Norwegian University of
Science and Technology

Ventilative cooling of Zero Emission Buildings (ZEB)

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Mechanical Engineering
Submission date: June 2017
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NTNU
Norwegian University
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Department of Energy
and Process Engineering

EPT-M-2017-12

MASTER THESIS

for

Student Solveig Blandkjenn

Spring 2017

Ventilative cooling of Zero Emission Buildings (ZEB)
Ventilasjonskjøling av nullutslippsbygninger

Background and objective

Super insulated buildings require cooling during longer periods of the year than ordinary buildings. Cooling can be rather energy consuming. Given the low outdoor air temperatures, using outdoor air can reduce energy needs to a minimum. However, the air should be supplied in a way that does not cause discomfort or annoyance for the occupants.

The objective of this master thesis is to study how to apply ventilative cooling (using window openings and mechanical ventilation) and to evaluate the effect on the indoor environment and energy use in super insulated residential or office buildings.

The master thesis is connected to the research programme for Zero Emission Buildings (FME ZEB) and the International Energy Agency's annex 62 on Ventilative cooling

The Living Lab situated at the NTNU Gløshaugen campus in Trondheim is the case to be studied. The goal is to determine a ventilation procedure that covers demands for hygienic ventilation and ventilative cooling. The system is supposed to work in hybrid mode, but strictly natural or mechanical ventilation are accepted in some periods in order to reduce energy use. Good thermal comfort throughout the year by means of an adapted control is the goal of the work.

The student is recommended to use an IDA ICE simulation in order to develop the control strategy, and measurements of the installed system.

The following tasks are to be considered for the master thesis:

1. Literature survey on ventilative cooling and indoor environment in super insulated buildings
2. Develop an algorithm for natural ventilation in Living Lab, based on measurements and calculations. This algorithm should be based on the algorithm previously developed in the project work.
3. Establish a model of the building with window and mechanical ventilation in IDA ICE. This model should be based on models previously developed in the project work
4. Use the IDA ICE model to develop ventilation strategies for the studied building

5. Evaluate the ventilation control strategy with measurements
6. Test the performance of the ventilation control strategy in different climates in IDA ICE.
7. Use IDA ICE to evaluate the ventilation control strategy with different window placements and designs.

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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, 15. January 2017

Hans Martin Mathisen
Academic Supervisor

Research Advisor:
Maria Justo Alonso

Preface

This master's thesis has been written for the course TEP 4910 – Energy and Indoor Environment, Master's Thesis, at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology. First and foremost, I would like to thank my supervisor Hans Martin Mathisen at the department of Energy and Process Engineering, and my co-supervisor Maria Justo-Alonso at SINTEF Byggforsk. Their guidance and support over the last year has been of great value. Thank you to the ZEB project for letting me use Living Lab for my experiments, to Francesco Goia for helping me with information, and especially to Svein Kristian Skånøy for rescuing me every time the technical systems in Living Lab broke down. These people have helped me during my final year of education, but I also thank my parents and all my previous teachers and professors. I move forward into adult life with the foundation of knowledge and imagination that they gave me, and for that I am grateful.

Solveig Blandkjenn
Trondheim, June 2017

Abstract

Well-insulated buildings, like Zero Emission Buildings (ZEB), have a high occurrence of overheating even in cool climates. It is important to have cooling systems installed to achieve thermal comfort for the occupants of these buildings, but the high energy consumption of mechanical cooling makes it hard to reach a goal of Zero Emission. This master's thesis investigates the possibility to use natural ventilation principles to supply ventilative cooling in a Zero Emission Building in a cool climate. The focus has been to supply natural ventilation through window openings without causing local thermal discomfort like draught - but still succeeding in cooling down the building. Natural ventilation can be used instead of mechanical ventilation to remove pollutants like CO_2. The energy saving potential of using only natural ventilation when the weather conditions allow it has also been evaluated in this thesis.

Living Lab is a ZEB built on the NTNU campus in Trondheim, and has been the subject of this thesis. Experiments have been conducted in the building to determine how natural ventilation can be used without causing local thermal discomfort. A control algorithm for ventilative cooling supplied by the windows has been proposed - based on experiments, findings in literature and previous studies of Living Lab. An IDA ICE building simulation model has been used to develop ventilative cooling strategies and evaluate them based on thermal comfort, indoor air quality and energy consumption.

Climatic limits for when natural ventilative cooling can be supplied in Living Lab has been chosen for the present window design. When using these limits in a control algorithm, simulations showed that thermal comfort could be achieved for 98.9 % of the annual hours of occupancy, with only a 0.6 % annual increase in energy for heating. Simulations with other window designs showed that it was possible to improve the cooling effect and energy efficiency by applying ventilative cooling in more rooms at the same time, but the energy consumption for heating was still increased by 0.4 % per year. It was possible to reduce the total energy consumption for heating and ventilation by using natural ventilation alone when the outdoor conditions allowed it. If the mechanical ventilation system was turned off when outdoor temperatures exceeded 14 °C, thermal comfort and good indoor air quality was achieved, while the total energy consumption for heating and ventilation was reduced by 2.2 % per year.

Sammendrag

Godt isolerte bygninger, som nullutslipps hus, har høy forekomst av overoppheting selv i kalde klima. Det er viktig å ha kjølesystemer installert i slike bygninger for å oppnå termisk komfort for folk som oppholder seg i bygningen, men den høye energibruken knyttet til mekanisk kjøling gjør det vanskelig å nå nullutslipps-målet. Denne masteroppgaven undersøker muligheten for å bruke naturlige ventilasjons-prinsipper for å tilføre ventilativ kjøling til et nullutslipps hus i kaldt klima. Fokuset har vært å tilføre naturlig ventilasjon gjennom vinduer uten å skape lokal termisk ubehag som trekk – men fremdeles klare å kjøle ned bygningen. Naturlig ventilasjon kan bli brukt isteden for mekanisk ventilasjon for å holde CO_2-nivået i inneluften nede. Det energisparende potensialet av å bruke kun naturlig ventilasjon når været tillater det har også blitt evaluert i denne oppgaven.

