeks.

Temperature Distribution Within Zones

The centered heating strategy depends on heat being distributed evenly throughout the open landscape and into the cell offices and meeting rooms. There is a risk that the PK sensors do not represent the temperature distribution in its dedicated zone as seen in figure 6.1. The chosen zoning is just an estimate, and does not necessarily reflect how it was divided by project planners. The goal is to show how well each PK sensor represents their zone, and how well the heat is distributed on the 2nd floor, and if it meets the requirements in terms of temperature. Almost all of the iButton and PK sensors were at the same height above the floor (150 cm).

Figure 6.1: Illustration of sensor positions at 2nd floor, block 4. Each zone is marked with its distinct color and is named after the PK sensor in its area. *Technical drawing: Entra.*

On the 2nd floor of block 4 there are five air diffusers (VAV) and six radiators in the open landscape area. There are four temperature sensors in addition to two sensors in two different meeting rooms. These four temperature sensors control each of their zones in the open landscape and are named zone A, B, C and D as seen in figure 6.1. The meeting rooms, 4239 and 4206 have sensors referred to as M1 and M2, respectively. A total of 14 iButton temperature sensors was placed around the 2nd floor in each of these zones also seen in figure 6.1.

Table 6.2 sorts the iButtons into their dedicated zone and PK sensors. The area of each zone has been estimated by the writer, and a more detailed description of the sensor positions are presented in the tables D.1 and D.2 in Appendix D.

Table 6.2: List of which iButton temperature sensors and zones being compared.

Zone	iButton
A	24, 25, 26
B	16, 17, 18, 19
C	20, 21, 22
D	23
M1	-
M2	27, 28, 29

Open and Closed Cell Office Doors

Since the cell offices do not have dedicated heat sources they are dependent on heat distribution from the central radiators and through the CAV displacement diffusers in each cell office. A study comparing two cell offices, one closed and one open, showed a temperature difference between the two offices of 2 °C during the whole working day. The closed office was not in use compared to the open office which had both an occupant and technical equipment running (laptop, monitors, lighting etc.). It indicating that a closed door might prevent the room reaching a satisfactory thermal environment during sub-zero temperatures. (Søgnen, 2015)

In this thesis the study will compare the temperature in the hallway outside the office to the temperature inside the office. The goal of this experiment is to see if the heat moving from the hallway into the office is enough when the door is closed. It was expected colder outdoor temperatures this time compared to the previous experiment.

Cell office 4104 was the chosen location, and 11 iButton sensors were placed around the office both individually and as a vertical temperature gradient sensor string (VTGS). The VTGS is a string connected to the ceiling, and five iButton sensors are attached to the string at 10, 60, 110, 160 and 210 centimeters above the floor. The positions of the sensors in the office are illustrated in figure 6.2. A more detailed description of the sensor positions is found in table D.1 and D.2 in Appendix D.

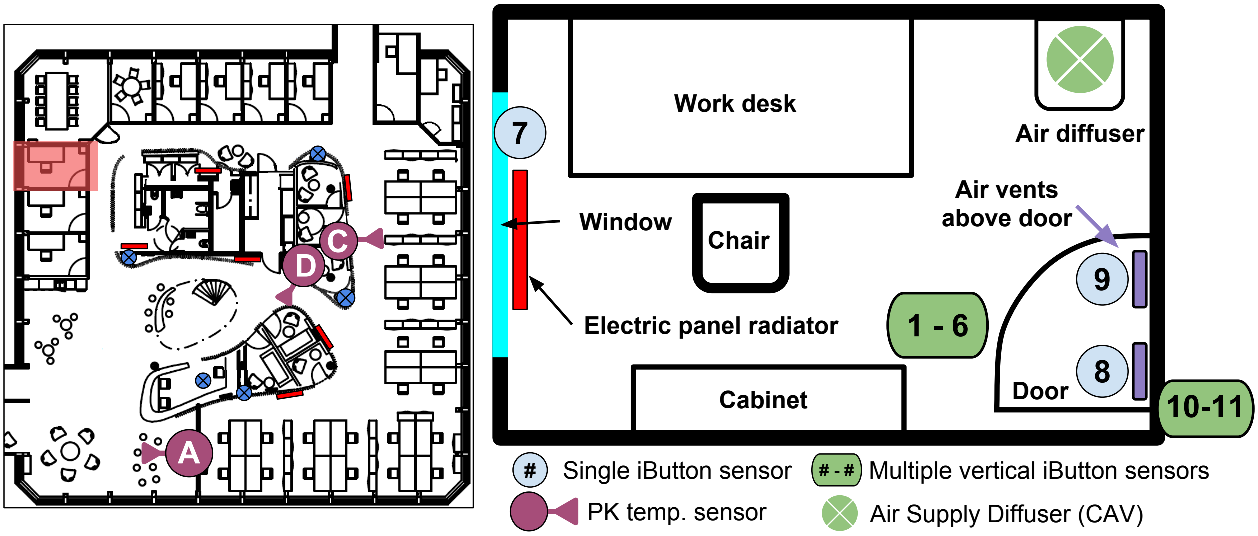

Figure 6.2: Illustration of sensor positions at 1st floor, block 4, in cell office 4104. *Technical drawing: Entra.*

6.1.2 Ventilation Efficiency

The indoor air quality was analyzed by studying the ventilation efficiency. This was done by following the tracer-gas method described by the REHVA "Ventilation Effectiveness" guidebook (Mathisen et al., 2004). The complete process of supply and measurement of the tracer-gas is presented in detail in Appendix C, but shortly explained, it is done by adding a tracer gas to the air supply and measuring its concentration in the zone of occupancy over time. The goal is to find out how well the air is exchanged and if it has the expected behavior of displacement ventilation. The methodology of how the ventilation efficiency is found is described in chapter 5 on page 43. Supervisor Hans Martin Mathisen and co-supervisor Maria Justo Alonso assisted with the ventilation efficiency fieldwork. The procedures are described below.

Tracer-gas Experiment

The ventilation efficiency was measured in different areas on the 2nd floor of block 4 as seen in figure 6.3. A tracer gas was chosen on the basis of what was recommended by Mathisen et al. (2004), which was Nitrous Oxide (N_2O).

The tracer gas (N_2O) was injected directly into the supply air of the ventilation unit in block 4 and from there it was distributed to all the four floors in the building. It was decided to keep the supply concentration of the tracer gas at 25 ppm, which is within the safe concentration levels and is suitable for the amount of tracer gas available in this experiment. The detailed process and setup of the tracer gas experiment is described in Appendix C.

Figure 6.3: The locations of the sampling points during the ventilation efficiency experiment at the 2nd floor, block 4. Sampling point 4 and 7 is at the 3rd and 4th floor respectively. The exhaust points are for wet rooms and a printer room. The main exhaust (VAV) is up the staircase in the center. *Technical drawing: Entra.*

Two experiments were conducted on Thursday March 12th and Friday March 13th, measuring both the rise and decay of the tracer gas in the indoor air. This allows for both a step-up and step-down analysis. The sample positions are given in figure 6.3 above, and described with detail in table D.3 in Appendix D.

The seven different sample positions are based on the following arguments:

1. **East Corner** - One of the positions with the largest distance from the main exhaust.
2. **North Corner** - One of the positions with the largest distance from the main exhaust.
3. **2nd Floor Staircase** - To monitor the concentration of the extracted air from the 1st and 2nd floor.
4. **3rd Floor Staircase** - To monitor the concentration of the extracted air from the 1st, 2nd and 3rd floor.
5. **Hallway Between Block 4 & 5** - To monitor if any airflow from block 5 affects the concentration of the tracer gas.
6. **Office Air Diffuser Inlet** - Used as a reference point to control the concentration of the tracer gas in the supply air. The cell office diffuser has a uniformly circular diffusion pattern (FläktWoods, 2015), assuring that placement of the sampling tube in the diffuser does not affect the results.
7. **4h Floor Staircase (main exhaust)** - Extra sample point only used in the second experiment for the concentration in the actual main exhaust.

The staircase sample points are compared to each other in order to analyze the extraction of air from each floor. The two experiments, Thursday and Friday, had a step-up and step-down sampling period with their distinct sample points described in table 6.3.

Table 6.3: The sample points for the step-up and step-down analysis conducted on Thursday and Friday. The "Channel" column indicates each of the six sampling channels found on the Multi-gas monitor, and which sample point is being monitored in each experiment.

Channel	**Thursday (step-up & step-down) and Friday (step-up)**		**Friday (step-down)**	
	Sample point	**Height (cm)**	**Sample point**	**Height (cm)**
1	1	150	1	150
2	2	150	1	10
3	3	130	1	290
4	4	130	7	130
5	5	150	5	10
6	6	-	6	-

Each experiment had its own time schedules. The first was conducted from the end of the working day to late night (see table 6.4). It was arranged so that the air supply was not cut before the experiment was completed.

The second experiment was conducted from early in the morning from when the ventilation unit started until some time after mid-day (see table 6.5). This time there were more people present compared to the first experiment.

Table 6.4: Time schedule for the first tracer-gas experiment and the duration of the step-up and step-down measurements.

THURSDAY MARCH 12th				
Time of day	**Time of experiment**	**What**	**Duration**	
15:57	00:00	Sampling started	**Step-up**	02:35
16:15	00:18	Gas turned on		
18:50	02:53	Gas turned off	**Step-down**	02:30
21:20	05:23	Sampling stopped		

Table 6.5: Time schedule for the second tracer-gas experiment and the duration of the step-up and step-down measurements.

FRIDAY MARCH 13th				
Time of day	**Time of experiment**	**What**	**Duration**	
05:43	00:00	Sampling started	**Step-up**	05:41
06:12	00:29	Gas turned on		
11:53	06:10	Gas turned off	**Step-down**	02:58
14:51	09:08	Sampling stopped		

The experiment was not conducted in an enclosed area, thus exposing it for air exchanges between compartments and building block 5. It is complicated to estimate the actual air supply volume to each floor since the building automation system only reports the total air volume supply. Ideally, it would be best to have a constant air supply volume from the ventilation unit.

The air supply, exhaust and air flow between compartments and the two building blocks is illustrated in figure 6.4. Air moves between the two blocks through a connected hallway which has no doors. Exhaust air for each block moves through the staircase in the center. Air also moves up staircase in the connected hallway. On the 4$^{\text{th}}$ floor there is an airtight glass wall enclosure around the staircase. This ensures that the air from the three first floor goes to its dedicated air exhaust. The 4$^{\text{th}}$ floor has as its own exhaust as seen in the figure.

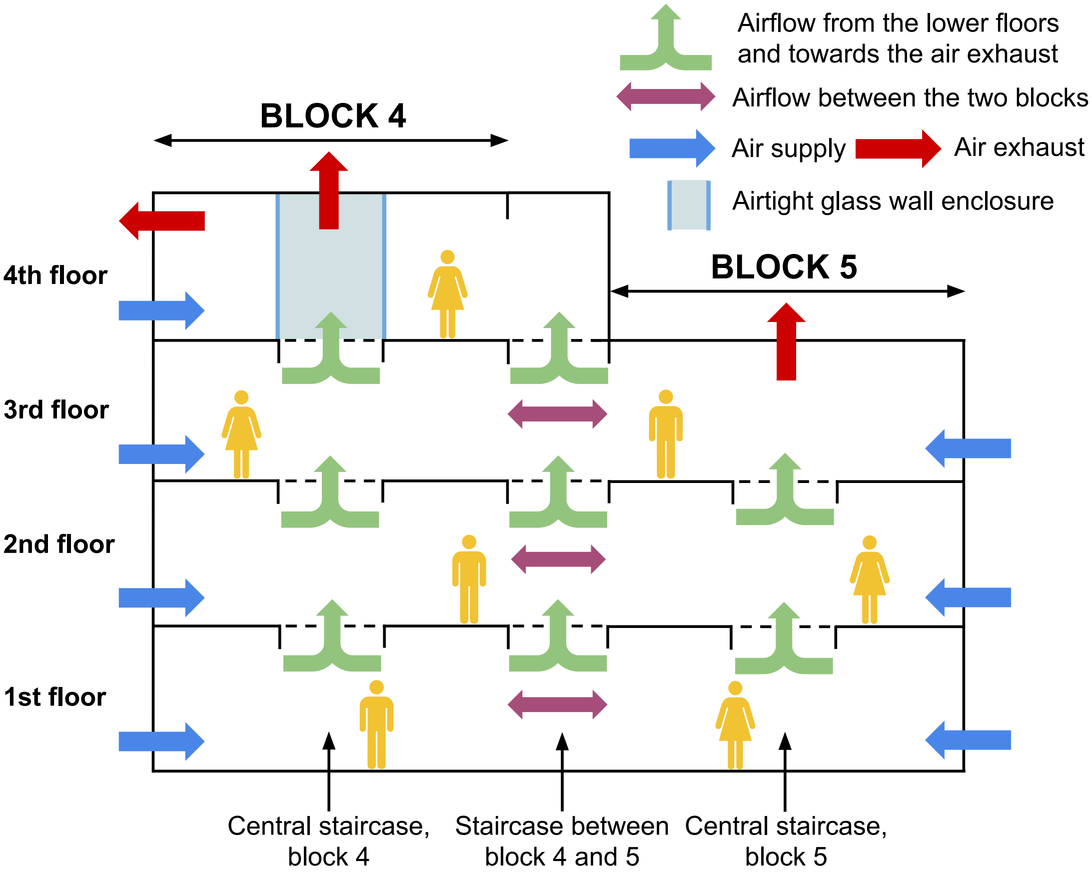

Figure 6.4: A simplified illustration of the air supply and exhaust at Powerhouse Kjørbo, in addition to the air movement between spaces. The air is actually supplied from the center, and not from the external walls as illustrated here. *Inspired by: Powerhouse Alliance (2012).*

6.2 The Perceived Indoor Climate

The perception of the indoor climate is essential for the understanding of how an occupant experiences a building. This can be analyzed by conducting a survey with the employees as participants. The goal of this survey is to study the perceived indoor climate at PK, in addition to compare the results with the occupants' perception in block 9, a renovated office building with lower standards.

The utilized survey is based on the Örebro model and a web-based survey from the Center for the Built Environment (CBE). The Örebro model is part of the MM Questionnaires, developed in 1985 at the Department of Occupational and Environmental Medicine at the University Hospital in Örebro, Sweden (Andersson et al., 2015). Both the Örebro model and the CBE survey is used by various studies, making it easy to do comparisons with other buildings.

The survey that was conducted contains many topics around indoor environment, but in this thesis only the perceived thermal environment and indoor air quality will be analyzed. They will be compared with the measured results from the temperature and ventilation fieldworks.

A notification form was sent to the Norwegian Social Science Data Services to get a permission for conducting the survey. This must be done according to the Personal Data Act when recording personal data (such as e-mails, names etc.). However, all personal data was deleted after the completion of the survey (only e-mails where collected in order to identify who had responded and who had not). The approval was given on May 19th 2015.

The survey was started on Tuesday May 26th and ended on Monday 8th June 2015. The survey (only in Norwegian) is attached in Appendix E.

Powerhouse - Block 4 & 5

Occupants of the 1st and 3rd floor in block 5 and all of the four floors in block 4 participated. The 2nd floor in block 5 uses activity based working (ABW), which means that the employees do not have a fixed workplace. Therefore they are excluded from this survey.

Renovated Office Building - Block 9

The 4th and 5th floor in the ROB is occupied by a company with equivalent work tasks as block 4 and 5 (engineering consulting). Only theses two floors in block 9 are studied due to comparable perceptions. The ROB is part of the Kjørbo office building complex.

Some technical specifications of the building were gathered after a conversation with the technical operator of the Kjørbo complex, Per Iversen, on May 20th 2015. The building has a simple ventilation unit equipped with a rotary heat exchanger, and a separate heating and cooling battery. The ventilation strategy is CAV and mixed ventilation, and the supply air temperature is adjusted after the outdoor air. There are no sensors communicating with the building automation system in terms of air supply volume and indoor temperature. The heat can be regulated with radiators by the employees, but the details around this is not known.

Chapter 7 | Results and Discussion

This chapter presents the results for the fieldwork and the indoor climate survey with a discussion on each result. The fieldworks consists of much data and not all can be included in this report. The results are selected to show the most important discoveries and to represent the answer to the goal of each experiment and the survey. The temperature results are illustrated with the individual number for each iButton sensor. The same goes for the sample point positions. Sources of error are presented in Appendix F.

7.1 The Measurable Indoor Climate

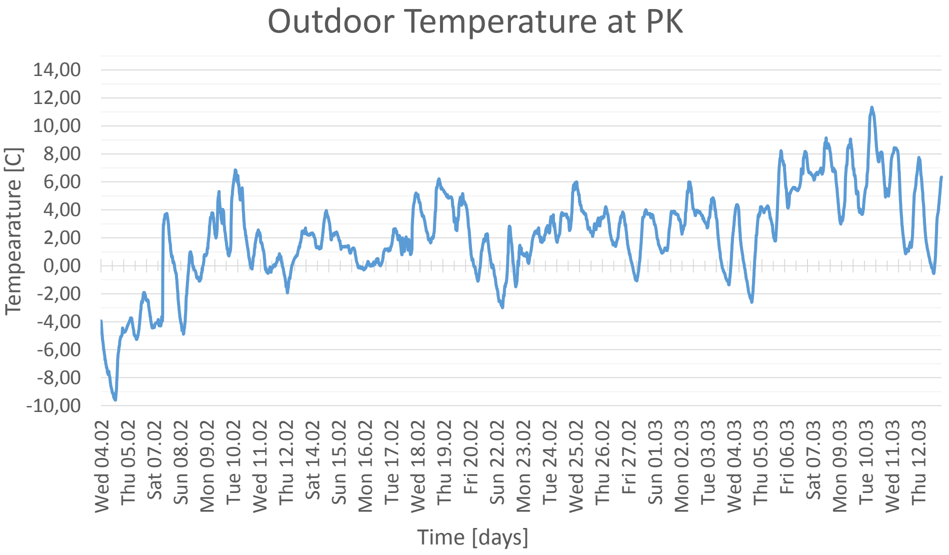

Figure 7.1: Outdoor temperature in Sandvika 04.02-13.03 2015

The outdoor temperature during the temperature experiment is presented in figure 7.1. Two days from the whole experiment period have been chosen for the temperature distribution analysis at PK. The days are picked based on the highest and lowest temperature at noon (12:00) during work hours. The highest temperature at noon is 10.8 °C on Tuesday March 10th. The lowest temperature at noon is -6.3 °C on Thursday February 5th. This gives a temperature difference of 17.1 °C between the coldest and the warmest day.

Figure 7.2 is an overview map and a collaboration of all the earlier floor illustrations. It shows the zoning in addition to the temperature sensor and tracer-gas sample positions. This figure will be used as a reference for each of the following relevant illustrations and tables, which will be marked with its page number. This is done to make it easier for the reader.

Figure 7.2: Division of zones on the 2nd floor of block 4. The iButton and PK temperature sensors, and the tracer-gas sample points are included in the figure *(Technical drawing: Entra)*.

The measured temperature from the fieldwork is the air temperature, and preferably it should have been the operative temperature. However, the mean radiant temperature only differs from the indoor air temperature when the surrounding surfaces are colder or warmer. PK is a very well-insulated building, and the inside of the windows and walls therefore have a higher temperature than in an average building. It was discovered earlier that the vertical temperature difference between the floor and ceiling is approximately 1 °C in the open landscape during work hours (Søgnen, 2015). This could lead to a less asymmetric radiation between the floor and the ceiling. Based on this one can estimate the mean radiant temperature to be close to the air temperature, thus also equal to the operative temperature (Equation 5.1). This makes it easier to compare the measured air temperatures with the recommended values for operative temperature in section 5.1.1.

7.1.1 Horizontal Temperature Distribution on a Building Floor

The horizontal temperature distributions for the coldest and a warmest day are presented in figure 7.3. These are values from the iButton and PK sensors, which have been two-dimensionally interpolated to visualize the temperatures in-between sensors.

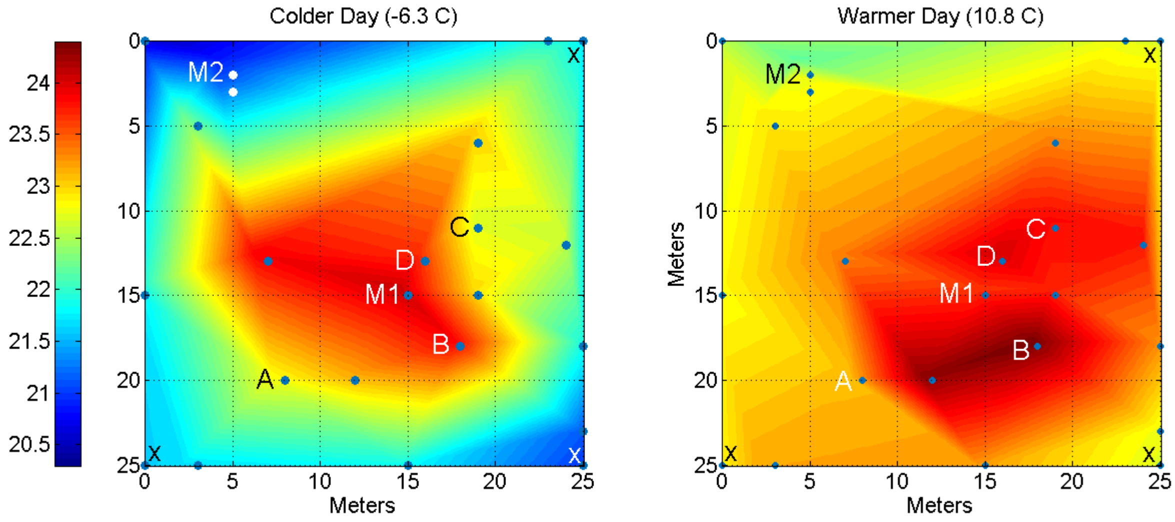

Figure 7.3: A heat map of the 2^{nd} floor of block 4. Both display the temperature distribution at noon on the coldest (left) and warmest day (right). See overview map on page 61.

Each PK sensor is marked on the maps. The rest of the sensors are unnamed but are visible as blue or white dots (color does not matter). Each corner marked with an *"x"* are virtual temperature values, meaning the temperature is estimated. The temperatures have been guessed to be close to 0.2 °C below the nearest iButton sensor (two meters away). The model is not 100 % accurate regarding the exact position of each sensor. The upper and left middle areas do not represent the temperature distribution well due to all the cell offices located there. It is likely warmer than what is shown on the figure.

The centered heating is less distributed on the colder day, as for the warmer day the heat is more evenly distributed. The difference between the highest and lowest temperature is approximately 2.7 °C and 1.7 °C for the coldest and warmest day, respectively. This is excluding the meeting rooms which would increase the temperature differences to approximately 3.7 °C and 2.2 °C. The warm center in both of the heat maps can be explained by the excess heat moving towards the main exhaust in the staircase. If one were to move from the warmest region to the coldest region (and vice versa) on the colder day, then such temperature change could be considered thermally uncomfortable, according to the requirements of temperature change in standard 55 ASHRAE (2004). However, the horizontal temperature change seems to be more of a problem if the meeting rooms are also considered.

It is most often coldest in meeting room 4206 (M2) and warmest in the central meeting room (M1) during noon. There have been some complaints about the corner meeting rooms earlier, and the indoor climate survey does also report that there is a slightly lower satisfaction with the temperature and air quality in meeting rooms than at the work desks at PK. This will be presented and discussed later in section 7.2.

The building automation system reports that on the coldest day, the radiators were working on 62 % of full capacity throughout the day. On the warmest day there had been no heating by radiators for the past 24 hours. Even though the outdoor temperature is 17.1 °C higher on the warmer day, it does not explain why there are warmer areas such as around zone B, where it could seem like the radiators are active. The heat could be explained by a large internal heat production and/or external heat from the sun which would at that time be directed towards that part of the building. It is also a possibility that the air flow from the local diffuser is not able to remove the excess heat in the area. This is discussed further together with the results of the ventilation efficiency in section 7.1.3 on page 79.

Horizontal Temperature Differences Within Zones

Figure 7.4 represents all the temperatures during work hours (07:00-17:00) Monday to Friday for the whole experiment duration. It shows the maximum, minimum and average temperature for each iButton sensor and PK sensor. They are divided into each of their respected zones, and arranged from the lowest to the highest average temperature.

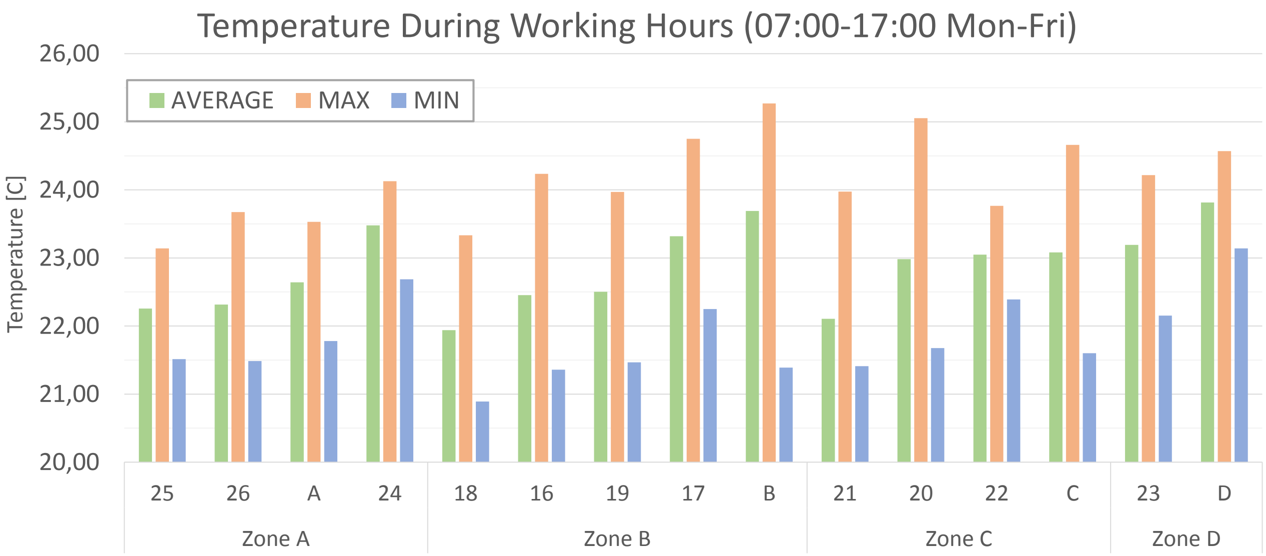

Figure 7.4: The temperature in each zone during work hours (Mon-Fri 07:00-17:00). See overview map on page 61.

The average temperatures seem to be closest to each other within Zone A and D. Zone B and C, however, have larger differences and show high temperature differences between both the measured minimum and maximum temperature. Zone B has the lowest average temperature (sensor 18) and the highest average temperature (sensor B). They are more than 1.5 °C apart in average, and a distance of less than nine meters. This is studied further in figure 7.5 and 7.6, which illustrate the temperatures during the coldest and warmest day. The outdoor temperature is included in both graphs, presented by the secondary y-axis.

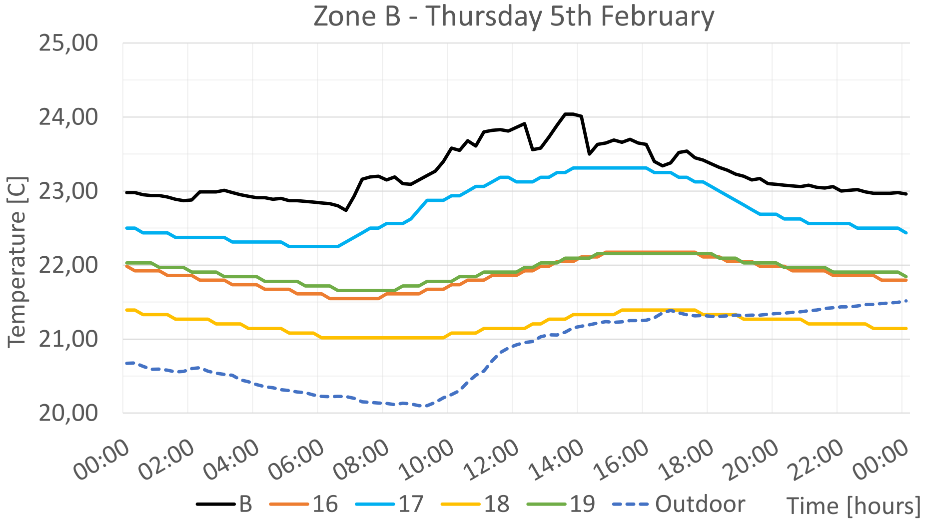

Figure 7.5: Temperature during the colder day (05.02) in Zone B. See overview map on page 61.

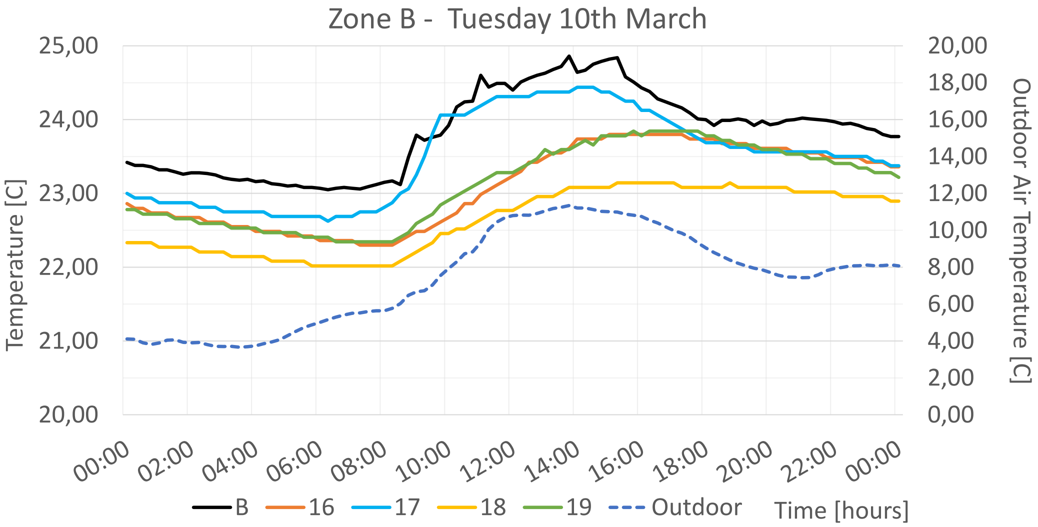

Figure 7.6: Temperature during the warmer day (10.03) in Zone B. See overview map on page 61.

Sensors 17 and B are located close to the radiators compared to sensor 16, 18 and 19, which are placed alongside the external wall. The temperature difference is almost 3 °C at noon between sensor 18 and sensor B. Sensor 16 and 19 are both around 1 °C higher than sensor 18 at the same time. During the work hours sensor 17 and B have a higher temperature increase rate than 16, 18 and 19. Sensor 18 does not increase with sensor 17 and B, but does increase when the outdoor temperature rises. There is a chance that the sensors could be affected by heat from the sun.

The warmer day shows a higher temperature with lower differences in zone B. The temperatures are more responsive to each other. The east corner temperature (sensor 18) has increased the most compared to the colder day - the reason might be the outdoor temperature, which reaches almost 12 °C on the warmer day. It is not certain if it is an overall higher indoor temperature or a higher outdoor temperature that is reducing the temperature difference, but it is likely a combination of both with a chance of external heat from the sun.

With the recommended temperature of 20-24 °C at winter time, the open landscape could be considered thermally comfortable. This is given that other requirements, such as air velocity and humidity, are within their recommended boundaries. None of the measured temperatures in the open landscape go below 20 °C, but some do surpass 24 °C. Sensor B is above 24 °C at 34 % of the time during work hours, followed by the centered sensor D which is 21 % of the time above 24 °C. There is a fine line here, and both of the sensors keep a temperature close to 24 °C most of the time spent above it. Seppänen et al. (2003) indicates a 2 % productivity loss per degree over 25 °C. A temperature range between 21.5 and 24.75 °C does not appear to significantly affect the level of productivity, and it seems like most of the measured areas are within those boundaries.

Temperature in Meeting Rooms

Figure 7.7 shows the temperatures in two meeting rooms during work hours. Meeting room 4206 (M2) and meeting room 4239 (M1) are quite opposite, being the coldest and warmest place measured in the experiment, respectively.

The temperature of office 4206 is below 20 °C, but only 2 % of the time and only in the morning. The low temperature can be explained by the large area of windows and the room being located in the western corner of the floor, where the sun does not shine in the morning. Considering that meeting rooms are mostly closed during meetings, there is a chance that this is the case when the room is empty as well. This would prevent more heat from getting into the room. The supply air temperature has the highest average among the sensors in meeting room 4206, and is most of the time (84 %) above the room temperature. This could prevent fresh air from rising upwards in the room like displacement ventilation is designed for. However, the higher air supply temperature seems necessary to keep the room at a high enough temperature when not in use. Meeting room 4239 is spends 34 % of the time above 24 °C. Being located in the center of the floor means no heat loss through windows or external walls. The extraction of excess heat is possibly a problem for this meeting room under heavy use. Further analysis of the meetings rooms is needed to determine how the temperature is affected by the user load, and how much the users are affected by these temperatures.

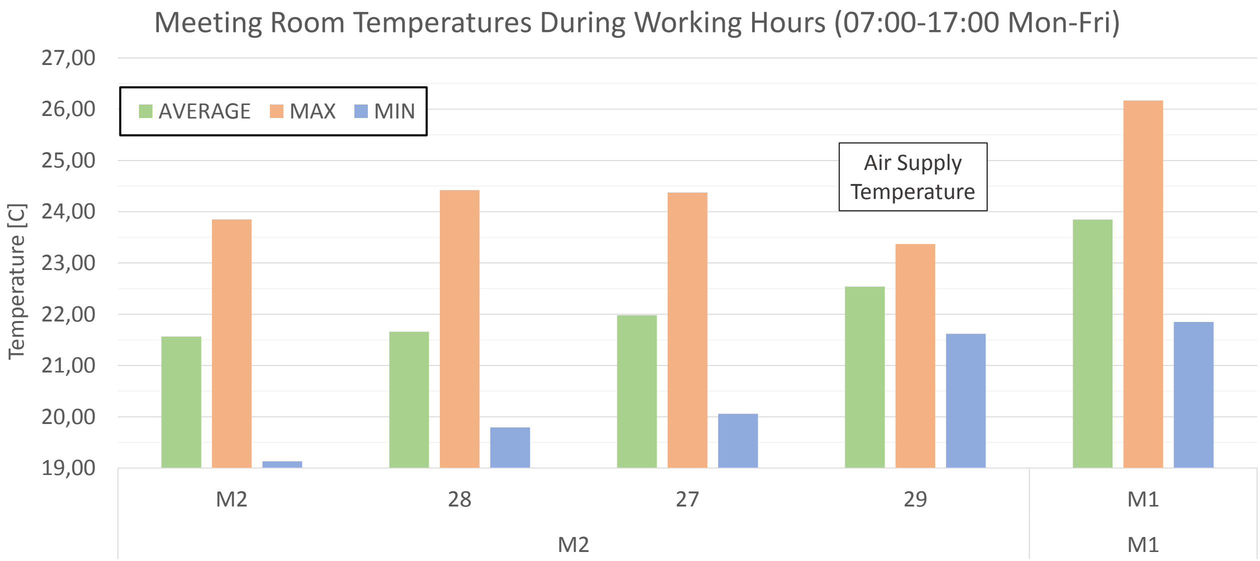

Figure 7.7: The temperature in each zone during work hours (Mon-Fri 07:00-17:00). See overview map on page 61.

7.1.2 Open and Closed Cell Office Doors

Cell office 4104 is located on the 1st floor, meaning the previous discussed temperatures for the 2nd floor will not be connected to the discussion of the cell office. The VTGS in the center of the office is shown in figure 7.8 for the coldest and warmest day during the experiment. The temperature in the hallway outside of the cell office is included to see the temperature drop for these two days.

The temperature increases vertically, and there is a difference between the floor and the ceiling of about 1 °C in both periods, which is expected from a room not in use. The temperature difference between the hallway and the cell office is approximately 1.75-2.00 °C on the coldest day and approximately 1.25 °C on the warmest day. While the overall cell office temperature increases with 1 °C, the hallway temperature increases around 0.5 °C from the coldest to the warmest period.

While the outdoor temperature difference is 17.1 °C between the warmer and colder day, there is only 1 °C difference in the cell office mean temperature. However, the coldest day shows that the indoor temperature is in the lower region for what is recommended. It is difficult to say how much an even lower outdoor temperature would affect the cell office temperature without doing a heat balance analysis between the hallway, office and outdoors. Even so, there is a risk of feeling cold during the coldest day, and with potentially lower outdoor temperatures. It is important to note that this was a closed, non-operational office during the measurements, meaning there were no internal heat sources such as people and technical equipment (lighting, computers etc.).

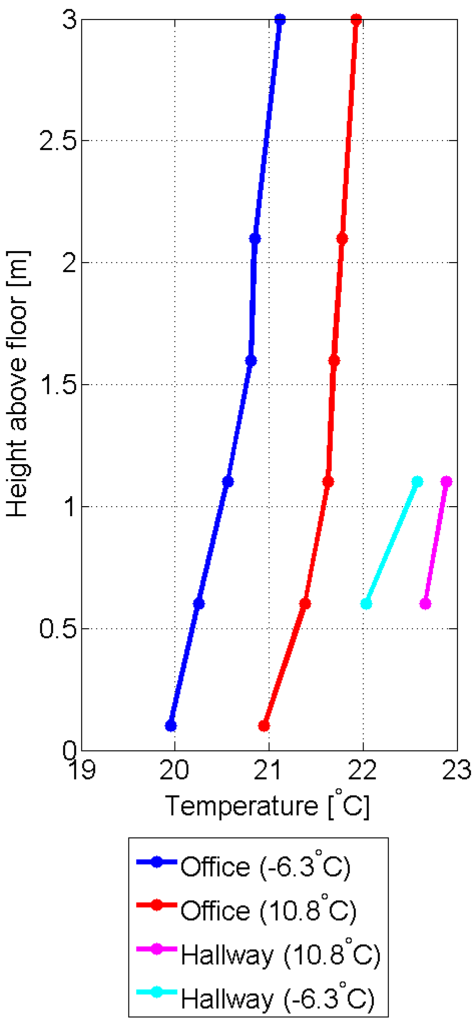

Figure 7.8: VGTS inside office 4104 and on the outside of the door of the office for the coldest and warmest noon temperature.

Figure 7.9 is from the indoor climate survey, and it shows how often the employees at PK who use a cell office have their door open during work hours. 26 out of 74 participants from PK use a cell office, and around 70 % state that their door is mostly open. Less then 10 % state it is almost never open. Of all cell office employees, 19 % are not satisfied with the temperature in their office, which is above the recommended level of dissatisfied people (10 %) according to Gunnarsen (2003).

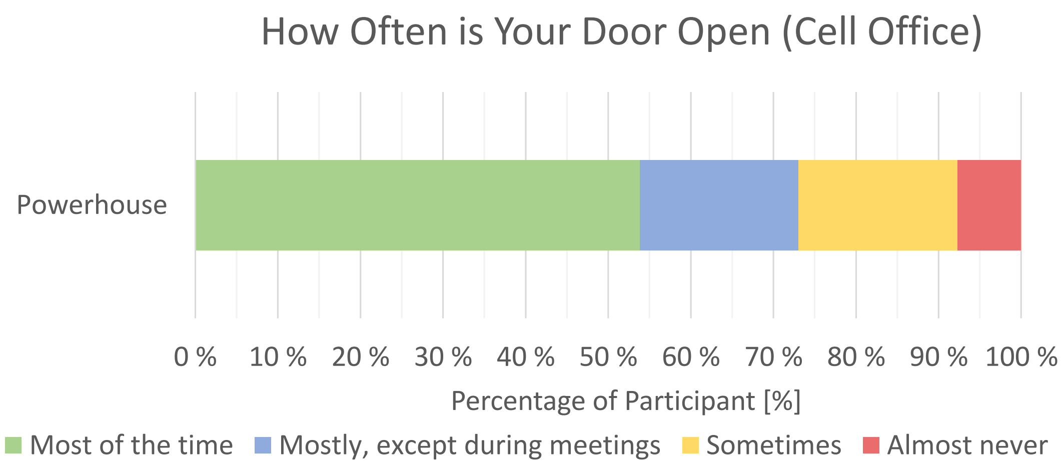

Figure 7.9: How often employees who use a cell office at PK have their door open.