Living Lab er et nullutslipps hus bygd på NTNUs campus i Trondheim, og det har vært brukt som eksempelbygg i denne masteroppgaven. Eksperimenter har blitt utført i Living Lab for å bestemme hvordan naturlig ventilasjon kan bli brukt uten å føre til lokalt ubehag. En kontrollalgoritme for ventilativ kjøling tilført gjennom vindusåpninger har blitt foreslått, basert på eksperimenter, funn i litteratur og tidligere studier gjort i Living Lab. En bygningssimulasjonsmodell i IDA ICE har blitt brukt til å utvikle strategier for ventilativ kjøling og evaluere dem basert på termisk komfort, luftkvalitet og energibruk.

Klimatiske grenser for når naturlig ventilativ kjøling kan bli brukt i Living Lab med dagens vindusdesign har blitt foreslått. Når disse grensene ble implementert i en kontrollalgoritme viste simuleringene at termisk komfort kunne oppnås i 98.9 % av årlige oppholdstimer, med kun 0.6 % økning i energibruk for oppvarming per år. Simuleringer med nytt vindusdesign viste at det er mulig å øke kjøleeffekten og energieffektiviteten ved å tilføre ventilativ kjøling til flere rom på en gang, men energibruken for oppvarming økte fremdeles med 0.4 % per år. Det var mulig å redusere den totale energibruken for oppvarming og ventilasjon ved å bruke naturlig ventilasjon alene når utetemperaturene tillot det. Hvis det mekaniske ventilasjonssystemet ble skrudd av når utetemperaturen overskred 14 °C, kunne termisk komfort og god luftkvalitet oppnås samtidig som total energibruk for oppvarming og ventilasjon ble redusert med 2.2 % per år.

Table of contents

Chapter 1 Introduction

1.1 Motivation

Zero Emission Buildings (ZEB) are usually very well insulated, which leads to high occurrence of overheating. Cooling has to be applied to ensure thermal comfort for the occupants of the buildings. Mechanical cooling has a high energy consumption and is therefore not permitted by the Norwegian standards for domestic buildings (NS 3700:2013). This makes passive cooling methods, like ventilative cooling through natural ventilation, necessary to achieve thermal comfort. Natural ventilation can lead to local thermal discomfort if the system is not designed with care, and these problems are the largest in cool climates because high air velocities and low temperatures can cause draught.

In Norway, the building sector accounts for 40 % of the energy consumption (Sartori et al., 2009). In the EU, it has been estimated that 40 % of the total CO_2-emissions to the atmosphere comes from the building sector. To reduce the impact this sector has on the environment, the goal in both Norway and the EU is that all new buildings should be zero energy buildings by 2020 (The European parliament and the council of the European Union, 2012). To achieve this, it is important to find ways to reduce the energy consumption of buildings.

The motivation for this master's thesis has been to find an energy efficient way to apply ventilative cooling in a ZEB. The thermal comfort of the occupants is of high priority, focusing both on achieving a comfortable room temperature and reducing draught rates. Energy savings are related to avoiding the use of mechanical cooling and reducing the use of the mechanical ventilation system when possible.

1.2 Scope

The goal of this master's thesis is to investigate ways to apply ventilative cooling through window ventilation in a zero emission building. The primary goal is to achieve thermal comfort, with hygienic ventilation supplied by the mechanical ventilation system and ventilative cooling supplied by window ventilation. The secondary goal is to reduce the energy consumption by reducing the use of the mechanical ventilation system when it is possible to use window ventilation for both hygienic ventilation and ventilative cooling.

Living Lab is built as a part of the ZEB research project hosted by NTNU, and is designed to be a zero emission building. No mechanical cooling is installed, and ventilative cooling by window ventilation is the chosen cooling strategy (Goia et al., 2014). Living Lab has been used as an example building in this master's thesis to test different ways of applying ventilative cooling in a cold climate. There are different window types installed in Living Lab, and during this work the ventilative cooling potential of these windows is evaluated experimentally. How and when ventilative cooling through window ventilation can be used will be discussed, and the resulting thermal comfort and energy consumption evaluated with simulations. The sensitivity of the chosen strategy for ventilative cooling will be investigated for different cardinal directions of the building, different levels of insulation in the building and different climates. The thesis also examines whether a change of window design can improve the performance of the ventilative cooling system. Finally, the possibility of reducing the use of mechanical ventilation to save energy while still ensuring good thermal comfort and indoor air quality is evaluated.

Originally, there was an intention to experimentally test the performance of the final ventilative cooling strategy, and compare those results to the simulations. This has not been possible, partly due to a tight Living Lab schedule that limited the time each student or researcher could have access to the building. Combined with technical difficulties and delays during the experiments, there was too little time to develop and test the algorithm within only one semester.

1.3 Research questions

The following research questions will be answered in this master's thesis.

1. How should ventilative cooling be applied in a ZEB in a cold climate, such as Living Lab? What ventilation principles and control principles are the best choices?
2. How do the different windows in Living Lab influence the indoor thermal environment under different climatic conditions? How can the windows be opened without causing local thermal discomfort?
3. How much can ventilative cooling with the present windows in Living Lab reduce the hours of overheating?
4. How does ventilative cooling with the present windows in Living Lab influence the energy consumption for heating of the building?
5. How does the performance of the ventilative cooling change when the building is turned to different cardinal directions, has different levels of insulation or is located in different climates?
6. How do the windows in Living Lab perform compared to more appropriate windows for natural ventilation?
7. Can energy consumption be reduced by using natural hygienic ventilation in the warm periods of the year? How will this influence the indoor air quality and thermal comfort?

1.4 Methodology

First, a background study was done to establish relevant theory, choose the goals for the indoor climate, and learn more about how to apply ventilative cooling. A review of Living Lab and the previous studies done on the building was also done. These two chapters creates the background, which the work in this master's thesis builds on. The choice of ventilative cooling mode and control algorithm was based on this background study.