7.1.3 Ventilation Efficiency

The results for the ventilation efficiency study are presented for Thursday March 12th and Friday March 13th, both linear and logarithmic. The figures will be introduced as the results of each day is revealed. The air supply volume for building block 4 is also included to show the variable supply during the experiments. The concentration of the tracer gas in the supply air is shown by "office inlet". A linear line is included as a reference for the step-down analysis in the logarithmic graphs. Each sample point is marked in the graphs with its number as seen in the overview map on page 61.

Before the gas is introduced to the air supply there is a background concentration of nitrous oxide (tracer gas) of about 0.5 ppm. This is possibly due to the accuracy of the multi-gas monitor, which can have problems with measuring very low concentrations (Mathisen et al., 2004). This should relatively not affect the rest of the sample measurements.

Unfortunately, the air volume supply was not fixed during the experiments. This makes it more difficult to calculate the actual ventilation efficiency without compensating for these factors. It is unknown how much air is moving between the two blocks, but the sample point "hallway" shows in both experiments that air is flowing both from and to block 5. This is seen by the fluctuating measured concentration. It is assumed that the air flow between the two blocks in total is equal in both directions, i.e. the resulting air flow is zero over the considered period.

The "east corner" and "north corner" are the only sample positions that can be considered a zone that is occupied over longer periods of time. The "hallway" sample point should be ignored since it does only show how air moves back and forth between block 4 and 5.

First Experiment Results - Thursday

The sample point measurements for the Thursday experiment are presented in figure 7.10 (linear) and 7.11 (logarithmic). The average supplied gas concentration is 31.1 ppm and it varies throughout the experiment between 27.6 ppm and 34.2 ppm. The variations are due to the variable air supply volume and the inaccurate human control of the gas supply. Figure 7.12 and 7.13 show a closer look at the step-up and step-down period, respectively.

This experiment had a rather high air supply volume during most of the experiment. It started decreasing around 1 hour and 30 minutes after start. Until then the average air volume supply was about 13 200 m^3/h.

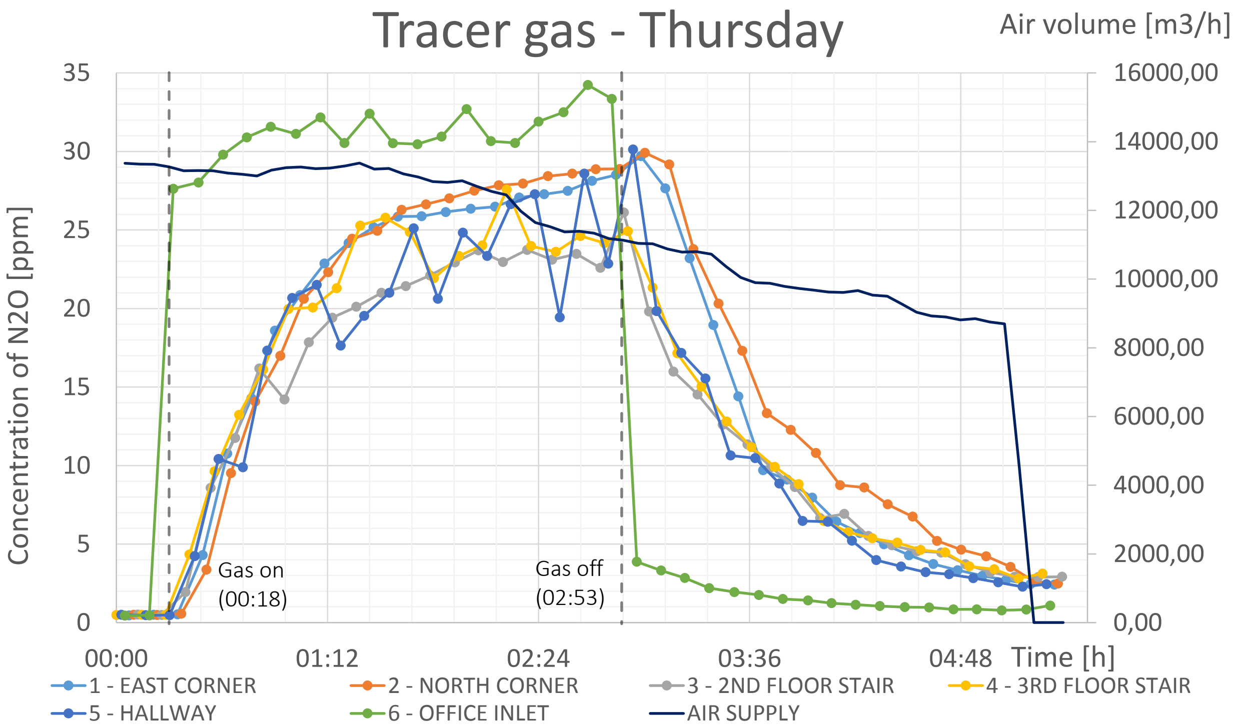

Figure 7.10: Tracer-gas measurements from Thursday 12.03 put together with the air supply volume for the whole building (block 4). See overview map on page 61.

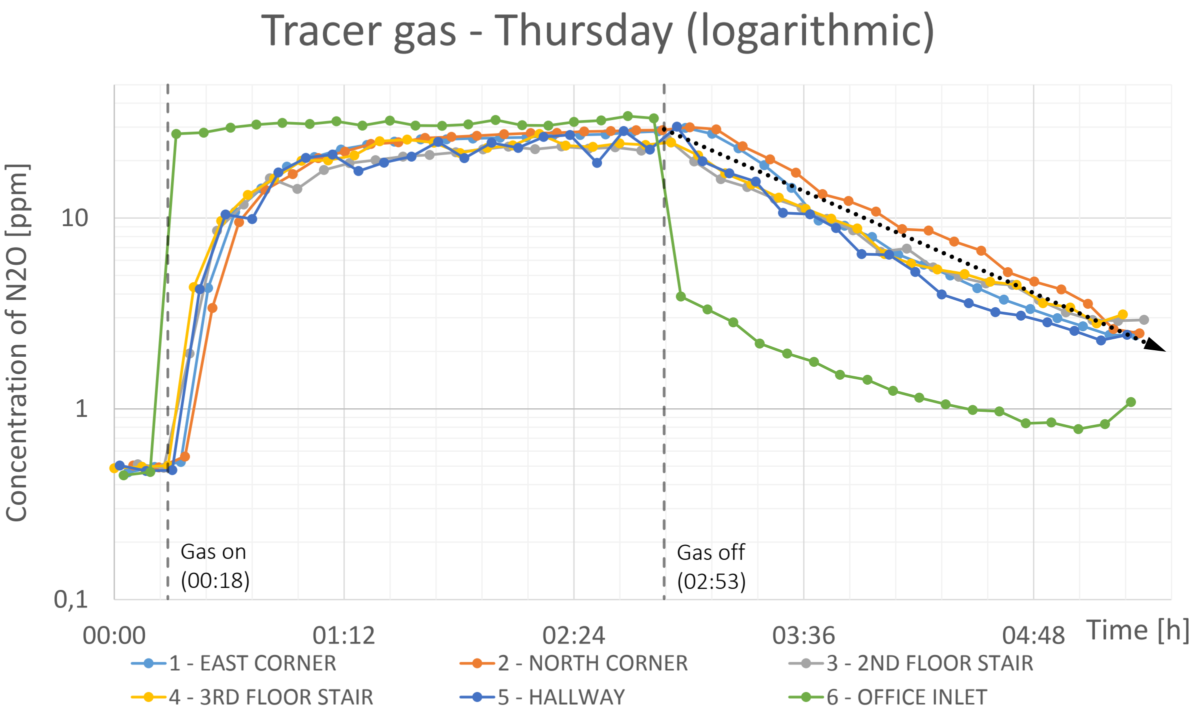

Figure 7.11: Logarithmic tracer-gas measurements from Thursday 12.03. See overview map on page 61.

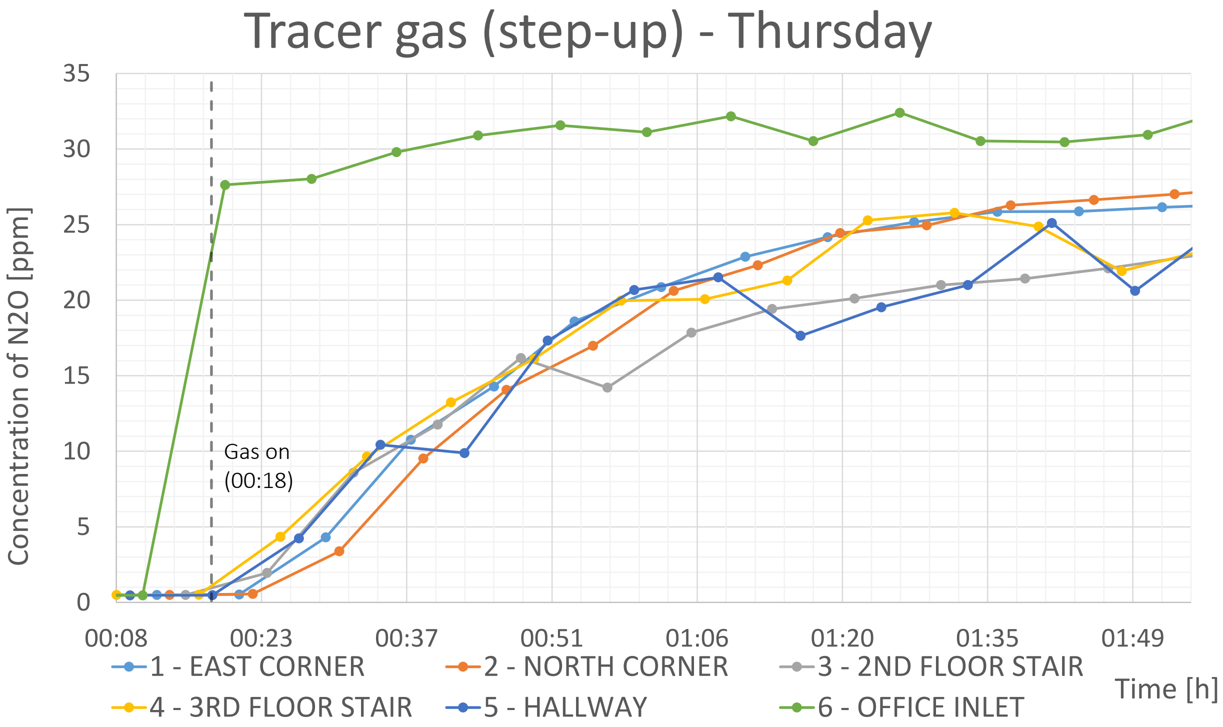

Figure 7.12: A closer look at the step-up tracer-gas measurements from Thursday 12.03. Only a part of the whole step-up method is shown here. See overview map on page 61.

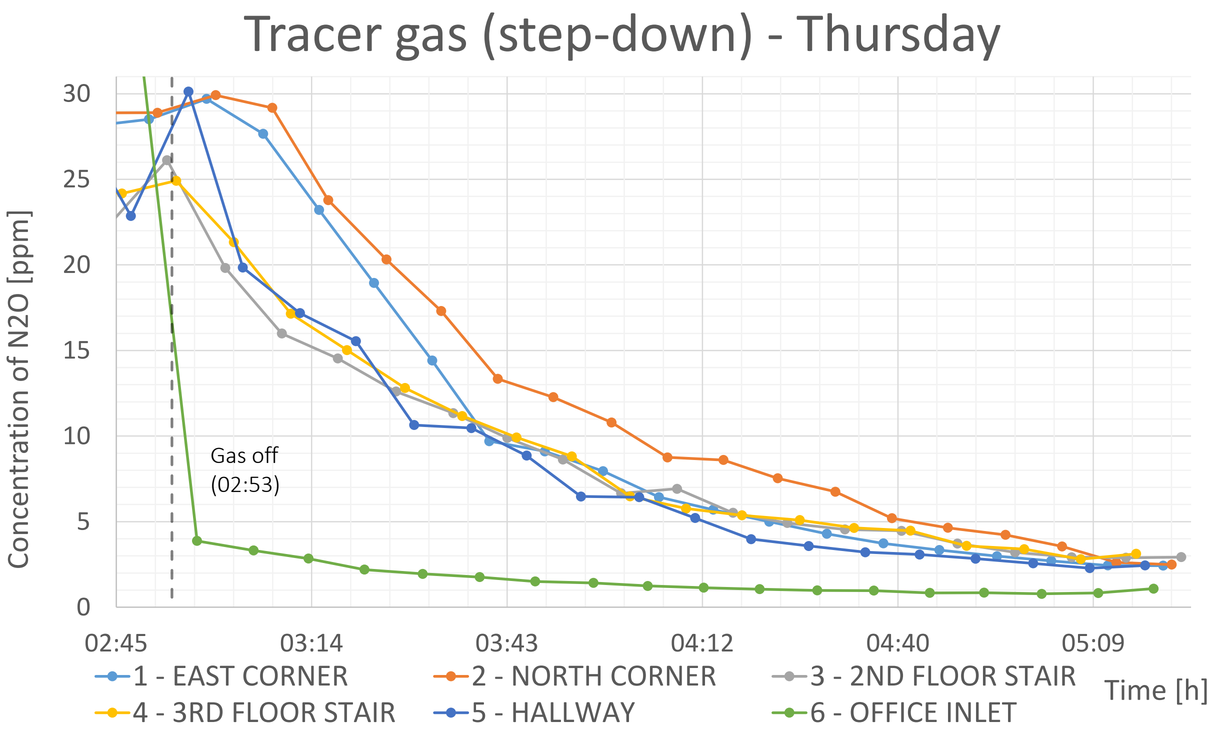

Figure 7.13: A closer look at the step-down tracer-gas measurements from Thursday 12.03. See overview map on page 61.

The experiment ended when the ventilation unit was turned off for the day, and it left a tracer-gas concentration of around 2.5 ppm in the building. This caused the next experiment the following morning to start with the same concentration from the night before.

Second Experiment Results - Friday

The Friday measurements are introduced in figure 7.14 (linear) and figure 7.15 (logarithmic). This experiment has (more or less) an increase of the air supply volume throughout the whole day, in contrast to the first experiment. Here the average gas supply concentration was 25.4 ppm and varied between 19.2 and 28.1. This is ignoring the first measured concentration of 50 ppm, which was due to a miscalculation, but was quickly corrected as seen in the second measurement for the air supply concentration "office inlet". Detailed step-up and step-down graphs are provided in figure 7.16 and 7.17, respectively.

The ventilation unit was activated early in the morning before any employee had arrived. It started with a stable air volume flow around 6500 m^3/h before it increased steadily throughout the rest of the day from around 3 hours into the experiment. Until then it was about 6 400 m^3/h.

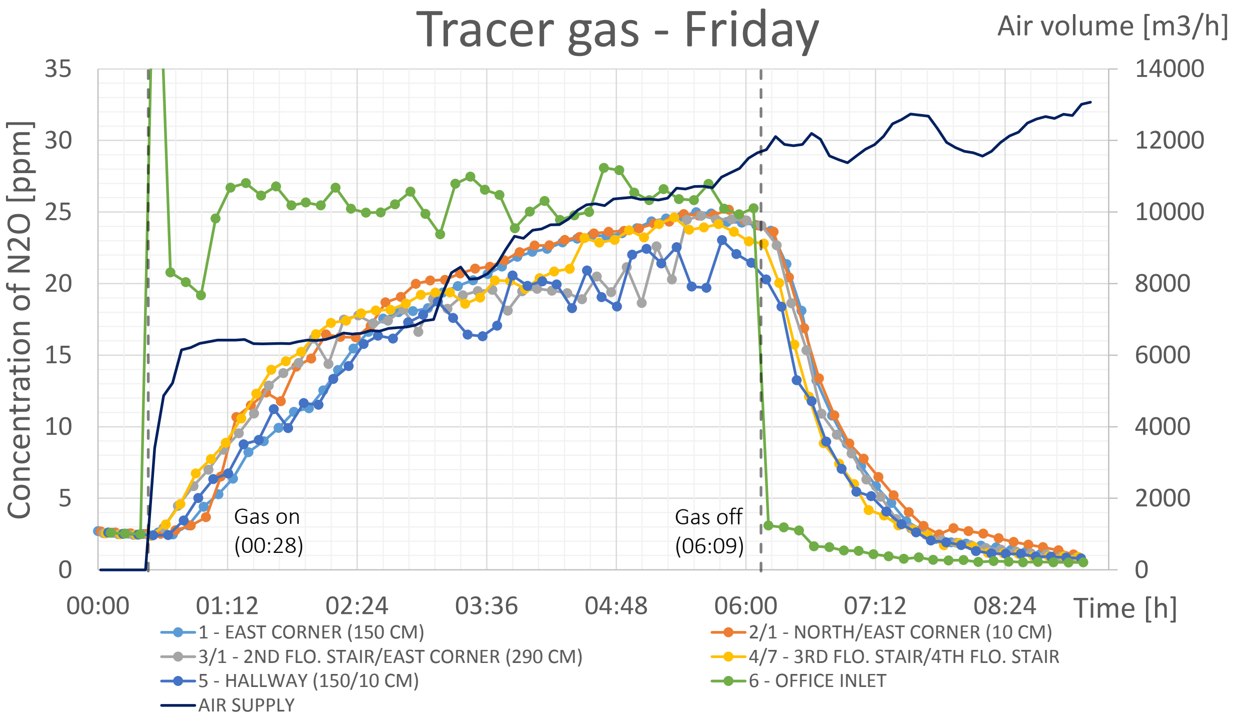

Figure 7.14: Tracer gas measurements from Friday 13.03 put together with the air supply volume for the whole building (block 4). See overview map on page 61.

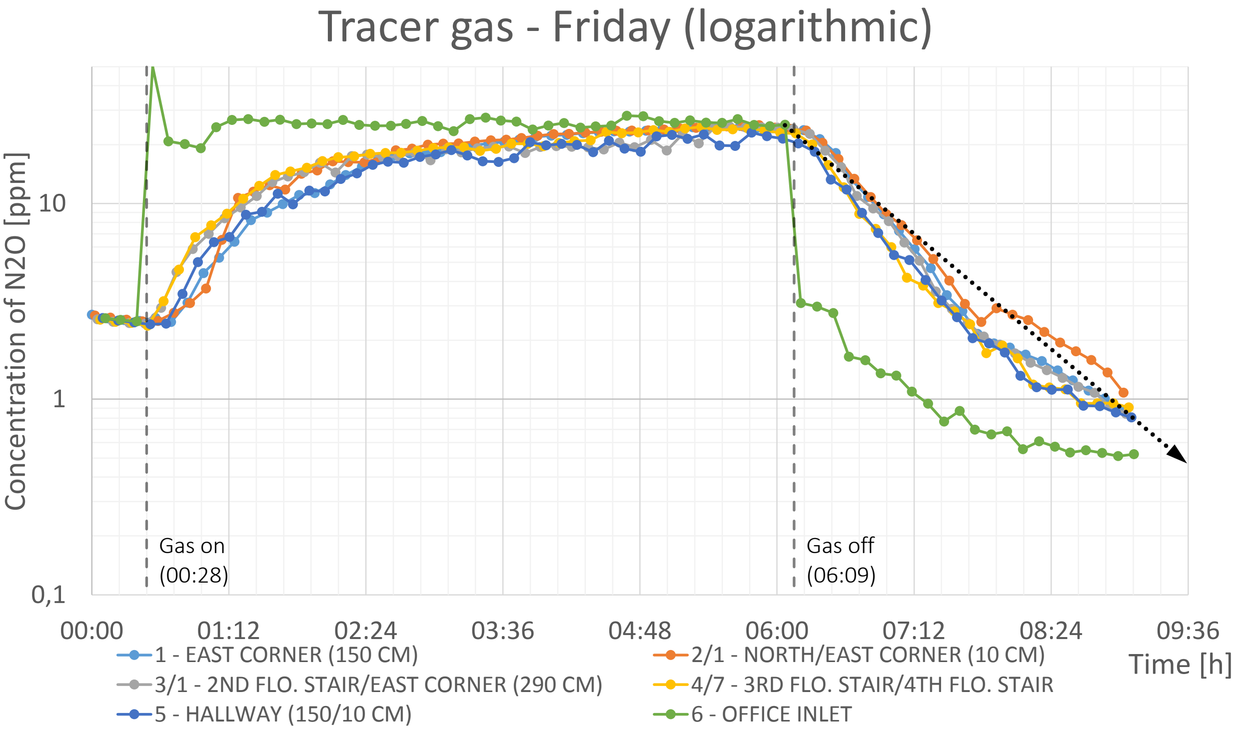

Figure 7.15: Logarithmic tracer-gas measurements from Friday 13.03. See overview map on page 61.

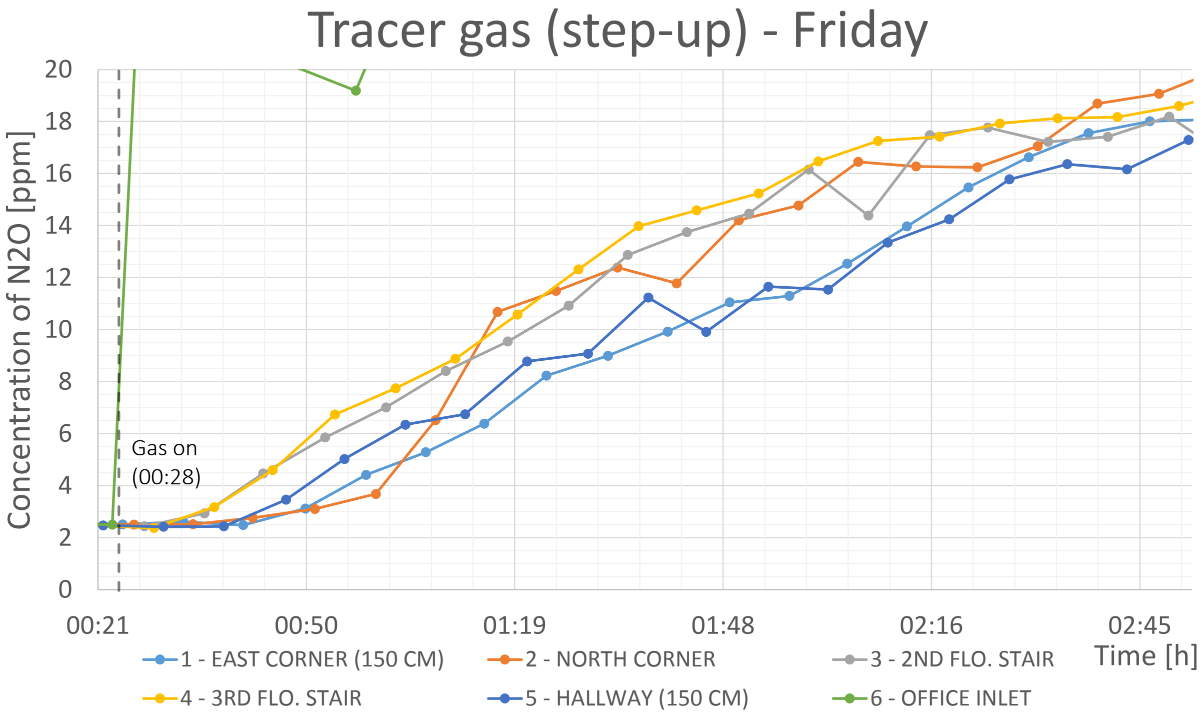

Figure 7.16: A closer look at the step-up tracer-gas measurements from Friday 13.03. Only a part of the whole step-up method is shown here. See overview map on page 61.

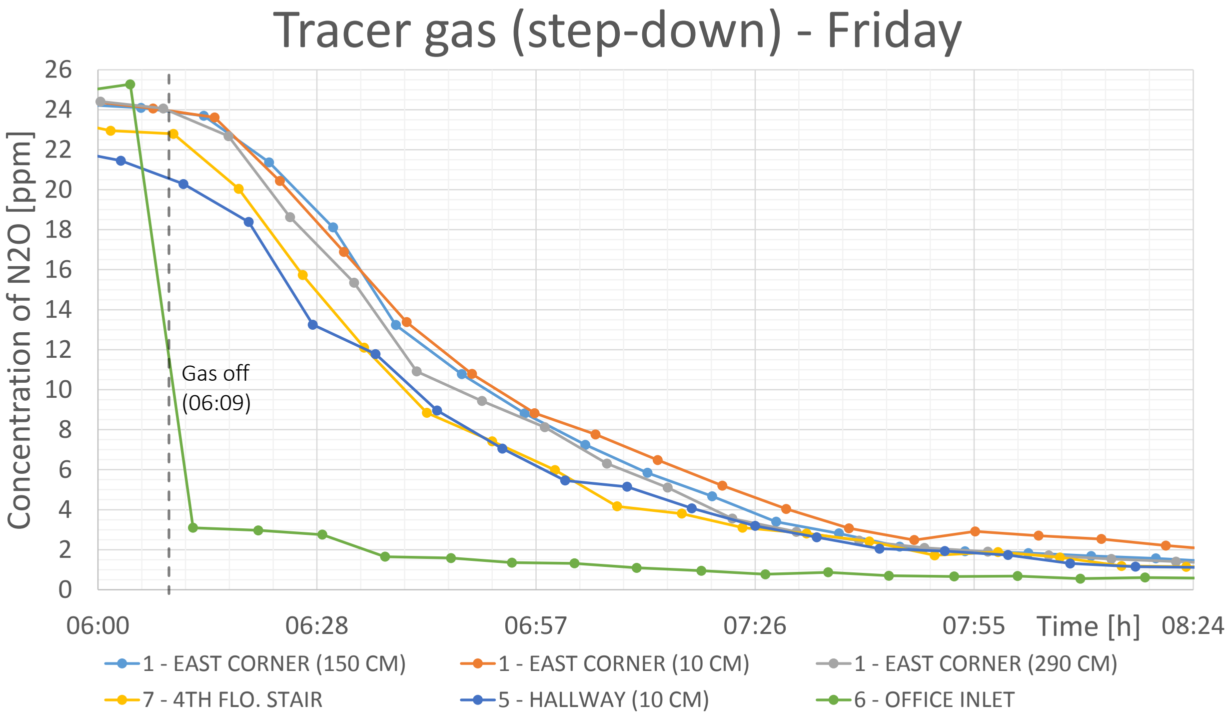

Figure 7.17: A closer look at the step-down tracer-gas measurements from Friday 13.03. See overview map on page 61.

Step-up Method Graphical Analysis

The sample points in the step-up period for both experiments increases at different rates. In the beginning, the "3rd floor staircase" point has a slightly larger increase then the other sample points. This is more noticeable for the Friday experiment where "2nd floor staircase" and "3rd floor staircase" have a higher concentration than both "North corner" and "East corner" in the beginning. The air moves towards the exhaust in the staircase at a higher rate than the two corners. This could indicate that there are possible areas where the air is stagnant or exchanged in a much slower rate. This would be due to a short circuit between the air supply and the exhaust. The increase in the exhaust does not reflect the characteristics of displacement ventilation, but rather mixing ventilation. The concentration is supposed to increase in the open landscape before the sample points near the exhaust.

Step-down Method Graphical Analysis

On Thursday, the "north corner" and "east corner" had a higher concentration than the "staircase" sample points had when the decay began. The overall concentration stabilizes after approximately 40 minutes, except for the "north corner", which has a lower rate of exchange than the "east corner".

The Friday experiment has three sample points in the same location ("east corner") at different heights, showing how the tracer gas is removed at three levels. The concentration is the same at all levels (10 cm, 150 cm and 290 cm above the floor) when the decay begins. In case of displacement ventilation the decay should happen first at the lowest level, and then the higher levels should follow according to the stratification model. It seems like there are tendencies towards the opposite in this case, but not enough to draw a conclusion.

Leakage in the Ventilation System

When the gas supply is cut the concentration measured from the inlet should quickly be reduced to the background concentration of 0.5 ppm. This is not the case as the concentration drops to around 3 ppm and then slowly decays to the background concentration. This is best seen on the second experiment where most of the tracer gas is removed from the indoor air before the sampling is complete. There is reason to believe that there is a leakage somewhere in the ventilation system causing some of the tracer gas to be returned through the air supply. Some of the causes might be:

- A leak in the heat exchanger or the damper for the air recycle duct.
- A short circuit between the outdoor intake and exhaust vent.

A leakage in the heat exchanger, or a short circuit between the exhaust and intake vent, could be measured by injecting a tracer gas directly into the main exhaust of the ventilation unit. Appropriate locations of sample points could then give an indication of how large a possible leak and/or the short circuit is. A leakage could lower the efficiency of the heat exchanger and the indoor air quality, and disturb the measurements of a tracer-gas experiment.

Three months later after the possible leakage was discovered it was confirmed by the supplier of the ventilation unit that the leakage came from the heat exchanger itself. Whether or not this will improve the efficiency of the heat exchanger remains to be seen. This was reported by Olav Rådstoga in an electronic correspondence on June 15th.

Step-Up and Step-Down Calculations

The theoretically expected nominal time constant for the whole building is calculated using equation 5.6 on page 45. An average air volume supply has been used for this calculation. The results are presented in table 7.1 by using the building volume of block 4 of 7485 m^3.

Table 7.1: The theoretically expected nominal time for the step-up and step-down method. The average air supply volume is based on the section of each experiment used for the step-up and step-down calculations.

		Average Air Supply [m3/h]	**Theoretical Nominal Time [h]**
Step-up	**Thursday**	13 200	00:34:01
	Friday	7 900	00:56:51
Step-down	**Thursday**	9 800	00:45:50
	Friday	12 000	00:37:26

The results from the calculations for the step-up and step-down method are presented in the tables 7.2, 7.3 and 7.4. The sixth sample point, "inlet", is not included in the results as it measured the supply gas concentration.

Table 7.2: The results from the step-up method on both Thursday and Friday. Overview map on page 61.

	STEP-UP METHOD					
	Mean age of air [h]		**Nominal time constant [h]**		**Air change efficiency [%]**	
	Thursday	**Friday**	**Thursday**	**Friday**	**Thursday**	**Friday**
1 - East corner	00:46:27	01:57:46	00:37:07	02:18:23	39,96	58,76
2 - North corner	00:48:49	02:01:24	00:42:53	01:54:49	43,92	47,29
3 - Staircase 2nd floor	01:40:31	02:02:43	01:12:34	01:51:20	36,09	45,36
4 - Staircase 3rd floor	00:51:03	01:57:07	00:41:04	01:42:34	40,23	43,79
5 - Hallway	00:59:55	02:37:18	00:49:51	02:23:30	41,60	45,61

Table 7.3: The results from the step-down method from Thursday. Overview map on page 61.

	STEP-DOWN METHOD - THURSDAY		
	Mean age of air [h]	**Nominal time constant [h]**	**Air change efficiency [%]**
1 - East corner	01:13:50	01:00:41	41,10
2 - North corner	01:19:05	00:57:44	36,50
3 - Staircase 2nd floor	01:28:12	00:54:57	31,15
4 - Staircase 3rd floor	01:24:49	00:57:31	33,91
5 - Hallway	01:31:36	00:45:24	24,78

Table 7.4: The results from the step-down method from Friday. Overview map on page 61.

	STEP-DOWN METHOD - FRIDAY		
	Mean age of air [h]	**Nominal time constant [h]**	**Air change efficiency [%]**
1- East corner (10 cm)	01:08:03	00:53:27	39,26
1- East corner (150 cm)	01:02:13	00:51:16	41,20
1- East corner (290 cm)	01:01:27	00:45:46	37,24
7 - Staircase 4th floor (exhaust)	01:00:32	00:40:27	33,41
5 - Hallway (10 cm)	01:02:25	00:48:25	38,78

The theoretically calculated nominal time constant can be compared to the sample point nearest the air exhaust from the fieldwork calculations, namely "Staircase 3$^{\text{rd}}$ floor" and "Staircase 4$^{\text{th}}$ floor". Their nominal time constants should be similar to the theoretical nominal time constants, which is the case for every step-change method, except for Friday step-up. It has been difficult to determine why the measured nominal time is around twice as big as the theoretical time for this measurement. It could be due to an uneven air supply to the different floors in block 4. Another explanation might be the weight of the tracer gas, nitrous oxide, which is heavier than air. The low air volume supply comes with a low air velocity, and this could cause the gas to fall down to the first floor when being supplied through the main air supply duct. Both explanations could cause the longer step-up period for the Friday experiment, but neither of them can be confirmed.

The calculated nominal time constants should also be similar to each other when the sample points are compared. This is not the case and indicates variable levels of air exchange in the different zones, which is seen the in the results of ventilation efficiency in tables 7.2, 7.3 and 7.4.

Overall the mean age of air is always smaller than the nominal time constant, except for "East corner" on Friday step-down. This affects the possibility of reaching the displacement ventilation goal of having an efficiency of 50 % or higher. The exception, "East corner", had almost 60 % efficiency during the Friday step-up experiment. The concentration increase in the "East corner" begins at a slow rate, but quickly catches up to the other sample points. This gives a smaller area under the curve, thus a shorter nominal time constant and a higher air exchange efficiency. However, the other results indicate that the displacement ventilation does not work properly. Everything under 50 % air exchange efficiency could also be an indication of short circuited air flows. This could cause areas to have low air exchange due to lack of supply air reaching the area.

Excess Heat and Short Circuit of Air Flow

As discussed earlier about the horizontal temperature distribution in section 7.1.1, page 63, Zone B seems to have excess heat even though the radiators are not operational. Since there is a reason to believe that there is a short circuiting of the air flow, then there is also reason to believe that this can cause excess heat not being removed at a high enough rate. This theory is illustrated in figure 7.18.

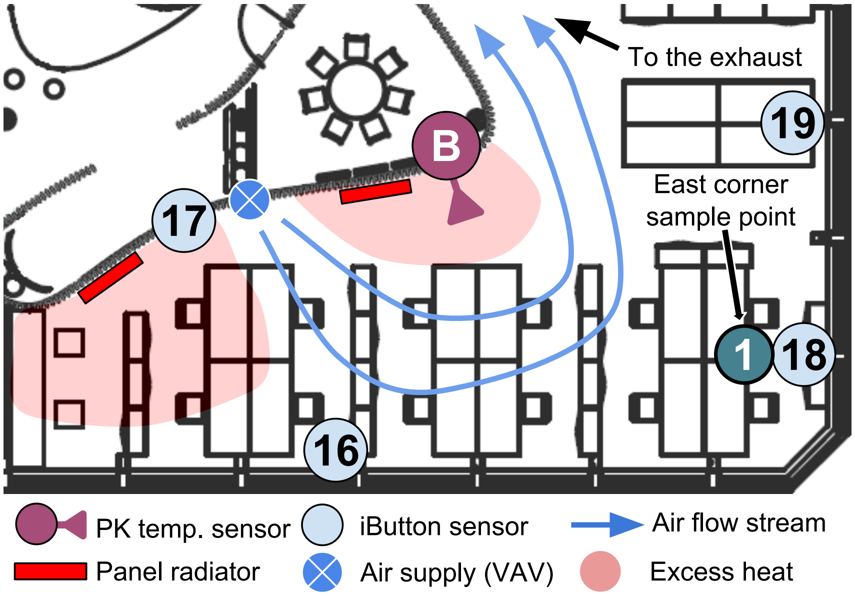

Figure 7.18: Short circuit in Zone B 2^{nd} floor of block 4 and excess heat not being removed.

The air is distributed from the diffuser, but before it can reach the right corner in the figure, it is drawn towards the main exhaust. Smoke tests conducted by Hans Martin Mathisen and Maria Justo Alonso during the ventilation fieldwork indicated that this might be the case. This could also mean that less heat is transported into the east corner, thus resulting in a lower temperature in this area. During warmer days, the opposite could be the case, where excess heat is not removed from

Figure 7.19: Illustration of personal ventilation at a work desk. *Figure: (Melikov, 2004)*

the corner at a high enough rate, risking too high temperatures. This goes for the other possible affected areas as well, which could also seem to be the left corner of figure 7.18 due to the excess heat. Other areas have not been examined, but it is suspected that there might be other short circuiting air flows on the same floor.

Certain measures would be recommended for those areas with risk of stagnant air, low air exchange and abundance of heat. If necessary, a personalized ventilation system, shown in figure 7.19, could be installed in these areas. The goal of personalized ventilation is to provide clean and cool air close to the occupant, and it can be regulated by temperature, flow rate and direction (Melikov, 2004). A study of ventilation and productivity by Wargocki et al. (2000) states that the overall performance of office work, with a constant pollution load, is estimated to increase by 1.9 % each time the ventilation rate is doubled. It is expected the same for each time the pollution load is cut in half, and with a constant ventilation rate. A personalized ventilation system could then improve both the air quality, temperature and productivity of the occupants in areas with low air exchange. It might, however, increase the energy use, which is not preferable. further studies of the air flow movement are necessary before any such measures can be considered implementing.

7.2 The Perceived Indoor Climate

Only the temperature and air quality related questions are presented comparing of PK and the ROB. The indoor climate survey is comprehensive with many questions, and not all of them can be studied here. It is expected a follow-up on the analysis of this survey by personnel at NTNU.

It is assumed that those who rate *very good*, *good* or *acceptable* are *satisfied*. *Poor* and *very poor* are considered *not satisfied*.

7.2.1 Reliability Analysis

There was total of 93 participants who completed the survey at both PK and the ROB. Table 7.5 shows the number of participants for each building, the response rate and the standard deviation with a 95 % confidence level.

Table 7.5: The amount of participants and response rate for PK and the ROB.

Where	**Population**	**Participants**	**Response rate**	**Standard Deviation (95 %)**
Powerhouse	154	74	48.05 %	**7.89 %**
Renovated	61	19	31.15 %	**11.62 %**
Total	**215**	**93**	**43.26 %**	5.56 %

The response rate should have been better for the ROB as it gave a relatively large standard deviation of 11.62 %. The answers from PK, however, has a standard deviation of 7.89 %, giving a more reliable result. These statistics could be a bit misleading as the population is much lower for the ROB, and with only 19 actual participants. This means that the ROB results' reliability is even worse compared to PK's results. Hence, it is concluded that the ROB statistics should be "taken with a grain of salt".

The age and gender distributions of the participants are shown in figure 7.20. PK has 50/50 gender response rate with an age average of 41-50 years old participants. The ROB has mostly males and slightly younger participants.

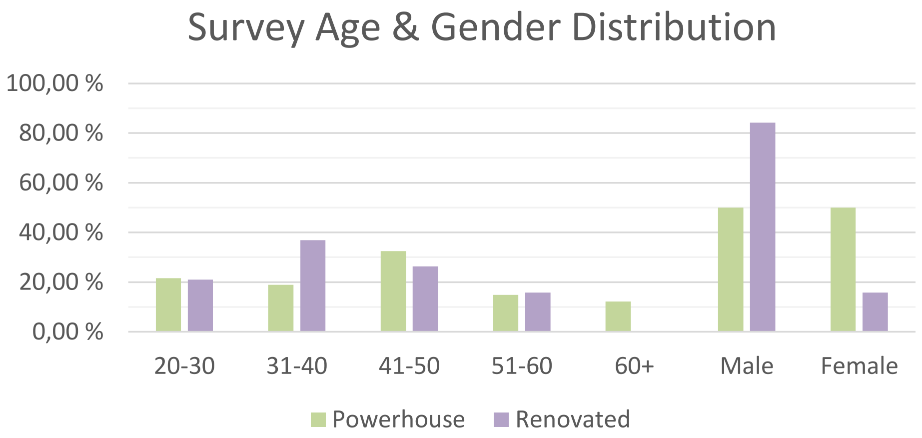

Figure 7.20: The age and gender distribution of the participants from both buildings.

7.2.2 Thermal Environment

Figure 7.21 shows the satisfaction with the indoor temperature, for both meeting rooms and the work desk. This is regardless of which meeting room(s) the employee is utilizing or where the work desk is located.