Experiments were conducted in Living Lab, measuring the indoor air velocities and temperatures. The results from the measurements were analyzed to choose appropriate window openings for the ventilative cooling system that did not compromise thermal comfort.

Simulations using IDA ICE software was used to determine the final details in the ventilative cooling control; which temperature sensors to use and the best window opening sizes. Simulations were also used to evaluate the effect of the ventilative cooling control in different scenarios, with different window designs, and when the use of mechanical ventilation was reduced.

Chapter 2 Literature review

The goal of this master's thesis is to study how to apply ventilative cooling in a Zero Emission Building to achieve a better indoor climate. A literature review has been conducted to establish the goals for the indoor climate and how to apply ventilative cooling. The literature review included in this chapter is based on the one done by Blandkjenn in the 2016 project work *"Ventilative cooling of Zero Emission Buildings (ZEB)"*, with some additions.

2.1 Indoor climate

The indoor climate consists of four components; thermal environment, atmospheric environment, acoustic environment and actinic environment (Nilsson and The Commtech, 2003). In this master's thesis, the thermal and atmospheric environments are in focus. This chapter presents the concepts of thermal and atmospheric environments, and the requirements for these environments to ensure comfort and health for the occupants of a building.

2.1.1 Thermal environment

The air temperature, radiant temperature, air velocity and relative humidity forms the thermal environment and are the important physical factors for the heat balance of a human. Human factors like levels of clothing and activity determines the desired thermal environment for thermal comfort (Nilsson and The Commtech, 2003). NS-EN ISO 7730 defines thermal comfort as "*that condition of mind which expresses satisfaction with the thermal environment*" (NS-EN ISO 7730:2005, p 10).

The PMV-PPD index developed by P. O. Fanger is used to evaluate the thermal environment. The predicted mean vote (PMV) is the predicted vote of a group of people on a thermal sensation scale with 7 values. (NS-EN ISO 7730:2005) The thermal sensation scale is presented in Table (2.1). Detailed formulas for calculating PMV for different activity levels, clothing levels and thermal environments can be found in NS-EN ISO 7730.

Table (2.1): Seven-point thermal sensation scale (NS-EN ISO 7730:2005)

	+3	*+2*	*+1*	*0*	*-1*	*-2*	*-3*
Thermal sensation	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold

Predicted percentage dissatisfied (PPD) is the predicted percentage of people who will vote Hot, Warm, Cool or Cold on the thermal sensation scale of Table (2.1). The PMV is an average of all votes, and there will always be some people who are dissatisfied - so when the PMV is 0 the PPD is 5 % (Nilsson and The Commtech, 2003). The PPD is given in NS-EN 7730 as a function of the PMV, shown in equation (1);

$$PPD = 100 - 95 * \exp\left(0.03353 * PMV^4 - 0.2179 * PMV^2\right). \quad (1)$$

The PMV-PPD index is used to establish acceptable ranges of the thermal environment, based on the intended use of the building and the chosen comfort class. There are three comfort classes as presented in NS-EN 15251, see Table (2.2).

Table (2.2): Three building categories (NS-EN 15251:2007)

Category I	Highest level of expectation. For building and zones used by fragile or sensitive people like young children, sick people or elderly.
Category II	Standard comfort class. Used in new or rehabilitated buildings.
Category III	Acceptable in already existing buildings.

Indoor environment conditions that fall outside of the three comfort categories can be accepted for short periods of the year. NS-EN 15251 defines that in the rooms that constitute 95 % of the hours of occupancy, an indoor climate parameter can be outside the allowed range for 3 % of the time of occupancy every day, week, month and year. Table (2.3) presents the amount of time this represents.

Table (2.3): Allowed deviation of indoor environment parameters (NS-EN 15251:2007)

	Daily	***Weekly***	***Monthly***	***Yearly***
Time of allowed deviation	43 minutes	5 hours	22 hours	259 hours

2.1.2 Thermal environment recommendations

In the heating season, the thermal environment is determined by the PMV-PPD index (NS-EN 15251:2007). The operative temperature ranges acceptable in a residential building during the heating season are presented in Table (2.4). The limits are applicable to spaces used for sedentary activities, such as an office or the living areas of a domestic building (NS-EN ISO 7730:2007). Categories A, B and C in NS-EN ISO 7730 correspond to categories I, II and III in NS-EN 15251.

Table (2.4): Design criteria for a residential building (NS-EN ISO 7730:2007)

Category	***Operative temperature in heating season [°C]***	***Draught rate [%]***
A	22.0 ± 1.0	< 10
B	22.0 ± 2.0	< 20
C	22.0 ± 3.0	< 30

The adaptive thermal model is applied in NS-EN 15251 to propose acceptable indoor temperatures outside of the heating season in buildings without mechanical cooling, where the acceptable indoor temperatures are given as functions of the continuous mean outdoor temperature (NS-EN 15251:2007). Figure (2.1) shows the upper and lower limits for the indoor operative temperature in the three building categories.

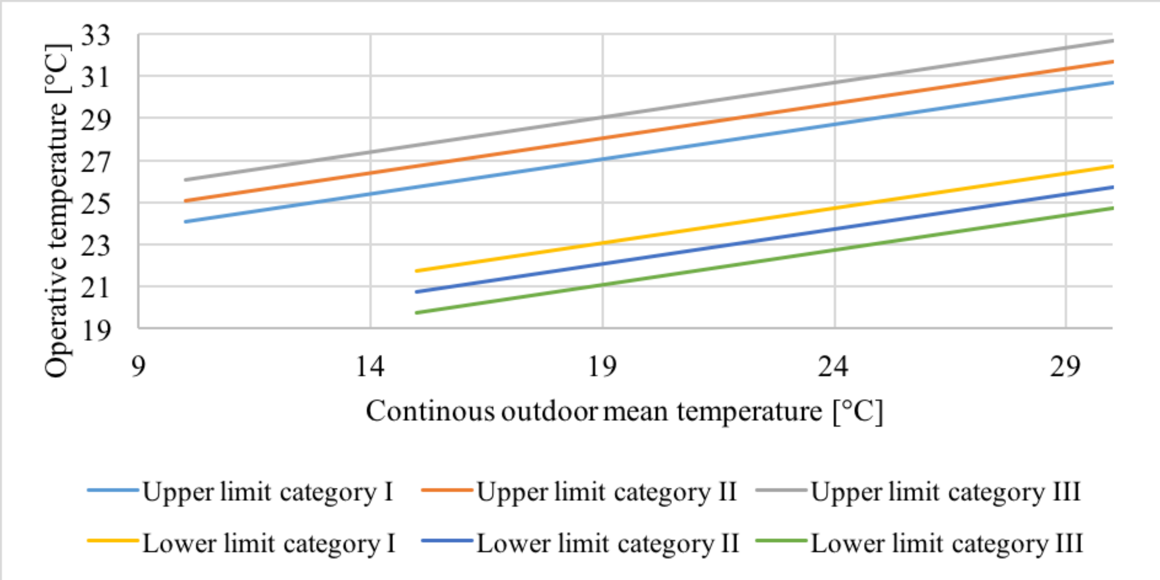


Figure (2.1): Limits to acceptable operative temperature (NS-EN 15251:2007)

Too high indoor air velocities can cause draught and dissatisfaction, even if the temperatures are within the recommended limits. Local cooling due to high air velocities is defined as draught (Nilsson and The Commtech, 2003). NS-EN ISO 7730 gives the following equation (2) for draught rate,

$$DR = (34 - T_{a,l})(\bar{v}_{a,l} - 0{,}05)^{0{,}62}(0{,}37 * \bar{v}_{a,l} * Tu + 3{,}14), \quad (2)$$

where DR is the draught rate in %, $T_{a,l}$ is the local air temperature in ^{o}C, $\bar{v}_{a,l}$ is the mean local air velocity in m/s and Tu is the local turbulence intensity. This formula is intended for use at 1.1 m above floor level (neck of a seated person), and might overestimate the draught rate when used closer to the floor (NS-EN ISO 7730:2005). Turbulence intensity is defined as the standard deviation of the local air velocity divided by the mean local air velocity (Nilsson and The Commtech, 2003). The acceptable draught rates in the three building comfort classes are presented in Table (2.4). It is estimated that air velocities above 0.19 m/s are outside of category comfort II for normal indoor temperatures in the cooling season (NS-EN 7730:2005).

Other parameters that influence the thermal comfort are humidity, vertical air temperature stratification, warm and cool floors, radiant asymmetry and temperature fluctuations. NS-EN ISO 7730 estimates that a 10 % increase in relative humidity corresponds to a 0.3 ^{o}C increase in operative temperature. NS-EN 15251 does not recommend humidifiers or dehumidifiers in normal buildings since the relative humidity only has a small effect on the perceived thermal environment. TEK10 states that an air temperature difference between head and ankles larger than 3-4 ^{o}C gives unacceptable thermal discomfort. Some other sources of local thermal discomfort are discussed in NS-EN ISO 7730. Warm or cold floor gives local thermal discomfort in the feet. Radiant asymmetry causes local thermal discomfort, especially warm ceilings or cold walls. Temperature fluctuations can cause thermal discomfort if the peak-to-peak variances are above 1K, or the temperature changes faster than 2 K/h. (NS-EN ISO 7730:2005)

2.1.3 Literature review of thermal comfort in super insulated domestic buildings

Berge and Mathisen (2016) did an evaluation of the thermal comfort in the Løvåshagen apartment complex with low-energy and passive house apartments outside of Bergen, Norway. The residents used manual window ventilation for cooling – and bedroom windows were on average open 10 hours each day in summer and 4 hours each day in winter. In general, the occupants were quite satisfied with the thermal environment, but there were many complaints about overheating in the bedrooms. On average, the bedrooms were kept about 2 ^{o}C colder than NS-EN 15251 recommends, and the bathroom was kept 1.5 ^{o}C warmer than recommended. This indicates that the recommendations in the standards differ can differ from the needs of the occupants. (Berge and Mathisen, 2016)

Kleiven (2007) performed a user survey on thermal comfort in the low-energy apartments Husby Amfi in Stjørdal, Norway. Even though building standards allow higher indoor temperatures in summer, the respondents of the survey preferred higher indoor temperatures in winter. Most people preferred indoor temperatures in the living areas of 20 – 22 °C in summer, and 22 – 24 °C in winter. In summer, 63.2 % of the respondents said that they had experienced too high indoor temperatures, and the most common way to combat this was to open windows and doors. The preferred indoor temperature in the bedrooms was 16 – 18 °C in winter, and 73 % of the respondents kept the bedroom windows open every night or some nights in winter. (Kleiven, 2007)

Mlecnic et al. (2012) did a review of end-user experiences in different nearly zero-energy houses in Germany, Austria, Switzerland and Netherland. Generally, the thermal comfort in winter was very good, while complaints about over temperatures in summer were more common. In one building, 40 % of the respondents had had to install extra solar shading. The bedrooms and living rooms were the ones where most people complained about high temperatures, and especially if the rooms were oriented toward south. Mlecnik et. al. concluded that sufficient summer comfort is important to get people to accept these highly insulated buildings, and that ensuring the quality of the heating and ventilation systems as well as giving proper instructions for the end users could help solve some of the problems. (Mlecnik et al., 2012)

2.1.4 Atmospheric environment

A good atmospheric environment means a good indoor air quality (IAQ) with acceptable levels of pollutants in the air. Air pollution in a building comes from the building materials, the outdoor air and from people and processes in the building. A bad IAQ can lead to discomfort or health issues for the occupants of the building. Odors or high levels of CO_2 causes discomfort, and harmful pollutants can cause health issues like allergies, infections or even cancer. To keep the IAQ in a building at acceptable levels it is necessary to ventilate it. (Nilsson and The Commtech, 2003)