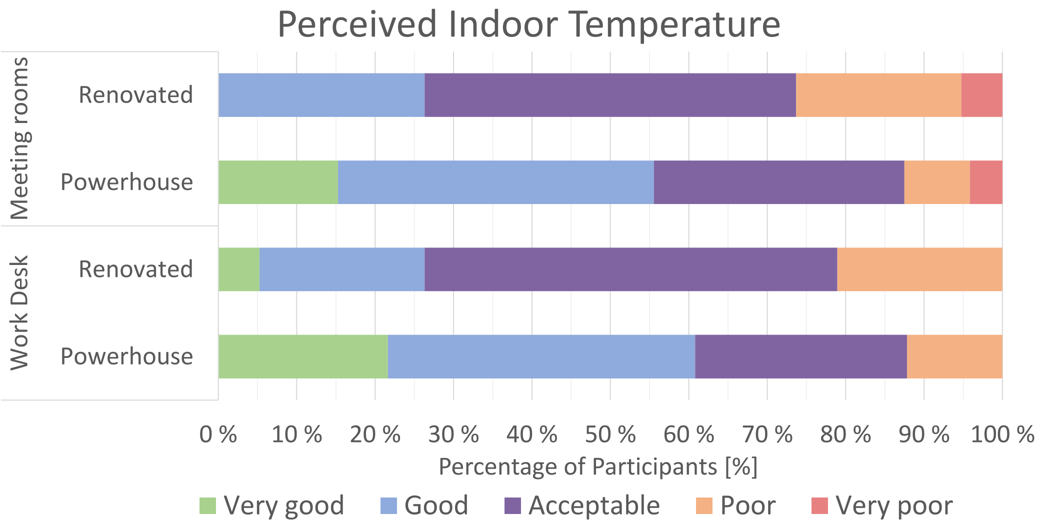

Figure 7.21: Perceived temperature at PK and a renovated office building for the work desk (both cell offices and open landscape) and for meeting rooms.

The satisfaction of the overall perceived temperature is better for PK than the ROB. This applies to both work desks and meeting rooms. At PK, approximately 88 % are satisfied with work desk and meeting room temperatures, and at the ROB it is 79 % for work desk and 74 % for meeting rooms. These are all below the lowest recommended satisfaction level of 90 % in terms of PPD (without regarding the standard deviation). It would be possible to calculate the PPD before the survey, and compare it to the results. However, due to a shortage of time and lack of data and resources this has not been done. It is important to note that PPD is based on a slightly different grading system in terms of satisfaction and therefore cannot be directly compared to the grading system of this survey.

Figure 7.22 shows if the employees feel too warm or too cold during summer, winter or other periods. This is also regardless of where the occupant is located in the building. PK employees are in general less bothered by both heat and cold compared to the employees at the ROB.

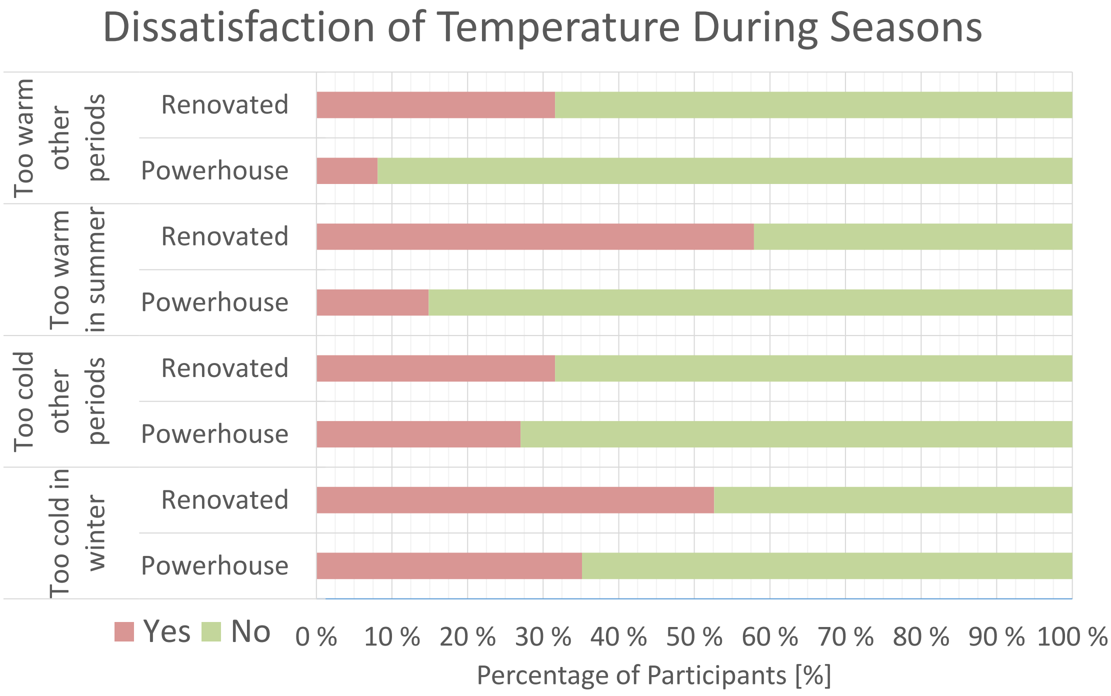

Figure 7.22: Perceived temperature during seasons at PK and the ROB.

Figure 7.23 shows how many have experienced different problems with the indoor air quality and the thermal environment. It goes into detail on how often these problems are perceived.

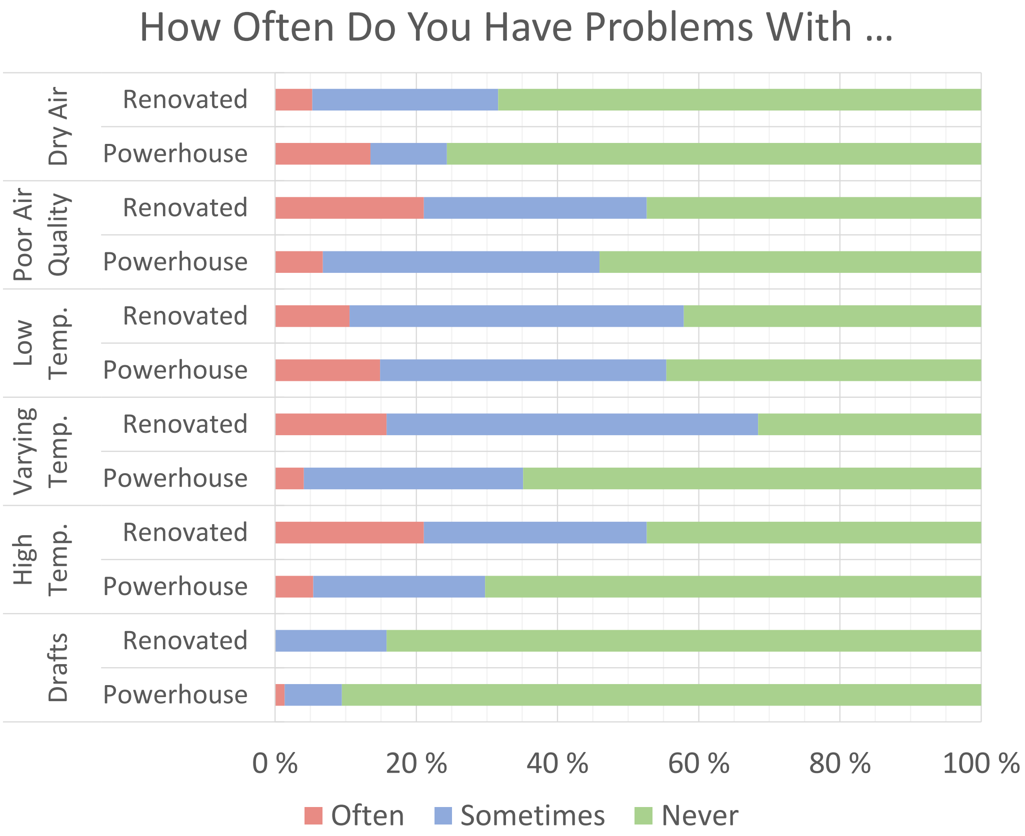

Figure 7.23: Frequency of experienced problems with the thermal environment and indoor air quality at PK and the ROB.

PK employees complain more about the indoor temperature being too cold in the winter than too warm in the summer. This is particularly pointed out in figure 7.23 where 40 % state that they experience low temperatures sometimes, and 7.5 % experience it often. It is the most frequent complaint regarding the thermal environment at PK, and around 75 % of those who complain are located close to the external walls. Females complain about experiencing lower temperatures *"sometimes"* two times more than men. This is illustrated in figure 7.24.

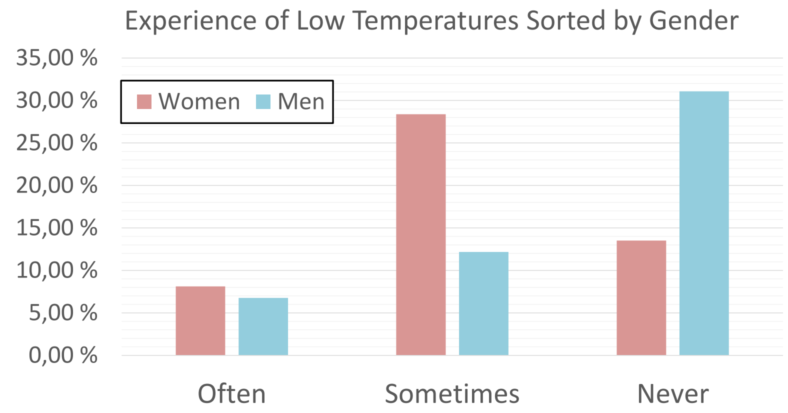

Figure 7.24: Frequency of experienced low temperatures at PK sorted by gender.

A comprehensive literature survey conducted by Kim et al. (2013) predicts that female office workers are significantly more likely to complain about specific indoor environment factors than their male counterparts. However, the overall satisfaction is usually the same for both genders. A field research conducted in Japan showed that females had an average neutral temperature of 25.1 °C, and males an average neutral temperature of 22.9 °C (Nakano et al., 2002). Comparing this to the measured temperatures at PK it is likely that female employees would feel cold, assuming these neutral temperatures are correct.

A literature review by Brager and de Dear (1998) suggests that allowing people greater control over their own indoor environment can potentially have significant and positive impacts on the thermal comfort. The employees can not adjust the temperature themselves at PK (except for opening windows). Out of all employees at PK that complained about low temperatures, 70 % claimed one of the reasons to the problem was the lack of personal control over the temperature. Those make up 27 % of all the participants from PK.

Drafts are rarely experienced at PK, meaning the air velocity should be within the recommended values. The measured air velocity from the open landscape diffusers (page 42) indicated that the feeling of draft should not be a problem as long as the occupants was located more than one meter away from the air diffusers. This survey also indicates that the meeting room and cell office diffusers most likely do not cause the feeling of draft, since it has not been reported.

Dry air seems to be a problem that almost 15 % of the employees experience often at PK, but it also seems that the problem is connected to a smaller group since about 75 % say they never experience dry air. This could either be a specific area where dry air is a common problem, or employees who are more sensitive to low relative humidity in the air. In the project work, relative humidity in the month of November 2014 was measured to be around 22 % with minor variations in the open landscape of the 2nd floor in block 4 (this was not included in the project work report). Cell offices kept a relative humidity around 25-35 %, and meeting rooms around 30-45 % (depending on the rate of meetings). This was measured with air temperatures around 22-23 °C. Søgnen (2015) A study of physiological and subjective responses to low relative humidity by Sunwoo et al. (2006) suggests that it is necessary to maintain a relative humidity larger than 30 % to avoid dry skin and eyes at a temperature of 25 °C. Of the 18 people who complained about dry air "often" or "sometimes", 14 of them are located in the open landscape, which was measured to have the lowest relative humidity in the month of November.

7.2.3 Indoor Air Quality

The satisfaction of the indoor air quality at the working desk, both cell offices and open landscapes, is shown in figure 7.25.

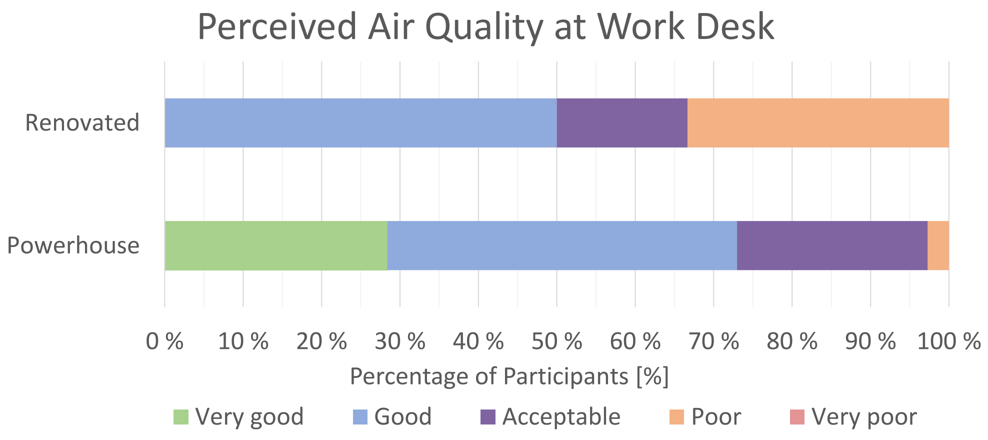

Figure 7.25: Perceived air quality at PK and the ROB

There is a satisfaction of air quality of 97 % at PK and 66.7 % at the ROB. Almost 30 % at PK perceives the air quality as very good, whereas no one chose this rating at the ROB. This indicates PK has an overall good indoor air quality according to the employees, even though 39 % of the same participants state that they sometimes have problems with poor air quality. Since the perception of air quality only regards the work desk it is possible that these problems are experienced elsewhere, such as in meeting rooms. There are additional comments in the survey which specify that certain meeting rooms tend to have bad air quality and high temperatures during longer meetings.

The measured ventilation efficiency was not as good as expected, but it is important to remember that this does not necessarily reflect the perceived air quality. A lower efficiency would mean a larger air volume supply to do the same job than what it was initially designed for. Thus it is suspected that the air volume supply is larger than originally planned. This however, can not be confirmed as such calculations has not been conducted. It could be done by analyzing the air volume supply in response to the heat load and CO_2 concentration on a specific floor.

Chapter 8 | Conclusion

By rehabilitating an old office building and pushing the bounds for what the Norwegian building industry have built before, Powerhouse Kjørbo sets a standard for a new generation of commercial and public buildings. However, like other buildings, it takes time before the building and its technical system is optimized, and it is impossible, in practice, to satisfy everyone at all times.

The open landscape temperature distribution shows a minor variation of horizontal temperature distribution depending on the outdoor temperature. This goes for both within zones and between zones. Corners tend to be the coldest areas, especially the western corner meeting room, where additional heating might be necessary during colder periods. The permanent temperature sensors at Powerhouse Kjørbo are not always the best to represent the temperature in their designated zone, as they in some zones are located close to a heat source.

The study of the temperature in a cell office shows that closing the door during work hours, and during sub-zero outdoor temperatures, could prevent the office from reaching the preferred temperature without any additional heat sources in the room. The average temperature difference between the hallway outside the office and inside the office shows a temperature drop of 1-2 °C depending on the outdoor temperature. Most employees report having their door open most of the time, but it might be necessary to have additional heat sources in the corner meeting rooms.

The ventilation efficiency is measured to be below what is expected from a displacement ventilation. It indicates a short circuit between the supply and exhaust, and overall, given that the displacement ventilation does not work optimally, it could result in a larger air volume supply than necessary, areas with stagnant air and excess heat, and a reduced horizontal temperature distribution. This could mean that more energy is used than what is necessary. The results also indicate a leakage in the ventilation unit between exhaust and supply air which later was confirmed, located and fixed. The experiment contained some irregularities, such as variable air supply, leakage in the heat exchanger and possible interfering movement of air between compartments. Therefore the results are far from final and require further analysis and fieldwork experiments.

The perceived indoor climate is highly rated for Powerhouse Kjørbo in terms of thermal environment (88 % satisfied) and indoor air quality (96 % satisfied). There are, however, complaints about events with low temperatures and dry air. Events of low and high temperatures in addition to poor air quality was reported about meeting rooms in particular. The comparison with the similar renovated office building has been labeled as inconclusive due to lack of proper statistical analysis. Still the general opinion show that Powerhouse Kjørbo is perceived as having a better indoor climate than the renovated office building in terms of thermal environment and air quality.

The measured indoor climate indicates that the heating solution works well enough in terms of thermal comfort, excluding the events of low and high temperatures in meeting rooms. This is also shown in the perceived thermal environment. The air exchange measurements indicates that the ventilation strategy is not optimal in the open landscape, but the positive responses of perceived air quality does not reflect this. Therefore, an analysis of air volume supply and air flow in the open landscape is recommended.

8.1 Proposals for Further Work

An analysis of the cooling system at Powerhouse Kjørbo has not been conducted. If possible, it is recommended to analyze this with simulations and/or fieldwork experiments. A comprehensive analysis with heat balance, including the thermal mass of the building, could be done while testing how well the cooling system performs during warmer periods in the summertime.

It is also recommended to analyze the results from the ventilation efficiency further. This can, among other things, be done through computer simulations such as CONTAM, a multi-zone airflow and contaminant transport analysis software. This software can compensate for the variable air supply and airflows between different floors and building blocks. A detailed analysis of areas with turbulent air movement and stagnant air could help to decide whether new ventilation solutions, such as personalized ventilation, is recommendable in order to increase the ventilation efficiency. If necessary, a new ventilation efficiency fieldwork experiment can be conducted, this time with more days, more sample points, and a constant air supply volume.

The study of the indoor climate survey was unfortunately affected by the late arrival of the results. First of all it should be compared to other surveys following the Örebro model "MM 040 Office" and/or the model from Center for the Built Environment (2014). This could grade the perceived indoor climate at Powerhouse Kjørbo compared to similar office buildings. Secondly, a new survey should be conducted, but this time during a warmer season to see if the general perception of the indoor climate has changed compared to the earlier survey conducted in the winter time.

Furthermore, when the building has been operational for some years it will be possible to study how it has affected the health and well-being of the users. Jan Vilhelm Bakke, a Norwegian Chief Physician, is among those who has expressed concerns about the health effects of well-insulated buildings, something he claims has not been documented well enough (Sjøberg, 2011). A comprehensive documentation for Powerhouse Kjørbo could help to guide the design and layout of future low-energy office buildings, both in general of course, and more specifically when it comes to health aspects.

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Appendix A | Equipment

All the equipment used for this thesis was borrowed from NTNU, except for the permanent temperature sensors at Powerhouse Kjørbo.

A.1 Temperature Measurements

A.1.1 iButton Temperature Sensors

Figure A.1: iButton sensor. *Photo: Maxim Integrated.*

The DS1922L iButton is a temperature logger the size of an average coin with a diameter of 1.7 centimeters. It is activated by a computer program through a docking device, where also the data is recovered after the measurements are complete. The specifications of the iButton DS1922L are described in table A.1. It measures the air temperature and not mean radiant temperature. It is rather shiny, which could reflect most of the radiative heat.

Table A.1: The specifications for the iButton DS1922L temperature logger. *(Maxim Integrated, 2013)*

Temperature range	-40 °C to +85 °C	
Data logger size (number of readings)	4096	8192
Temperature resolution	± 0.0625 °C (11-bit)	± 0.5 °C (8-bit)
Temperature accuracy	± 0.5 °C (in range of -10 °C to +65 °C)	
Frequency of logging	1 second to 273 hours	

For this fieldwork the data resolution for the loggers is acceptable. The number of iButton sensors borrowed was 30.

A.1.2 Johnson Control Sensors

Johnson Control has several sensors at Powerhouse Kjørbo measuring both temperature and CO_2 concentrations. In this thesis only the room temperature sensors are of interest.

A99RY-1C Temperature Sensor

The A99RY-1C sensor is used for room temperature monitoring. It is the results from these sensors that the iButtons are compared with for the fieldwork done on the 2nd floor in block 4.

The A99RY-1C is a temperature sensor from the A99 series designed by Johnson Controls. Its specifications are listed in table A.2. The sensors give a live feed to the building automation system so that the heating and cooling system can act accordingly.

Figure A.2: The A99RY-1C temperature sensor at Powerhouse Kjørbo. *Photo: Odin Søgnen.*

As seen in figure A.3, the sensor accuracy is within ±0.5 °C between -15 °C and 75 °C. The temperature range within the building will never operate outside this range, thus one can conclude that the accuracy will always be ±0.5 °C.

Table A.2: The specification for the A99RY-1C temperature sensor *(Johnson Controls, 2014)*

Temperature range	-20 °C to +60 °C
Data logger size (number of readings)	Indefinite
Temperature resolution	0.01 °C or better
Temperature accuracy	See graph in figure A.3 below
Frequency of logging	Each 5 minutes (at Powerhouse Kjørbo)

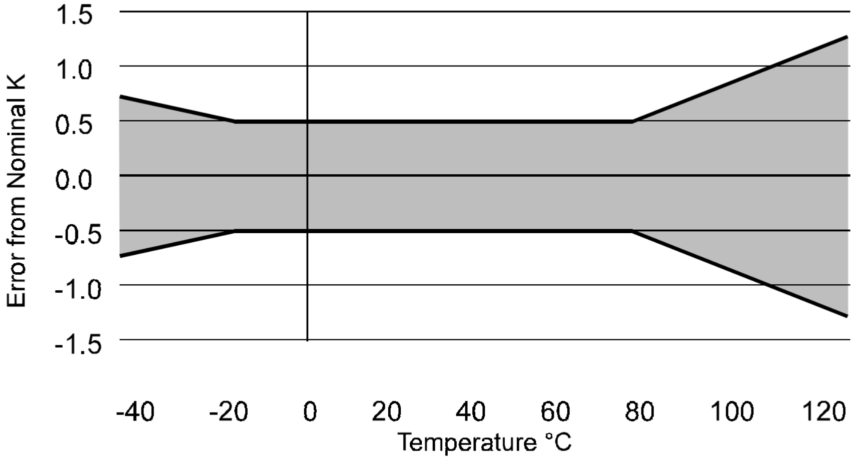

Figure A.3: Temperature accuracy of the A99RY-1C. *(Johnson Controls, 2014)*

A.2 Ventilation Efficiency

See figure C.2 in appendix C for how the sampling and analysis of the indoor air was done.

A.2.1 Brüel & Kjær - Tracer Gas Equipment

Brüel & Kjær Sound and Vibration Measurement A/S is a Danish multinational engineering and electronics company and was founded in 1942. In 1992 Brüel & Kjær was sold to the German company AGIV (Agentschap voor Geografische Informatie Vlaanderen). AGIV split the company into different engineering fields, including *Innova Air Tech Instruments A/S* which develops gas analysis instrumentation (Brüel & Kjær, 2015). They have developed a multipoint sampler and doser and a multi-gas monitor (seen in figure A.4), which are both described in the sections below. In addition to these instruments a computer with the appropriate software is needed for control and data collection.

Multipoint Sampler and Doser - Type 1303

The *Multipoint Sampler and Doser - Type 1303* (for short 1303) from Brüel & Kjær is used in conjunction with the *Multi-gas monitor -Type 1302,* and is remote-controlled from a computer with the LumaSense Technologies Application Software - Type 7620 through a connection between the Multi-gas monitor and the Multipoint sampler and doser. The 1303 has six outputs and six inputs for tracer-gas dosing and air sampling, respectively. This means that it can both supply tracer-gas up to six points in the room, and take samples of the air from up to six points

Figure A.4: Brüel & Kjær Multi-gas Monitor - Type 1302 (left) and Multipoint Sampler and Doser - Type 1303 (right). *Picture: Odin Søgnen*

in the room. Using both the doser and the sampler, it can measure the ventilation efficiency. Using only the sampler it monitors the indoor air and further calculations are necessary to find the ventilation efficiency. (Brüel & Kjær, 2015). The 1303 also has six inputs for temperature sensors, but only the sampler function was used during the fieldwork at Powerhouse Kjørbo.

The sample air is gathered through plastic tubes (up to 50 meters long) and is delivered to the Type 1303 by suction through the six different sampler channels on the device. One by one each of the channels transfer the air samples from the sampler.

For more in-depth information about the Type 1303 technical specifications, please refer to Brüel & Kjær (2015).

Multi-gas Monitor - Type 1302

The *Multi-gas Monitor* type 1302 (for short 1302) from Brüel & Kjær is a field-portable photo-acoustic infrared spectrometer with a headspace water sampling accessory. (Christensen, 1990). It can analyze the six different gases mentioned in table A.3.

The 1302 is used in conjunction with the *Multipoint Sampler and Doser - type 1303*, and is remote-controlled from a computer with the LumaSense Technologies Application Software - Type 7620 through an IEEE/IEC interface. Today the 1302 by Brüel & Kjær has been replaced by the Type 1312 developed by Innova Air Tech Instruments.

Table A.3: List of gases the multi-gas monitor - type 1302 can analyze. *(Lumasense Technologies, 2008)*

Chemical name	**Chemical formula**	**Molar weight** $[g/mol]$	**Density** $[kg/m^3]$	**Boiling point** **[°C]**
Sulfur hexafluoride	SF_6	146,05	6,17	-83,2
Carbon dioxide	CO_2	44,01	1,98	-57
Carbon monoxide	CO	28,01	1,15	-191,5
Dinitrogen oxide	N_2O	44,01	1,98	-88,48
Toluene	C_7H_8	92,14	866,9	110,6
Water vapour	H_2O	18,02	0,804	100

Comparison: Air	-	28,97	1,204	-

Application Software - INNOVA 7620

The software used in conjunction with the 1302 and 1303 is the application software INNOVA 7620 developed by LumaSense Technologies A/S.

It can perform ventilation measurements using both the doser and sampler function or gas-monitoring tasks, using only the sampler function on the 1303. The INNOVA 7620 can configure and control the 1302 and 1303, and receives data from the 1302 during measurements (Lumasense Technologies, 2008). All data is saved to a database and can be viewed graphically or numerically. Exported data will give clean text files with a chosen delimiter (comma, period, colon etc.) and a spreadsheet file for Microsoft Access (can be copied into Microsoft Excel through Microsoft Access).

A.2.2 Tracer-gas

See figure C.1 in Appendix C for how the distribution of tracer gas was conducted. A 10 liters gas cylinder containing 7.5 kg of Nitrous Oxide (N_2O) was used in the tracer-gas experiment.

Tracer gas - Nitrous oxide N_2O

The tracer gas used was Nitrous oxide (N_2O). Table A.4 shows some of the chemical data of nitrous oxide. It is sometimes used in medicine as an anesthesia, and is possible to use as a tracer gas since it does not occur naturally in the air and mixes fairly good with the air when injected to the air supply (Mathisen et al., 2004).

Nitrous oxide is not directly dangerous to humans over shorter periods of time, but can cause indirect damages. The gas is oxidizing and can cause or boost intensity of fire. While obtained in a gas cylinder, nitrous oxide is under very high pressure and may explode if heated. When exiting a gas cylinder, the nitrous oxide will have a very low temperature that may cause frost damages if exposed to the naked skin. The gas is asphyxiant at high concentrations, meaning it suppresses the oxygen in the air making it difficult to breathe (AGA, 2015).

Table A.4: Chemical data of nitrous oxide (N_2O). *(AGA, 2015)*

Chemical name	Nitrous oxide
Chemical formula	N_2O
Physical state at 20 °C and 1 atm	Gas
Color	Colorless
Smell	Slightly sweet-scented
Molar weight	44 g/mol
Melting point	-90,81
Boiling point	-88,5
Critical temperature	36,4
Relative density, gas (air=1)	1,5
Relative density, liquid (water=1)	1,2
Density	1.98 kg/m^3 or g/L
Conversion (ppm = mg/m^3)	1 ppm = 1,8 mg/m^3
Toxicity	No known toxicity

Pressure Control Valve

A pressure control valve is used to keep the pressure constant from the gas cylinder. There are both single-stage and two-stage pressure regulators. The control valve in figure A.5 is a single-stage regulator which reduces the pressure from the gas cylinder with one valve. The two gauges at the control valve show the pressure in the gas cylinder (left gauge) and the reduced pressure (right gauge). The flow is controlled by the rotameter. (Air Liquid, 2013)

Figure A.5: Picture of the pressure control valve used at Powerhouse Kjørbo. It shows the inlet pressure from the bottle (left gauge) and the outlet pressure for the gas flow through the plastic tube (right gauge). *Photo: Odin Søgnen.*

Rotameter

A rotameter consists of a transparent conical tube containing a *float*. From each side of this tube there is an opening allowing fluids to pass through the tube from the bottom and up. The fluid flow will lift up the float which then again will indicate the volume flow or mass flow by a scale on the conical tube (Hanssen et al., 2007). The rotameter used at the fieldwork at Powerhouse Kjørbo had an indication of the volume flow in liters per minute.

The Platon NG series rotameter is shown in figure A.6. In this picture the volume flow is just below 4 liters of nitrous oxide per minute. Its specifications are listed in table A.5.

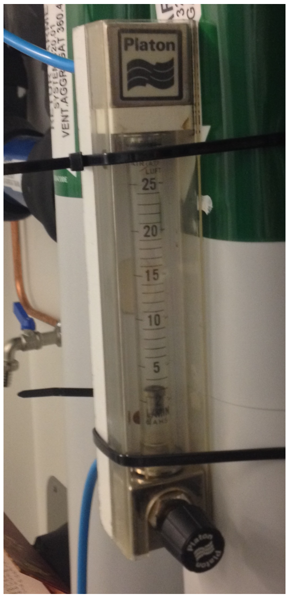

Figure A.6: Picture of the rotameter used at Powerhouse Kjørbo. The nitrous oxide is supplied at the bottom, through the conical tube and exits at the top. *Photo: Odin Søgnen.*

Table A.5: Some of the specifications for the Platon NG series rotameter. *(Platon, 2002)*

Range	2-25 L/min
Scale length	100 mm
Maximum temperature	100 °C
Maximum pressure	16 bar
Accuracy	±1.25 %
Standard temperature calibration	20 °C
Standard pressure calibration	1.013 bar

Appendix B | Preparations

Before the measurements could begin it was important to test the sensors and understand how they function. To do this, several tests were conducted to see how the sensors were affected under certain conditions, and if they still measured the right temperature. The testing was only done to the DS1922L iButton, and therefore only those tests are presented here.

B.1 Pre-Fieldwork Tests of the iButton Temperature Sensors

The iButton is never calibrated as it has a singular battery lifespan. The lifespan is dependent of usage conditions and the amount and frequency of samples. After a certain number of samples it is no longer operative and must be replaced with a new sensor. To make sure that the iButtons were recording the right temperatures, several pre-fieldwork experiments were conducted.

The goal of these tests were to establish an understanding of how the temperature sensors recorded the temperature under certain conditions, and to measure the chance of error in the measured temperatures. Not all of the sensors used in the fieldwork were available at the time of these tests.

B.1.1 Calibration Tests

Two calibration tests have been conducted on the iButton temperature sensors.

Collective Temperature

During the end of the temperature fieldwork, all of the iButton sensors was gathered in one confined space over time to see if there were any temperature irregularities between the sensors. In figure B.1 they are all shown with their individual ID-tag used during the fieldwork.

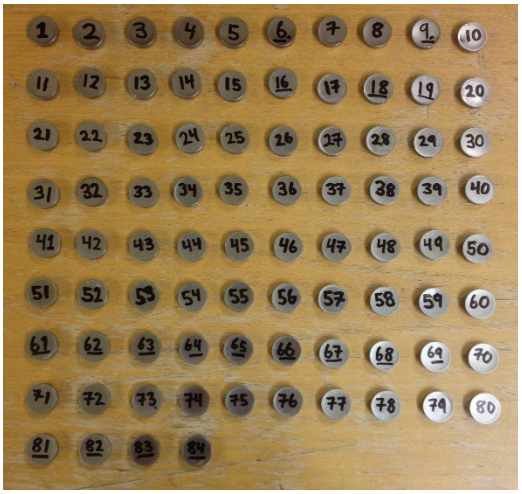

Figure B.1: This is all the iButtons temperature sensors used in the first fieldwork October 2014. The same ID-tag was used during the fieldwork in February-March.

Ice Point Temperature

To see if the iButtons measured the right temperature, an ice point field check was conducted. Only 16 of the 30 sensors used during the fieldwork was available at that time. The sensors were put in a plastic bag to avoid any direct contact with liquid. The plastic bag was then put in a thermos filled with ice water. After an hour and a half they were removed from the ice water and placed together until they had reached the room temperature.

B.1.2 Thermal Mass from Adhesive

Each iButton has to be attached to a surface so it does not fall down or go missing. To solve this problem a pressure-sensitive adhesive, also known as “tack-it” or “blu-tack”, was used. It is shown in figure B.2.

Figure B.2: The iButton sensor and the pressure sensitive adhesive used to attach it to various surfaces.

There was a question of whether the tack-it would function as a thermal mass, and disturb the readings of the iButton sensors or not. Four sensors were used during this experiment; two with tack-it and two without tack-it. The tack-it was applied to two of the sensors before all four sensors were exposed to different temperature stresses, both warm and cold. The results are presented in the next section.

B.2 Results and Conclusions From the Experiments

B.2.1 Collective Temperature

Figure B.3 is a comparison in temperature measurements for all of the sensors used at PK in February-March. The temperature differences vary between 2.0 to 0.2 °C between the highest and lowest measured values. As marked in the figure the temperature difference between the highest and lowest measured temperature exceeded 1 °C at a given interval. This happened when the sensors were transported outside. Even though they were always together in a single plastic bag, it might seem that the movement or sudden change of temperature could have affected the measurements. This has not shown to been a problem other times, and since the sensors are not subject to such sudden temperature changes and transport, then this should not be a problem.

It is concluded that the iButton temperature sensors have an acceptable accuracy relatively to each other.

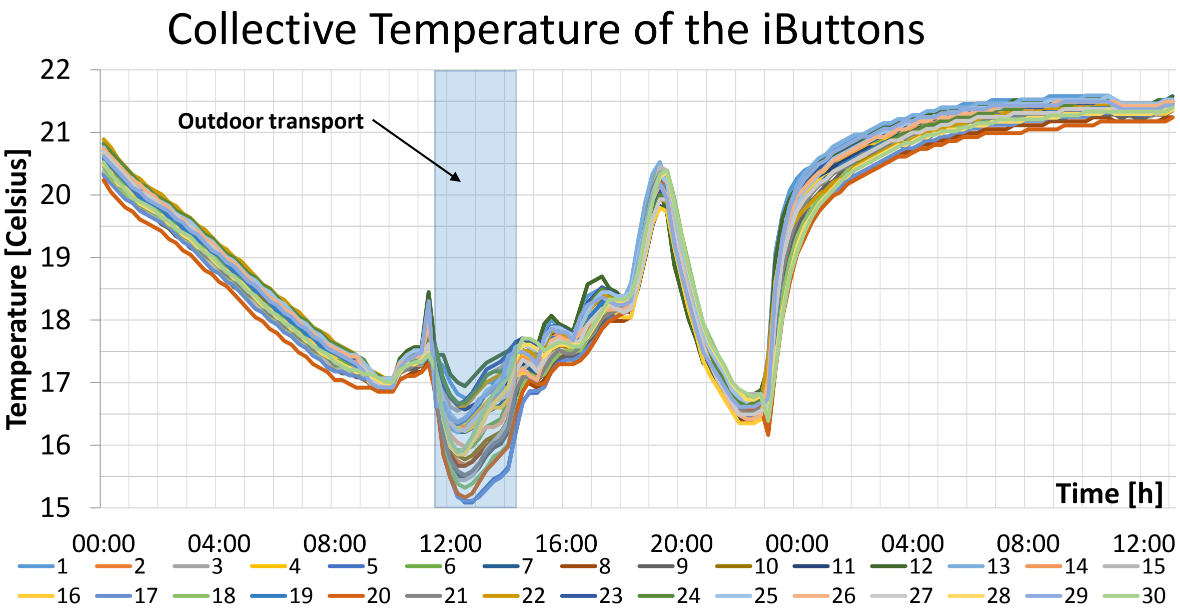

Figure B.3: The results from the collective temperature experiment with the iButton sensors.

B.2.2 Ice Point Temperature

Figure B.4 shows the temperature measurements for 16 of the 30 sensors used at PK in February-March. The results show that all of the sensors have an acceptable accuracy for 0 °C, and thus are calibrated according to the ice point temperature test.

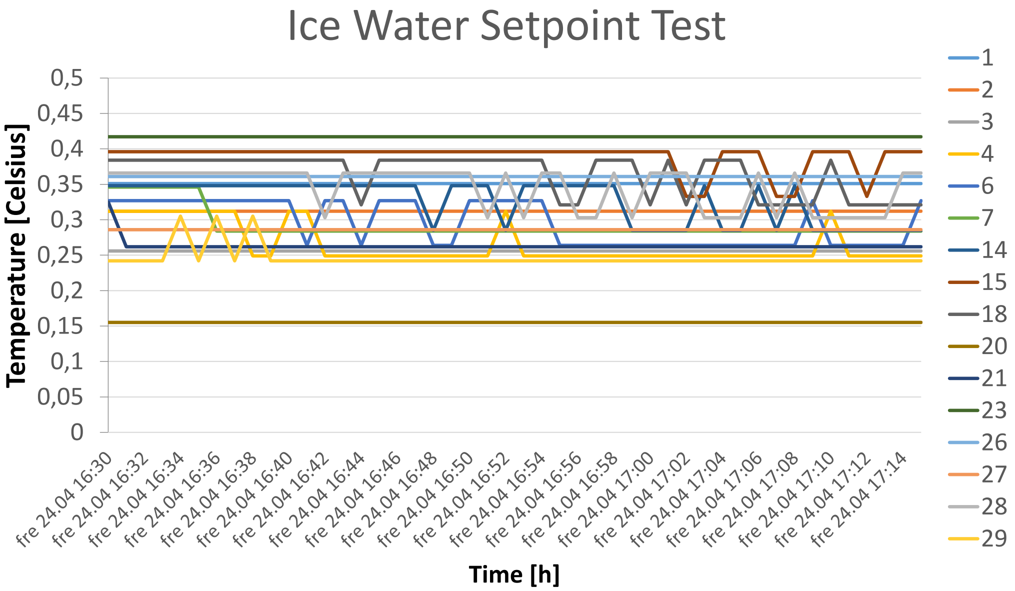

Figure B.4: The results from the ice point calibration test with the iButton sensors.

B.2.3 Thermal Mass of Adhesive

The thermal mass experiment results is shown in figure B.5 and B.6. There are some minor temperature differences that could be explained by the accuracy, but there is also a slower temperature change in figure B.6 for the tack-it iButton sensors. The delay is about 5 minutes (measure frequency is every minute), and the temperature differences are about 1.5 °C. Since the iButton sensors will not be exposed to similar temperature changes it is concluded that the thermal mass of the tack-it will have little effect on the final results of the fieldwork.

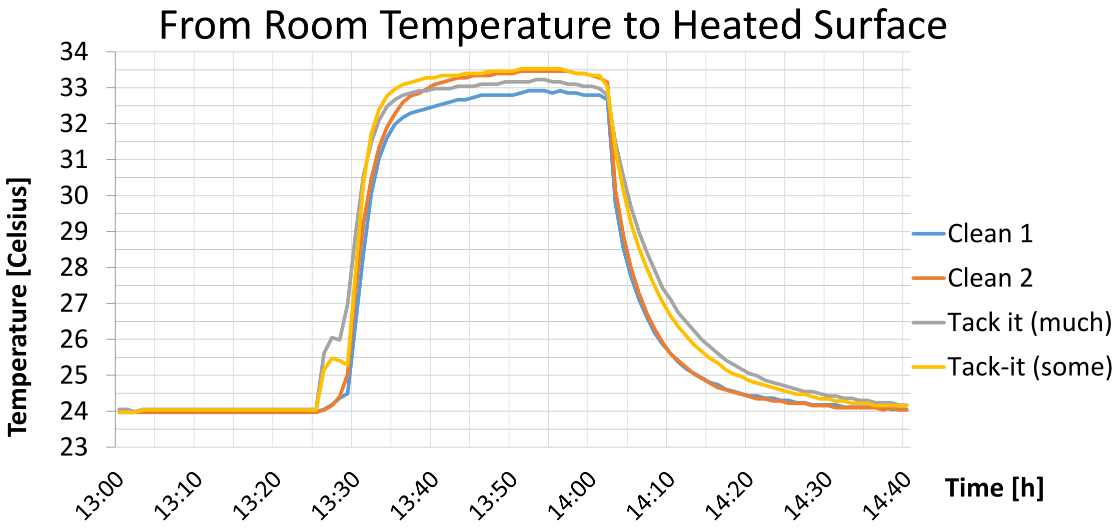

Figure B.5: Temperature change from room temperature to a heated surface and back again.