To assess the IAQ, an acceptability scale is used where people rate the IAQ on a scale from clearly acceptable to clearly not acceptable. The average score (ACC) is calculated between -1 and 1, and can be used to calculate the percentage of people dissatisfied (PD) with the air quality with equation (3) (Nilsson and The Commtech, 2003).

$$PD = \frac{e^{(-0,18-5,28*ACC)}}{1+e^{(-0,18-5,28*ACC)}} * 100\ \% \tag{3}$$

2.1.5 Atmospheric environment recommendations

CO_2-concentration is a way of assessing the indoor air quality in a residential building, where humans are one of the main sources of pollution. NS-EN 15251 suggests limits to the difference in indoor and outdoor CO_2-concentration for the three building categories presented in Table (2.5).

Table (2.5): Acceptable CO_2-concentration (NS-EN 15251:2007)

Category	***PD [%]***	***Difference between indoor and outdoor CO_2-concentration [ppm]***
I	15	350
II	20	500
III	30	800

TEK 10, chapter 13 states that the ventilation rate in a residential building during normal use should be at least 1.2 m^3/h per m^2 of floor area, or 26 m^3/h per person sleeping in the building. This will cover both the CO_2-emissions from humans and emissions of pollutants from materials. (TEK 10 Chapter 13, 2010)

2.2 Ventilative cooling

This section presents ways to apply ventilative cooling and ventilative cooling potential in different climates.

2.2.1 Applying ventilative cooling

Ventilative cooling can be applied by mechanical ventilation, natural ventilation or a combination of the two – hybrid ventilation. The cooling happens when the warm air in the building is replaced with cooler outdoor air, or when increased indoor air velocities makes the air feel cooler for the occupants in the building. (Kolokotroni and Heiselberg, 2015)

Mechanical ventilation uses fans to supply and extract air from the building, and is a reliable source of fresh air. Because of the possibility to recover heat from the extract air to the supply air, mechanical ventilation is an energy efficient choice in cold periods. However, increasing the mechanical ventilation airflow rates in a ventilative cooling scenario will increase the energy consumption of the AHU fans. Natural ventilation uses only natural driving forces. Therefore, it is an energy efficient choice when outdoor temperatures are high and heat recovery is of less importance. On the other hand, natural ventilation is unstable and highly reliant on weather conditions that are outside of human control. (Novakovic et al., 2012)

A hybrid ventilation system uses both natural and mechanical ventilation principles, and the operation mode varies according to the season or the time of day. Hybrid ventilation gets the benefits from both natural and mechanical ventilation. The natural ventilation reduces energy consumption of the fans in the warm periods – while the mechanical system ensures a reliable source of fresh air and the possibility for heat recovery in the heating season. The disadvantage of using hybrid ventilation is that two ventilation systems has to be designed and installed. (Heiselberg, 2002)

2.2.2 Ventilative cooling potential in different climates

In Norway, 100 % of the cooling need can be covered by ventilative cooling, either by increasing the airflow from the mechanical ventilation system or by applying natural ventilation (Kolokotroni and Heiselberg, 2015). A study done by Finocchiaro et al. (2010) on buildings located in Oslo, Gothenburg and Copenhagen concluded that natural ventilation as a cooling method has higher potential in warmer climates, and that even small increases in outdoor temperature will have significant effect on the cooling potential. A higher potential in this case means that ventilative cooling is able to reduce the hours of overheating by a higher percentage. The same study also found that higher insulated buildings had a higher potential for ventilative cooling, because of the larger occurrence of overheating (Finocchiaro et al., 2010). A 2014 study done on a passive house in Denmark showed that natural ventilation could reduce the hours of mechanical ventilation by 90 % in the summer months, and also reduce the hours of thermal discomfort by 90 % (Oropeza-Perez and Østergaard, 2014). These findings show that it is possible to use ventilative cooling for ventilative cooling in moderate and cool climates.

In warmer climates, the need for cooling is large and the hours of overheating many. Studies have shown that ventilative cooling through natural ventilation can reduce the hours of overheating in the Mediterranean climates of both Cyprus (Michael et al., 2017) and Corsica (Faggianelli et al., 2014). Oropeza-Perez (2015) studied natural ventilative cooling in the central region of Mexico and found that thermal comfort could be achieved 90 % of the time using only this cooling method. The study suggested that using natural ventilation could reduce the energy consumption for cooling by 96.5 %. (Oropeza-Perez, 2015)

2.3 Natural ventilation

Natural ventilation uses natural driving forces to achieve air circulation. Air can enter and exit the building through vents, windows or ductwork. (Novakovic et al., 2012) When the outdoor air is colder than the indoor air, natural ventilation due to wind pressure or the stack effect can be used as ventilative cooling by lowering the indoor air temperature. When the outdoor and indoor temperatures are about the same, wind-driven ventilation can be used as ventilative cooling by increased air velocities. (United Nations Centre for Human Settlements, 1990) If there are openings on both sides of the room or building, there will be cross ventilation. If openings are on only one façade, it is called single-sided natural ventilation. (Allard, 1998) Figure (2.2) shows examples of different types of cross or single-sided natural ventilation.

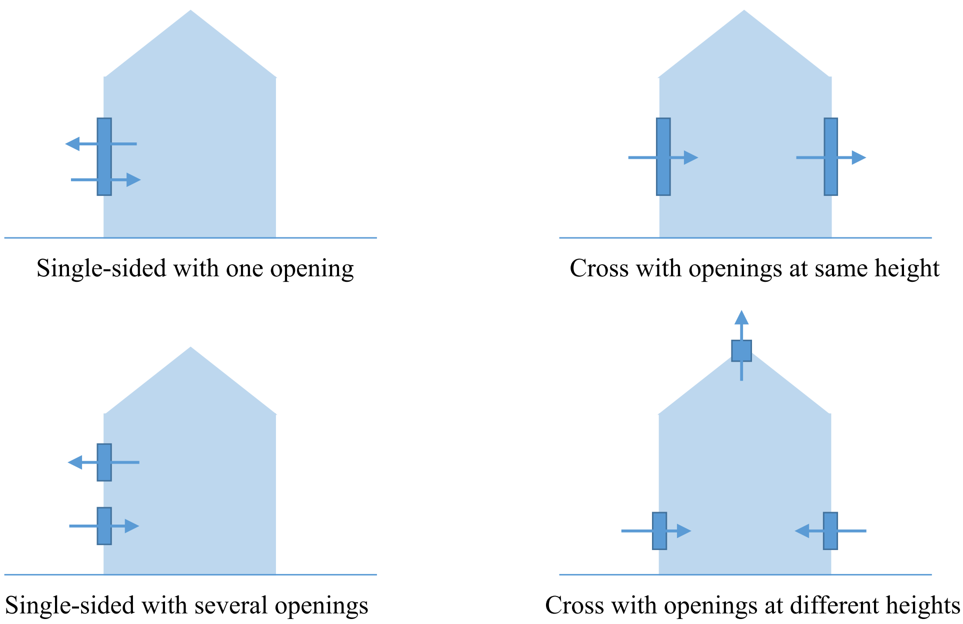


Figure (2.2): Examples of cross and single-sided natural ventilation

2.3.1 Stack effect

The stack effect is an effect of buoyancy, utilizing the fact that cold air is denser than warm air. Inside a building, there will be an overpressure at ceiling level and an under pressure at floor level – if the outside air is colder than the inside air. If there are openings in the façade at ceiling and floor level, cold air will enter the building at floor level and warm air will exit the building at ceiling level (Novakovic et al., 2012). This is presented in Figure (2.3). If the outside air is warmer than the inside air, the warm air in the upper zone of the room will be pushed back down to the zone of occupancy. This is unwanted in a cooling situation and the stack effect cannot be utilized for ventilative cooling in that case (Allard, 1998).

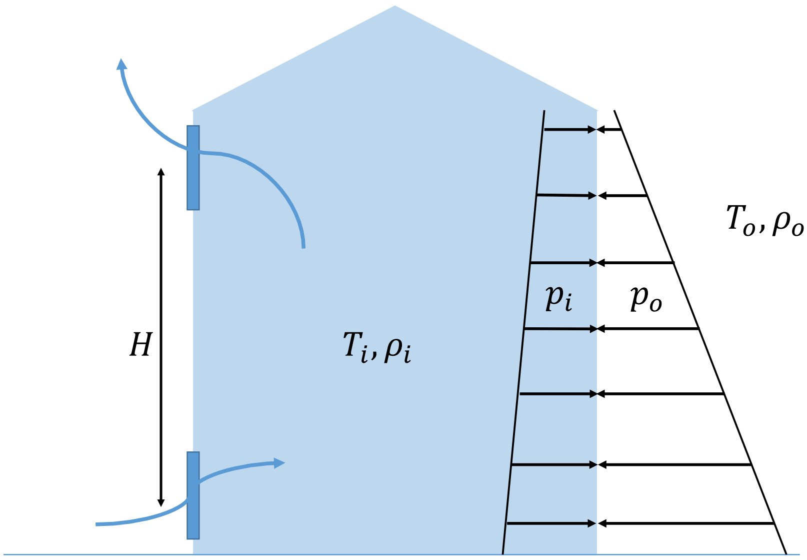


Figure (2.3): Stack effect in single-sided ventilation with two openings (Allard, 1998)

The driving pressure of the stack effect with two window openings like in Figure (2.3) is the pressure difference between the indoor and outdoor air at the height of the highest window opening. The driving pressure, Δp, is expressed as in equation (4);

$$\Delta p = \rho_o g H (T_i - T_o)/T_i, \tag{4}$$

where ρ_o is the density of the outdoor air in kg/m^3, g is the standard gravity 9.81 m/s^2, H is the height between the windows in m, T_i and T_o is the indoor and outdoor temperatures in K and T_m is the average of the indoor and outdoor temperatures in K (CoolVent, 2017). The airflow rate will increase with the total opening area of the windows, the height between the openings and the temperature difference between the indoor and outdoor air (Allard, 1998). To best utilize the stack effect, window openings should be placed both at floor level and ceiling level and the ceilings should be vaulted (Northern Regional Building Research Institute, 2015).

Perén et al. (2015) performed a CFD-study of ventilation efficiency with windows at different heights and different roof angles. It showed that roof angle had a larger influence on the ventilation efficiency than the height between the inlet and outlet windows, and that a 45 ° inclined roof could increase airflow rates by 25 % compared to a flat roof. Increasing the height difference between the openings could increase the airflow rate by 2 – 4 %. (Perén et al., 2015)

Schulze and Eicker (2013) performed another study of ventilation efficiency in a small office with different window configurations. During single-sided ventilation, using two small windows at different heights in the façade performed better than having one larger window on the middle of the façade. Using only one small window performed poorly, and could only provide air change rates to remove pollutants, not enough to use for ventilative cooling. Generally, buoyancy-driven or wind and buoyancy-driven cross ventilation gave higher air change rates than single-sided buoyancy-driven ventilation. (Schulze and Eicker, 2013)

2.3.2 Wind pressure

Wind creates an overpressure on the windward side of a building, and an under pressure on the leeward side of the building. The difference between these pressures will drive the air through the building if there are openings in the façades (Novakovic et al., 2012). The driving pressure of wind-driven natural ventilation, Δp_w, is expressed as equation (5)

$$\Delta p_w = \frac{1}{2}\rho_o v_w^2 (C_{w1} - C_{w2}), \tag{5}$$

where ρ_o is the density of the outdoor air in kg/m^3, v_w is the wind speed upstream of the building in m/s, and C_{w1} and C_{w2} are the wind pressure coefficients (CoolVent, 2017). Figure (2.4) shows how wind pressure will create air flow through a room with openings on opposite façades.