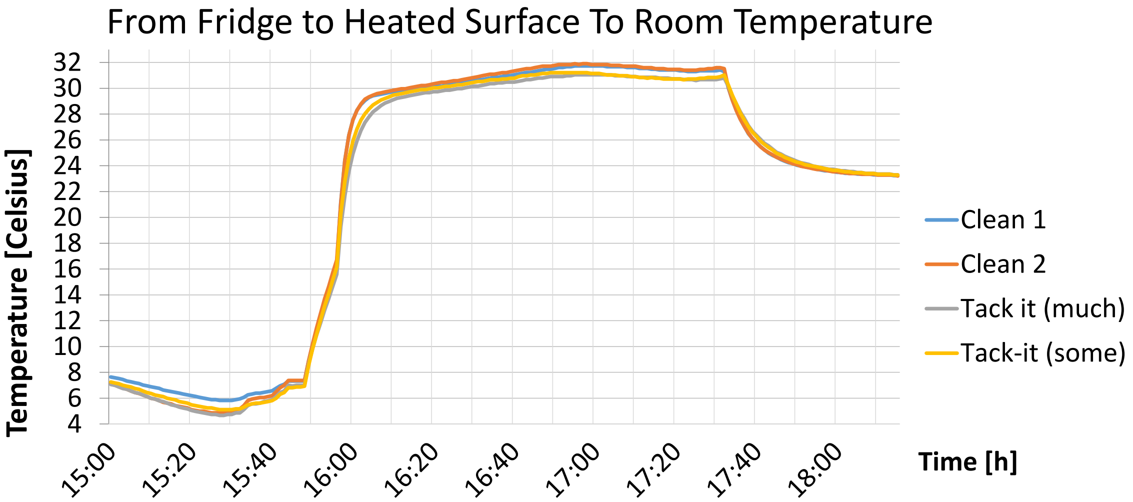

Figure B.6: Temperature change from a fridge to a heated surface to room temperature.

Appendix C | Fieldwork Procedures

C.1 Tracer-gas Experiment

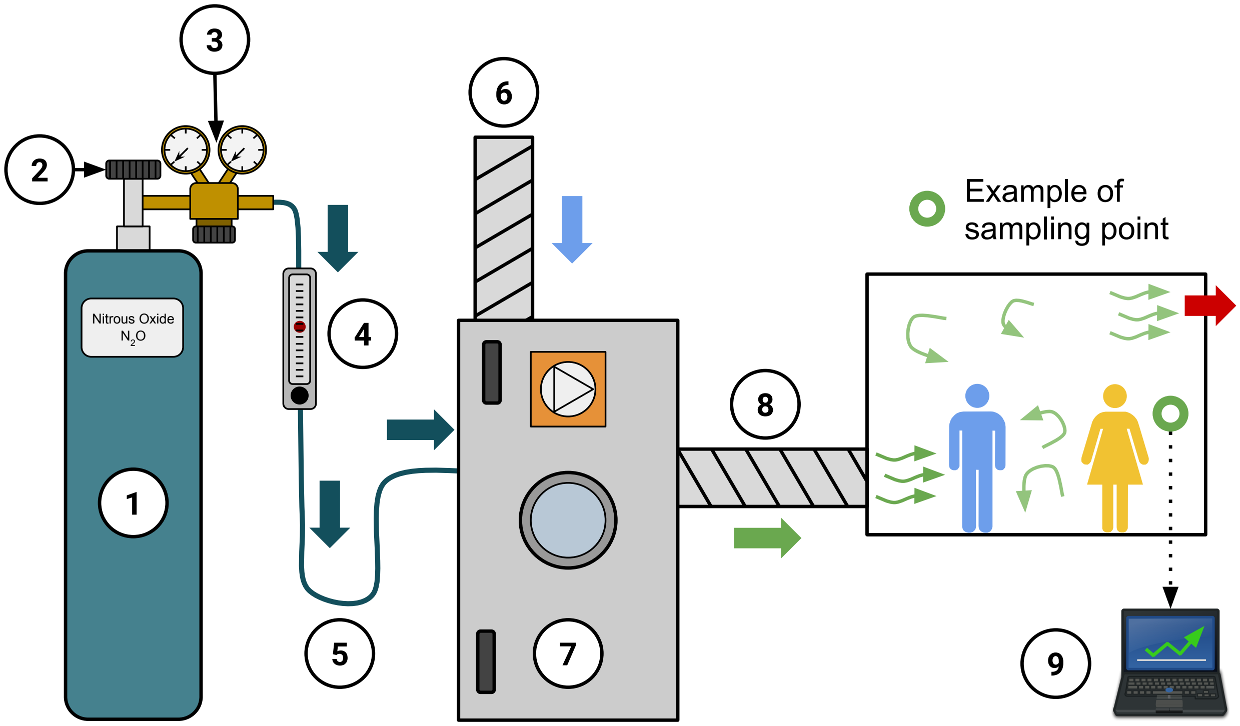

Figure C.1: An illustration of how the tracer gas is used in this fieldwork. The description of activities in this figure is found in the list below. *Inspired by: Mathisen et al. (2004).*

Description of figure C.1:

1. Gas bottle filled with 7.5 kg of nitrous oxide.
2. Main closing valve of the gas bottle.
3. Pressure control valve and regulator making sure that a constant flow of gas is supplied.

4. Flowmeter/rotameter giving the mass or volume flow (depending on the instrument) of the gas. In this case it showed the volume flow as liters of gas per minute.
5. A rigid plastic tube delivers the gas from the gas bottle to the ventilation unit.
6. The duct from where outdoor air enters the ventilation unit.
7. The tracer gas and the outdoor air is mixed in the ventilation unit by the mechanical fan.
8. A mixture of the tracer gas and outdoor air is transported trough the ventilation ducts and to the ventilated space in the building.
9. Several sampling points gathers samples of the indoor air and analyzes the amount of tracer gas in those specific locations.

Gas is supplied from the gas cylinder through a plastic tube via a rotameter regulating the volume flow. The gas continues into the ventilation unit were it is mixed with the supply air by the rotating fan and from there distributed to all the active diffusers in block 4 through the main air supply duct in the center of the building. This means that the concentration of the tracer gas will be equal throughout the whole building. The goal is to have a nitrous oxide (N_2O) concentration of 25 ppm. This is done by adding the right amount of gas depending on the total air supply volume in the ventilation unit. How much tracer gas to add is calculated from the following equation:

$$\dot{V}_{tg} \approx ((c_{tg} \cdot 10^{-6}) \cdot \dot{V}_s) \cdot 1000 \frac{L}{m^3} \cdot 60 \frac{min}{h}$$

c_{tg}	$[ppm]$	The favored concentration of the tracer gas in the air supply volume
$\dot{V}_s$	$[m^3/h]$	The air supply volume of the given ventilation unit
$\dot{V}_{tg}$	$[L/min]$	The amount of tracer gas that must be added to the air supply volume

The tracer-gas flow is measured in liters per minute since that is the scale of the rotameter used in the fieldwork for this thesis. Therefore it is converted from m^3/h to L/min in the equation above.

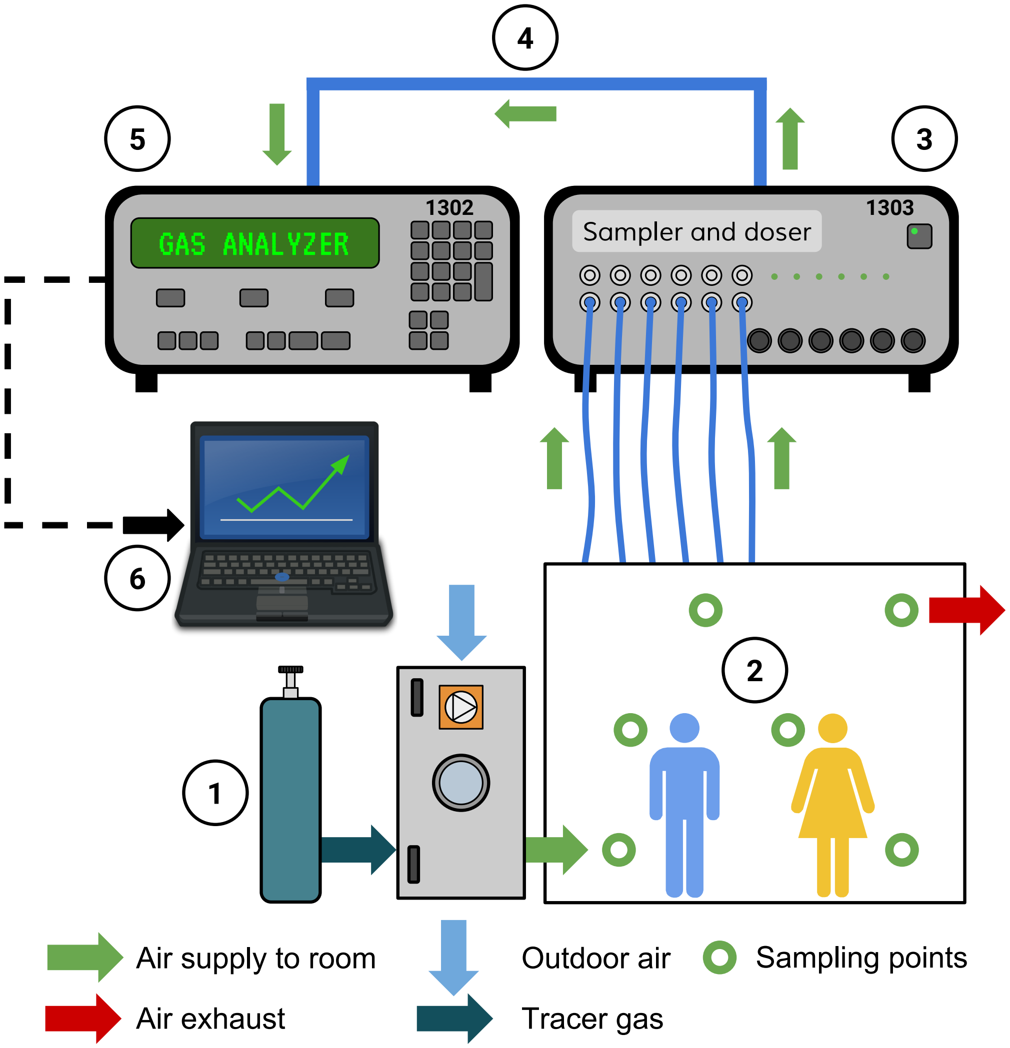

Figure C.2: An illustration of how sampling of the indoor air are done by the sample and analyzing equipment. The description of activities in this figure is found in the list below. *Inspired by: Mathisen et al. (2004)*.

Description of figure C.2:

1. Tracer gas is added at 25 ppm (approximately) to the air supply and mixed with the air before it is supplied to the indoor area.
2. Up to six different sample points in the area has a plastic tube from where samples of indoor air in that specific location are taken.
3. The air sample is transported in the plastic tube from the sample point to the *Multipoint sampler and doser - type 1303* described in appendix A.

4. One air sample at the time is transferred from the 1303 to the *Multi-gas monitor - type 1302*, also described in appendix A.
5. The air sample is analyzed for specific gases based on the instructions given by the user. In this case it analyzes nitrous oxide (N_2O).
6. The results from the analysis is transferred to the computer and presented continuously during the measurements.

Appendix D | Fieldwork Positions

D.1 Introduction

This appendix contains lists of sensor positions and illustrations of where they are placed at PK. Each sensor has a specific number that can be connected to the results. All of the iButton sensors were placed in block 4 (with the exception of number 30, which was placed in block 5, 1st floor).

The list is sorted after which floor the sensors are located on. The specific location indicates where the sensors was placed. Each floor was split into nine parts as shown in figure D.1. The column named "area" in table D.1 and table D.2 indicates in which region the sensor is located.

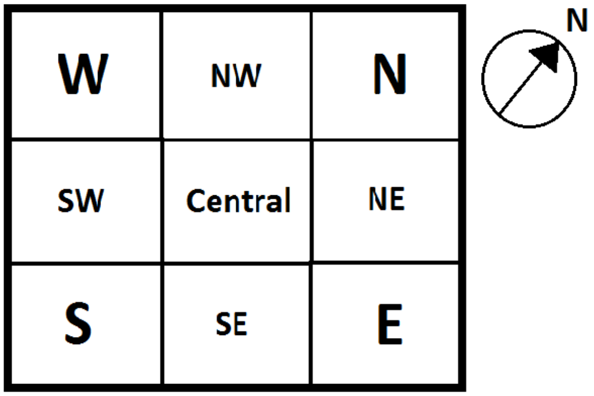

Figure D.1: A floor divided into nine areas defined after the orientation of the building.

D.2 The iButton Temperature Sensors

In table D.1 and table D.2 the position of each sensor used in the fieldwork experiment is listed. The visual position on the technical drawings of each floor is illustrated in figure 6.1 and 6.2 on page 51 and 53, respectively.

Not all of these sensors have been used in this report. This is an overview for both the report and reference if the data is needed in the future.

Table D.1: First table of positions of the iButton temperature sensors used for the fieldwork conducted during February-March 2015

Floor	No.	Room number	Use	Specific position	Height (cm)	Area
1st	1	4104	Office	In center	10	W
1st	2	4104	Office	In center	60	W
1st	3	4104	Office	In center	110	W
1st	4	4104	Office	In center	160	W
1st	5	4104	Office	In center	210	W
1st	6	4104	Office	In center	300	W
1st	7	4104	Office	Upper window	160	W
1st	8	4104	Office	Right air vent over door	250	W
1st	9	4104	Office	Left air vent over door	250	W
1st	10	4104	Office	Outside door	60	W
1st	11	4104	Office	Outside door	160	W
4th	12	Technical room	Ventilation	Exhaust air before heat exch.	-	N
4th	13	Technical room	Ventilation	Supply air after heat exch.	-	N
4th	14	Technical room	Ventilation	Supply air before heat exch.	-	N
3rd	15	Main air supply vent	Air supply	In the central air supply vent	-	C

Table D.2: Second table of positions of the iButton temperature sensors used for the fieldwork conducted during February-March 2015

Floor	**No.**	**Room number**	**Use**	**Specific position**	**Height (cm)**	**Area**
2nd	16	Open landscape	Open office	External wall	150	SE
2nd	17	Open landscape	Open office	Internal wall	150	SE
2nd	18	Open landscape	Open office	External wall	130	E
2nd	19	Open landscape	Open office	External wall	150	E
2nd	20	Open landscape	Open office	Bookshelf	140	NE
2nd	21	Open landscape	Open office	External wall	150	N
2nd	22	Open landscape	Open office	Internal wall	150	N
2nd	23	Open landscape	Open office	Internal wall	150	NE
2nd	24	Open landscape	Open office	Internal wall	150	C
2nd	25	Open landscape	Open office	External wall	150	SW
2nd	26	Open landscape	Open office	External wall	150	S
2nd	27	4206	Meeting room	Internal wall	150	W
2nd	28	4206	Meeting room	Corner by window	60	W
2nd	29	4206	Meeting room	On air diffuser	20	W
1st	30	5106 (Block 5)	Meeting room	In corner	150	W

D.3 Multipoint Sampler and Doser - Type 1303

Table D.3 describes the location of each sample point in the tracer-gas experiment. Please see figure 6.3 in chapter 6 for a graphical overview.

Table D.3: List and description of the sampling positions during indoor air monitoring of the 2nd floor, block 4. The parentheses describe the height used in the Friday step-down analysis.

Multipoint Sampler and Doser - Type 1303						
Floor	**No.**	**Room number**	**Use**	**Spec. position**	**Height (cm)**	**Area**
2nd	1	Open landscape	Open office	Next to office desks	150 (10, 150 & 290)	E
2nd	2	Open landscape	Open office	Next to office desks	150	N
2nd	3	In central staircase	Staircase between 2nd and 3rd floor	Open area of staircase	130	C
3rd	4	In central staircase	Staircase between 3rd and 4th floor	Open area of staircase	130	C
2nd	5	Staircase between the two blocks	Walk-through	In center	150 (10)	S
2nd	6	4211	Office	In center	20	NW
4th	7	In open central staircase	Airtight glass wall enclosure around staircase	Open area of staircase	130	C

Appendix E | Additional

This appendix includes the indoor climate survey conducted at Powerhouse Kjørbo and the non-renovated office building. It is, as discussed in section 6.2, based on the Örebro model and the model from Center for the Built Environment (2014).

It also inlcudes the agreement between the project owner of Powerhouse Kjørbo, Entra, and the Zero Emission Building (ZEB) board. This agreement revolves around the cooperation between ZEB and Entra and the scientific research conducted by researchers and/or students at NTNU, and by ZEB.

The most important part for this thesis is written on the bottom of the second page. This was mentioned in the introduction of this thesis. Roughly translated it states:

> *"The student is responsible for any data and results from the project [Powerhouse Kjørbo] presented in this thesis. The results are not approved by the project owner of the building or the ZEB Board."*

Both the survey and the agreement is written in Norwegian.

ZEB The Research Centre on Zero Emission Buildings

AVTALE

mellom

ZEB og Entra

om gjennomføring av pilotprosjekt
for perioden 01.10.2014 til 31.12.2015

Navn på pilotprosjekt:

Powerhouse Kjørbo

Generelle retningslinjer for samarbeidet er gitt i notatet
"Kriterier og prosedyrer for gjennomføring av pilotbygg i ZEB"
(rev. 2014-12-03), vedlagt.

Spesielle hensyn:

Trondheim 3/12-2014
Sted, dato
Arild Gustavsen
For ZEB
Arild Gustavsen, leder

Oslo 4.12.2014
Sted, dato
For Tiltakshaver
ASSISTERENDE DIR.
PROSJEKT UTVIKLING
OG TEKNISK.

Vedlegg:
Notat "Kriterier og prosedyrer for gjennomføring av pilotbygg i ZEB", rev. 03.12-2014

MEMO

MEMO CONCERNS

Kriterier og prosedyrer for pilotbygg i ZEB, Forskningssenteret for Zero Emission Buildings

Utkast

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Utkast 09.09.2014 / Inger Andresen (rev. 03.12.2014 Arild Gustavsen)	2

Ambisjonsnivå

Ambisjonsnivå for energibruk skal være minst ZEB-O÷EQ[1], ref. Dokka et. al (2013).
I tillegg skal det gjøres vurderinger rundt klimagassutslipp for materialbruk. Konkrete mål for hvert enkelt pilotprosjekt defineres i samarbeid mellom NTNU/SINTEF og tiltakshaver for byggeprosjektet. Dette skal gjøres i tidligfase.

Deltakere

Pilotprosjektet skal om mulig involvere minst to av partnerne i ZEB, i tillegg til NTNU/SINTEF. ZEB skal bidra til kunnskapsoverføring fra alle ZEB-partnerne til pilotprosjektene, f.eks. gjennom felles workshops, tidlig i prosjektet.

Godkjenning

Status som pilotprosjekt i ZEB skal godkjennes av ZEB styret på innstilling fra senterledelsen.

Publisering

Publisering av FoU-resultater knyttet til pilotprosjektene skal godkjennes av ZEB-styret iht. konsortieavtalen[2] og tiltakshaver. For hvert pilotprosjekt skal det som et minimum lages en rapport fra designfasen og en "as-built" rapport, dette skal være åpne rapporter, tilgjengelig for alle ZEB-partnere.

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[1] ZEB-O÷EQ: **Z**ero **E**missions **B**uilding, including **O**peration minus **EQ**uipment: Fornybar energiproduksjon på bygget kompenserer for klimagassutslipp fra energibruk i drift (*operation*) med unntak av energibruk til teknisk utstyr (*equipment*), dvs. plug-in laster som PCer, kjøleskap og fjernsyn.

[2] For studentoppgaver er det i praksis vanskelig å oppfylle denne publiseringsprosedyren. Alle studentoppgaver knyttet til pilotprosjekter i ZEB, skal i stedet inneholde et avsnitt med følgende tekst: "Datagrunnlag og resultater fra pilotprosjektet står for studentens egen regning, og er ikke godkjent av tiltakshaver for pilotbygget eller ZEB-styret."

Markedsføring

ZEB-partnerne som er involvert i pilotprosjektene skal bidra til å markedsføre pilotprosjektene som en del av forskningssenteret. Tiltakshaver for pilotprosjektene forplikter seg til å lage en kommunikasjonsplan i samarbeid med ZEB.

Tilgang til og behandling av datagrunnlag

Det forutsettes at forskere og studenter fra ZEB-senteret får tilgang til nødvendig datagrunnlag for å gjennomføre forskningsarbeidet gjennom prosjektering, bygging og drift. Dette avtales nærmere med byggeier/tiltakshaver og eventuelt andre involverte på forhånd, inkludert evt. assistanse ifb. tilrigging/nedrigging/innsamling av data. Tiltakshaver for pilotprosjektet skal medvirke til at følgende data (som et minimum) skal gjøres tilgjengelig fra prosjektet: energi- og klimagassberegninger fra prosjekteringsfasen, kostnadstall[3], samt målinger av energibruk i drift. Tiltakshaver plikter å instrumentere bygget for formålsdelt energimåling, dersom ikke annet er avtalt.