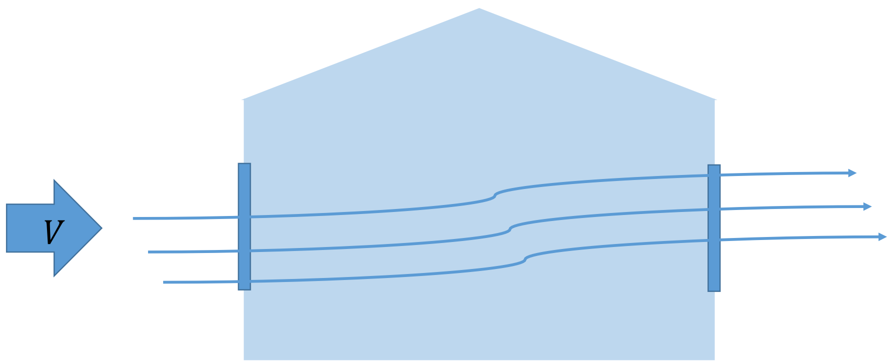


Figure (2.4): Cross natural ventilation due to wind pressure (Allard, 1998)

The airflow rates obtained from wind pressure are reliant of the wind speed, the size of windows and the layout of the building. The effect will be better if the windows are on opposite façades, than if they are on the same façade. (United Nations Centre for Human Settlements, 1990) To maximize the effect of wind-driven natural ventilation, large, wide-opening windows should be placed on as many façades as possible to accommodate for changing wind directions, and there has to be large openings between rooms so that the air can move through the building (Northern Regional Building Research Institute, 2015).

In Larsen's Ph.D. thesis from 2006, the air change rate with cross and single-sided ventilation was experimentally tested with different wind speeds and wind incident angles. During cross ventilation, air change rates increased with wind speed and was largest when the wind hit the windows perpendicularly. At an air speed of 5 m/s the air change rate with cross ventilation was about twice that of single-sided ventilation when the incidence angle of the wind was near 0 °. (Larsen, 2006)

Unless there is absolutely no wind or the indoor and outdoor temperatures are equal, a combination of stack effect and wind pressure will drive the natural ventilation. It is easier to calculate the airflow when there is one dominating driving force. When the stack effect and the wind pressure contribute equally it is difficult to predict the airflow and even complex CFD-calculations give uncertain results (Fracastoro et al., 2002).

2.3.3 Performance of different window types in natural ventilation

Window ventilation is a simple and practical choice for ventilative cooling, because most buildings have windows installed. The window type will affect the ventilation efficiency and the airflow in the room (von Grabe et al., 2014). Generally, ventilation supplied by windows gives higher thermal discomfort than other ventilation supply units (Heiselberg et al., 2001). Figure (2.5) presents the window opening types discussed in this section.

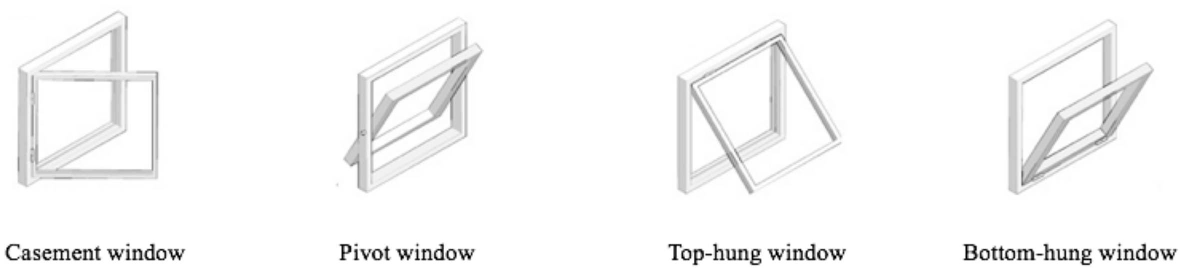


Figure (2.5): Types of window openings

A study done by von Grabe in 2014 investigated the ventilation efficiency of different window in single-sided natural ventilation. The study concluded that casement and pivot windows gave larger air flow rates and better ventilation efficiency than top-hung and bottom-hung windows. The casement window was the best choice for ventilation efficiency when openings areas were large, but for small opening areas it performed worse than top-hung windows. (von Grabe et al., 2014)

In a 2008 study of an office building with different types of windows for manual ventilation, Herkel et al. found that bottom-hung windows were left open for longer periods of time than larger windows, often for several days at a time (Herkel et al., 2008). This could be due to the fact that this type of window reduced the occurrence of draught and produced a more comfortable airflow pattern (Roetzel et al., 2010).

A study done by Heiselberg et al. (2001) compared the obtained airflows when using a large casement window and a smaller bottom-hung window. When a casement or a bottom-hung window was used in single-sided ventilation, the airflows from the windows were small and fell directly to the floor. When the casement window was used in cross ventilation, the airflow was large and continued straight into the room before it fell slowly to the floor. Because of this, there was a high risk of draught, and casement windows were not preferred in natural ventilation systems. The bottom-hung windows performed well in the cross-ventilation scenario. The air from the window behaved similarly to a line jet, where the jet sticks to the ceiling and is heated by the room air before it enters the zone of occupancy. Traditional jet equations could be used to calculate the air velocities and temperatures in the jet. (Heiselberg et al., 2001) The jet equations (6) for line jets are

$$U_m = U_0 \left[\frac{\rho_0 * i * A_0}{\rho_r * \varepsilon * A_s * I_4} \right]^{\frac{1}{2}}$$

$$\Delta T_m = \Delta T_0 \left[\frac{I_4 * \varepsilon * U_m}{I_3 * i * U_0} \right] \tag{6}$$