Ved brukerundersøkelser skal det følges prosedyre iht. Personvernombudet for forskning (NSD). For forsknings- og studentprosjekter som medfører meldeplikt eller konsesjonsplikt skal NSD meldeskjema sendes inn 30 dager før datainnhentingen startes opp, og tilbakemelding fra personvernombudet må avventes før prosjektet igangsettes. Det gjøres evt. særskilte avtaler mht. eventuell fortrolig informasjon.

Roller og ansvar

NTNU/SINTEF har ansvar for gjennomføring og resultater av FoU-arbeidet knyttet til pilotprosjektet. Forskerne kan bidra med råd og veiledning mht. valg og utforming av løsninger, men tiltakshaver og de prosjekterende må ta de endelige beslutninger samt ansvar for de løsninger som blir valgt. For pilotprosjekter av denne art, vil det alltid være en risiko for at målsetningene ikke vil bli fullstendig oppfylt. For å oppnå gode resultater, er det en forutsetning at forskerne respekterer prosjektets betingelser mht. fremdrift og beslutningsprosedyrer, samt at tiltakshaver og andre prosjektdeltakere involverer forskerne i beslutninger som kan påvirke forskningsaktivitetene og energimålsetningene.

For hvert pilotprosjekt lages det en beskrivelse av hva som skal undersøkes/måles/evalueres av ZEB, og på hvilke måter resultatene fra forskingen skal formidles (rapporter, notater eller vitenskapelige artikler). Kostander for denne forskningen dekkes av ZEB. Dersom tiltakshaver eller andre aktører som er involvert i prosjektet ønsker ytterligere bistand/rådgivning/FoU fra ZEB, er dette fullt mulig, men da må kostnadene for dette dekkes av oppdragsgiveren, evt. kan det søkes egne FoU-prosjekt/støttemidler for dette.

Referanser

Dokka, T.H., I. Sartori, M. Thyholt, K. Lien og K.B. Lindberg (2013): "A Norwegian Zero Emission Building Definition", Artikkel presentert på konferansen PassivhusNorden 2013, Göteborg, ref: http://www.laganbygg.se/UserFiles/Presentations/18._Session_5_T.Dokka.pdf.

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[3] Omfang defineres nærmere for hvert pilotprosjekt, i samarbeid med tiltakshaver og evt. andre involverte ZEB-partnere.

Spørreskjema

Inneklima og arbeidsmiljø

Dette spørreskjemaet omhandler inneklimaet på din arbeidsplass og mulige symptomer som du kanskje opplever.

BAKGRUNNSINFORMASJON

- Bedrift/institusjon
  - [FYLL INN]
- Avdeling
  - [FYLL INN]
- Yrke
  - [FYLL INN]
- I hvilken etasje er din arbeidsplass
  - [FYLL INN]
- Husnummer (blokknummer)
  - [FYLL INN]
- Type arbeidsplass
  - Eget rom
  - Delt rom
  - Kontorlandskap
  - Annet
- Type arbeid
  - Kontorarbeid
  - Feltarbeid/arbeid utenfor egen bygning
  - Blanding
- Hvor lenge har du jobbet ved denne kontorpulten
  - [FYLL INN]
- Hvor lenge har du jobbet i denne bygningen
  - [FYLL INN]
- Stilling
  - Leder/sjef
  - Annet
- Stillingssituasjon
  - Fast ansatt
  - Vikar
  - Prosjektansatt
  - Annet
- Gjennomsnitt antall timer tilbrakt ved din kontorpult
  - Mer enn 30 t/uke
  - 30-15 t/uke

    - Mindre enn 15 t/uke
- Overtidsarbeid
    - Sjelden
    - Mindre enn 20 t/mnd
    - Mer enn 20 t/mnd
- Mot hvilken retning peker de vinduene som er nærmest din arbeidspult?
    - Nordøst
    - Nordvest
    - Sørøst
    - Sørvest
- Sitter du nær en yttervegg eller lenger inn i rommet?
    - Yttervegg
    - Intern vegg ved radiator
    - Intern vegg ikke ved radiator
    - Midt i mellom
- Alder
    - 20-30
    - 31-40
    - 41-50
    - 51-60
    - >60
- Kjønn
    - Mann
    - Kvinne
- Røyker du?
    - Ja
    - Nei
- Høyeste fullførte utdanning (Disse må vi ser over)
    - Grunnskole (9/10 år)
    - Videregående
    - Universitet/høgskole (bachelor eller master) eller høyere
- Hvor lenge arbeider du med datamaskin per dag?
    - 0-2 t/dag
    - 2-4 t/dag
    - Mer enn 4 t/dag
- Bruker du kontaktlinser
    - Ja
    - Nei
- Anser du din arbeidsplass (området du arbeider på) som
    - Romslig
    - Nok plass
    - Ikke nok plass

- Har du noen gang hatt problemer med astma?
- Har du noen gang hatt problemer med høysnue (pollenallergi)?
- Har du noen gang hatt problemer med andre allergiske reaksjoner i øyne og nese?
- Blir du lett irritert i øyne eller luftveier av tobakksrøyks, sterke lukter eller eksos?
- Blir du ofte forkjølet eller får du ofte andre infeksjonssykdommer

Hvert spørsmål besvarer med enten

  - Ja
  - Nei
- **Dersom ja på én eller flere alternativer**: Har du hatt dette/disse problemene i løpet av det siste året?
  - Ja
  - Nei

- Andre kommentarer
    - ○ [FYLL INN]

ARBEIDSMILJØ

Har du vært ***plaget*** *i løpet av de* ***siste tre månedene*** *av noen av de følgende faktorer* ***på arbeidsplassen din****? (Svar på alle spørsmål selv om du ikke har vært plaget!)*

- Trekk
- For høy romtemperatur
- Varierende romtemperatur
- For lav romtemperatur
- Innestengt/dårlig luft
- Tørr luft
- Ubehagelig lukt
- Statisk elektrisitet, som ofte forårsaker støt
- Passiv røyking
- Støy
- Lys som er svakt eller forårsaker blending og/eller refleksjoner
- Lys som automatisk slukker mens du arbeider
- Støv og skitt
- Farger (på vegger, objekter osv.)

Hvert spørsmål besvarer med enten

1. Ja, ofte
2. Ja, noen ganger
3. Nei, aldri

ARBEIDSFORHOLD

- Ser du på arbeidet ditt som interessant og stimulerende/lærerikt?
- Har du for mye arbeid å gjøre?
- Har du noen mulighet til å påvirke ditt arbeidsforhold?
- Hjelper dine medarbeidere deg med problemer du måtte ha i ditt arbeid?
- Er du bekymret for at arbeidssituasjonen vil endre seg?

Hvert spørsmål besvarer med enten

4. Ja, ofte
5. Ja, noen ganger
6. Nei, sjelden
7. Nei, aldri

- Hvor fornøyd er du med komforten til kontormøblene på din arbeidsplass?
  - Veldig fornøyd
  - Fornøyd
  - Akseptabelt
  - Lite fornøyd
  - Veldig lite fornøyd
- Tilfredsstiller interiøret dine behov?
  - Ja
  - Nei

- Hvilke av følgende punkter justerer du selv for å påvirke inneklimaet på din arbeidsplass:
  - Åpne vindu
  - Stille på termostat
  - Ventilasjonen
  - Belysning
  - Annet
    - [FYLL INN]

Hvert spørsmål besvarer med enten (utenom «Annet»)

- Ja
- Nei
- **Dersom nei**: Skulle du ønske du kunne justere det?
  - Ja
  - Nei

NÅVÆRENDE SYMPTOMER

*I løpet av de **siste tre månedene**, har du opplevd noen av de følgende symptomene? (Svar på alle spørsmål selv om du ikke har opplevd noen symptomer!)*

- Tretthet/Slapphet
- Tung i hodet
- Hodepine
- Kvalme/svimmelhet
- Konsentrasjonsvansker
- Kløe, svie eller irritasjon i øyne
- Irritert, tett eller rennende nese
- Neseblod
- Hes, tørr hals
- Hoste
- Tørr eller rød ansiktshud
- Flass/kløe i hodebunnen eller ører
- Tørre hender, kløe, rød hud
- Lider av stress
- Lett irritert over små ting/bagateller
- Vanskeligheter med å sove
- Annet
    - [FYLL INN]

Hvert spørsmål besvarer med enten

1. Ja, ofte (hver uke)
2. Ja, noen ganger
3. Nei, aldri

- Hvis du har opplevd plager, tror du det skyldes inneklimaet på arbeidsplassen?
    - Ja
    - Nei
    - Jeg vet ikke

UTFYLLENDE SPØRSMÅL

- Anser du at ditt fysiske arbeidsmiljø virker inn på dine muligheter for å gjøre godt arbeid?
- Anser du at ditt psykososiale arbeidsmiljø virker inn på dine muligheter for å gjøre godt arbeid?
- Har du vært sykemeldt i løpet av de siste 12 månedene på grunn av symptomer du mener skylder arbeidsmiljøet?
- Har du vært til legen i løpet av de siste 12 måneder på grunn av symptomer du mener skylder arbeidsmiljøet?

Hvert spørsmål besvarer med enten

1. Ja
2. Nei

DET FYSISKE INNEMILJØET

- Anser du at noe av det følgende har en merkbar virkning på din følelse av velbehag, helse og/eller din evne til å utføre et godt arbeid:
    - Bruk av planter
    - Fargebruk i lokalet
    - Bruk av spesifikke materialer
    - Møbler
    - Åpent areal/cellekontor

Hvert spørsmål besvares med enten

1. Ja
2. Nei

- **Dersom ja**: Spesifiser hvordan dette påvirker deg (både positivt og negativt):
    - [FYLL INN]

TEMPERATURFORHOLD VED DIN ARBEIDSPULT

- Hva er din opplevelse av romtemperaturen ved din arbeidspult?
    - Veldig god
    - God
    - Akseptabel
    - Dårlig
    - Veldig dårlig
- Problemer med romtemperaturen (det kan være mer enn ett svar!)
    - For kaldt om vinteren
    - For kaldt til andre tider
    - For varmt om sommeren
    - For varmt til andre tider
- Når på dagen er det eventuelt for varmt?
    - Morgenen (kl. 07-10)
    - Midt på dagen (kl. 10-13)
    - Ettermiddag (kl. 13-16)
    - På kvelden (kl. 16-19)
- Når på dagen er det eventuelt for kaldt?
    - Om morgenen (kl. 07-10)
    - Midt på dagen (kl. 10-13)
    - Om ettermiddagen (kl. 13-16)
    - Om kvelden (kl. 16-19)
- Dersom du føler at det er kaldt, hvor føler du deg kald?
    - På føttene
    - På hendene
    - I nakken
    - Hele kroppen

- Hvis du opplever misnøye med temperaturen, hva mener du er kilden til problemet? (Det kan være mer enn et svar!)
    - Fuktigheten er for høy
    - Fuktigheten er for lav
    - For mye sol
    - Gulvet er for kaldt
    - Veggene er for kalde
    - Taket/himlingen er for kald
    - Vinduene er for kalde
    - Varme fra teknisk utstyr (datamaskiner, lys osv.)
    - Trekk fra vinduene
    - Min arbeidsplass er varme enn andres
    - Det er ikke mulig å justere temperaturen selv
- Hvordan kontrollerer du temperaturen ved din arbeidspult?
    - Kontrollerer det gjennom oppvarmingssystemet
    - Ved å åpne et vindu
    - Jeg kan ikke kontrollere noe som helst
- Dersom du sitter i cellekontor, hvor ofte har du døra åpen
    - Stort sett alltid
    - Stort sett aldri
    - Av og til
    - Bare stenger den når det er møte
    - Arbeider ikke på cellekontor
- Aksepterer du daglig temperaturforandringer (1-3 grader celsius opp eller ned)
    - Ja
    - Nei
- Under hvilke tilfeller aksepterer du temperaturvariasjoner på din arbeidsplass? (Det kan være mer enn ett svar!)
    - Tekniske problemer med oppvarmings-/kjølesystemet
    - Sesongforandringer

TEMPERATURFORHOLD PÅ DINE MØTEROM

- Hva er din opplevelse av temperaturen av temperaturen på møterommene du bruker?
    - Veldig god
    - God
    - Akseptabel
    - Dårlig
    - Veldig dårlig
- Problemer med romtemperaturen (det kan være mer enn ett svar!)
    - For kaldt om vinteren
    - For kaldt til andre tider
    - For varmt om sommeren
    - For varmt til andre tider
- **Dersom for varmt:** Når på dagen er for varmt?
    - Om morgenen (kl. 07-10)
    - Midt på dagen (kl. 10-13)
    - Om ettermiddagen (kl. 13-16)
    - Om kvelden (kl. 16-19)
- **Dersom for kaldt:** Når på dagen er det for kaldt?
    - Om morgenen (kl. 07-10)
    - Midt på dagen (kl. 10-13)
    - Om ettermiddagen (kl. 13-16)
    - Om kvelden (kl. 16-19)
- **Dersom for kaldt:** Hvor på kroppen føler du deg kald?
    - Kalde føtter
    - Kalde hender
    - Nakke
    - Hele kroppen
- Hvis du opplever misnøye med temperaturen, hva mener du er kilden til problemet? (Det kan være mer enn et svar!)
    - Fuktigheten er for høy
    - Fuktigheten er for lav
    - For mye sol
    - Gulvet er for kaldt
    - Veggene er for kalde
    - Taket/himlingen er for kald
    - Vinduene er for kalde
    - Varme fra teknisk utstyr (datamaskiner, lys osv.)
    - Trekk fra vinduene
    - Min arbeidsplass er varme enn andres
    - Det er ikke mulig å justere temperaturen selv
    - Jeg er ikke misfornøyd
- Hvordan kontrollerer du temperaturen på dine møterom?
    - Kontrollerer det gjennom oppvarmingssystemet
    - Ved å åpne et vindu

    - Jeg kan ikke kontrollere noe som helst
- Finnes det noe annet rom som har problemer med temperaturen?
    - Ja
    - Nei
- **Dersom ja:** Hvilke(t) rom og hva er problemet?
    - [FYLL INN]

RENHOLD

- Hva synes du om renholdet på din arbeidsplass?
    - Veldig godt
    - Godt
    - Akseptabelt
    - Dårlig
    - Veldig dårlig
- Problemer med renholdet (det kan være mer enn ett svar)
    - Manglende renhold
    - Dårlig utført renhold
    - Støv og skitt på skap og lignende
    - Manglende renhold på toaletter
- Anser du din arbeidsplass som enkel å rengjøre?
    - Ja
    - Nei
    - Jeg vet ikke
- **Dersom det er et problem med renholdet**: Hva anser du som problemet? (Det kan være mer enn ett svar!)
    - Tobakksrøyk
    - Kopimaskiner
    - Printere
    - Tepper
    - Andre personer
    - Vaskeprodukter
    - Annet (spesifiser)
    - [FYLL INN]

BELYSNING

- Hvordan kontrollerer du belysningen på din arbeidsplass? (Det kan være mer enn ett svar!)
    - Lysbryter
    - Lysdimmer
    - Solavskjerming (persienner o.l.)
    - Egen lampe på pulten
    - Jeg kan ikke kontrollere noe som helst
- Hvor fornøyd er du med den visuelle komforten (blending, refleksjoner, kontraster)
    - Veldig fornøyd
    - Fornøyd
    - Akseptabelt
    - Lite fornøyd
    - Veldig lite fornøyd
- Når føler du deg eventuelt forstyrret av sollys?
    - Morgenen (kl. 07-10)
    - Midt på dagen (kl. 10-13)
    - Ettermiddag (kl. 13-16)
    - På kvelden (kl. 16-19)
- Hva forstyrrer deg med belysningen?
    - For mørkt
    - For lyst
    - Ikke nok dagslys
    - For mye dagslys
    - Fargen på lyset
    - Vinkelen på belysningen
    - Frekvensen på lyset er for lav (flimring)

AKUSTIKK

- Hva synes du om det akustiske miljøet på arbeidsplassen (lydnivå, støy o.l.)
    - Veldig godt
    - Godt
    - Akseptabelt
    - Dårlig
    - Veldig dårlig
- Problemer med det akustiske miljøet (det kan være mer enn ett svar)
    - Ventilasjonen er forstyrrende
    - Støy fra utsiden av bygget (trafikk o.l.)
    - Dårlig akustikk
    - Forstyrrelser fra andres samtaler/telefonsamtaler

LUFTKVALITET

- Hva synes du om luftkvaliteten på arbeidsplassen?
  - Veldig god
  - God
  - Akseptabel
  - Dårlig
  - Veldig dårlig
- Problemer med luftkvaliteten (det kan være mer enn ett svar)
  - Verre tidlig om morgenen
  - Verre om ettermiddagen
  - Forskjellig fra sted til sted
  - Ingen muligheter for gjennomlufting av rom/områder (ved hjelp av vindu, dører etc.)
  - Forstyrrende og/eller ubehagelige lukter
- **Dersom noen ble krysset av (utenom lukt):** Spesifiser hva problemet er:
  - [FYLL INN]
- **Dersom det er forstyrrende og/eller ubehagelige lukter:** Spesifiser hvilke lukter og hvor de kommer fra:
  - [FYLL INN]
- Hvordan kontrollerer du luftkvaliteten?
  - Ved å åpne vinduer
  - Ved å justere ventilasjonen (bryter)
  - Jeg kan ikke kontrollere noe
  - Jeg har ikke behov for å kontrollere luftkvaliteten
- Anser du luften utendørs som mer eller mindre «frisk» enn luften fra ventilasjonssystemet?
  - Uteluften er friskere
  - Uteluften er mindre frisk
  - Omtrent like frisk
- Finnes det rom med dårlig luftkvalitet?
  - Ja
  - Nei
- **Dersom ja:** Hvilke(t) rom og hva er problemet?
  - [FYLL INN]

ANNET

- Kommentarer
  - [FYLL INN]

Appendix F | Error Analysis

Please refer to appendix A to see the accuracy and other specifications of the equipment used in this thesis. Temperature and calibration tests has been conducted on the iButton sensors and are presented in Appendix B. The reliability of the indoor climate survey is presented in section 7.2 on page 81. The following presents possible sources of error for the fieldwork experiments.

F.1 Sources of Error

Any errors in the results could be caused either by internal irregularities or unwanted external influence on the measurements. Internal irregularities can be errors in the electronics or similar.

Temperature Distribution Experiment

- Nearby heat sources that give a wrong impression of the general thermal environment at that specific area. E.g. lamps, computers, small electronic devices etc.
- Touching the sensors
- Covering the sensors up
- Exposing them to direct sunlight
- Exposing them to outdoor air (such as opening a window)
- The sun could affect any iButton exposed to sunlight.

The accuracy for all temperature sensors mean the measured temperature can vary with up to 1 °C between two sensors in the same spot. It seems like the Powerhouse Kjørbo sensors tend to be a small fraction lower than the iButton sensor in colder locations and a small fraction higher in warmer locations.

It was important to place the sensors carefully so that they could not be affected by any unwanted external sources.

Ventilation Efficiency Experiment

- The equipment is not calibrated in addition to the measurements not being accurate relatively to each other.
- The tracer gas distribution could be affected by airflows set in motion by people, opening of windows and/or air movement between the two blocks or other compartments.
- The air supply volume is not constant, and the amount of supplied tracer-gas does not follow the desired concentration. Instead there is a fluctuation in the measured concentration. This would alternate the way the concentration in the room rises compared to a steady-state supply concentration.

Appendix G | Risk Assessment Report

The ventilation efficiency fieldwork was conducted with assistance from the supervisors of this thesis. The risk assessment was done by Hans Martin Mathisen before the experiment at Powerhouse Kjørbo on March 12th and March 13th 2015. Mathisen was in charge of the safety and operation of equipment involved in the risk assessment, and therefore it is not needed to conduct such a risk assessment for this thesis. A field card for participants was filled out and delivered to the Department of Energy and Process Engineering before the fieldwork was conducted.

The specifications of the gas used during the ventilation efficiency fieldwork and its necessary equipment are described in appendix A. There, some risks regarding the nitrous oxide are mentioned. There were no risks involved in the temperature measurements fieldwork done prior to the ventilation efficiency fieldwork.