$$U_0 = q_o / A_0$$

$$A_s = 2 * \tan\alpha * (x + x_p) * B,$$

where U_m is the mean air velocity in the middle of the jet at distance x from the inlet in m/s, U_0 is the mean air velocity in the inlet in m/s, A_0 is the inlet area in m^2, A_s is the area of the jet at distance x from the inlet in m^2, ΔT_m is the temperature difference between the room air and the jet at distance x from the inlet in K, ΔT_0 is the temperature difference between the room air and the inlet air in K, q_0 is the air flow at the inlet in m^3/s, x is the distance from the inlet in m, x_p is the distance from the inlet to the virtual start of the jet in m and B is the width of the inlet opening in m. Additionally, ρ_0 is the density of the outside air in kg/m^3, ρ_r is the density of the inside air in kg/m^3, i is the momentum loss coefficient, ε is the contraction coefficient, I_3 and I_4 are moments of inertia and α is 12.5 ° (Skåret, 2000).

2.3.4 Thermal comfort in buildings with natural ventilation

Modern buildings with advanced technical systems increases the user's expectations and desires when it comes to the indoor climate (Brager and de Dear, 1998). The PMV-PPD index gives a good prediction for observed comfort temperatures in mechanically ventilated buildings, but not in buildings with natural ventilation. The reason is psychological; in naturally ventilated buildings the user feels a larger sense of control and will allow higher temperatures (de Dear and Brager, 2002). Giving users greater control of the indoor climate and letting indoor temperatures follow the trend of the outdoor temperature gives higher user satisfaction. People living in naturally ventilated buildings will recognize the varying temperature and adjust their expectations for the building performance accordingly, so that they not only tolerate these fluctuations but come to prefer them (Brager and de Dear, 1998). However, the occupants do not want to work too hard to maintain the indoor climate. Ideally, the building management systems does the job while the occupant feels like he is in control (Mishra et al., 2016).

This approach to thermal comfort is called the adaptive thermal model. Traditionally, human thermal comfort has been determined by measuring the heat exchange between a person and the environment in a laboratory (Humphreys and Nicol, 1998). The basis of the adaptive thermal model is that a person is not a passive receiver of the indoor climate, but interacting with the indoor climate through behavioral adjustment, physiological acclimatization and psychological expectation. In the built environment, behavioral adjustment and psychological expectation are the most important factors (Brager and de Dear, 1998).

2.4 Controlling natural and hybrid ventilation

This chapter presents possible control principles for window operation and operation modes of a hybrid ventilation system.

2.4.1 Control principles

One group of controls is the feedback controls, which uses the measured value of the control parameter to determine the reaction from the system. The most common feedback control principle is the on-off control. An on-off control system for window ventilation will open the windows when the control parameter reaches a certain value, and close the windows when the parameter reaches another value. Other feedback control principles are proportional (P), proportional and integral (PI) and proportional, integral and derivative (PID) control. The P-control increases the reaction from the system when the error between the measured value and setpoint value increases. PI- and PID-controls have a higher complexity, and account for the rate of change in the system in addition to the error from the desired value. A more complex control principle will give a more accurate result, but that might not always be necessary. (Nilsson and The Commtech, 2003)

Another group of controls is feed forward controls, which uses predictions and forecasts to determine the reaction of the system. In a ventilative cooling situation, a feed forward control could use the weather forecast and knowledge of the thermal response of the building to anticipate and prevent overheating. (Nilsson and The Commtech, 2003)

The criteria for a good control system is accuracy, speed and stability. A good control of a ventilative cooling system should give the right indoor temperature, without long delay or large fluctuations in temperature. People have wide comfort ranges, and simple on-off controls are often enough to keep the indoor environment at acceptable levels. (Nilsson and The Commtech, 2003) According to a study by Schultze and Eicher in 2013, simple control strategies performed just as well as complex ones when controlling natural ventilation in energy efficient buildings. In fact, the choice of set points was more important than the choice of control strategy. The study also concluded that it is important that the user has power to override the control system. (Schulze and Eicker, 2013) Feed forward controls that take into account the building's thermal properties and weather prognosis perform even better than simple controls. However, to justify using a feed forward control, an accurate thermal model of the building has to be made to be able to predict how the building will react to changing boundary conditions (Spindler and Norford, 2009).

2.4.2 Operation modes of hybrid ventilation system

In a hybrid ventilation system, the control system switches between the mechanical and natural ventilation mode. The natural and mechanical ventilation can work together at the same time (concurrent mode), or have change-over operation where the control system changes between mechanical and natural ventilation according to predetermined setpoints. In a hybrid ventilation system, different controls for winter, summer and shoulder seasons should be established, to accommodate for different priorities in different seasons. In cold climates, the hybrid ventilation system should focus on minimizing ventilation energy in winter, and eliminating the need for mechanical cooling in summer and shoulder seasons. (Heiselberg, 2002)

Dhalluin and Liman (2012) did a study of two classrooms in La Rochelle, France where the thermal comfort and energy consumption of four different operational modes of a hybrid ventilation system was measured. The operation modes were manual window operation, automatically controlled windows, and manual or automatic windows with concurrent mechanical ventilation. The automatic window operation mode gave the best thermal comfort in summer and the lowest energy consumption, but could give too low air change rates in warm weather. Using concurrent mechanical and natural ventilation gave generally better IAQ, but lower user satisfaction than change-over operation. This study was done in classrooms with a high occupancy, so the result may be different for a domestic building with lower internal heat gain from occupants. In that case, using windows alone might increase the energy consumption for heating more because of the large airflows during window ventilation. (Dhalluin and Liman, 2012)

2.5 Reference buildings with ventilative cooling through windows

This sections presents some of the ventilative cooling solutions and control systems used in reference buildings in IEA's Annex 62 "*Ventilative Cooling State-of-the-art review"* from 2015, and IEA's Annex 35 "*Hybrid Ventilation State-of-the-art review"* from 2002. The buildings in this section are located in northern Europe, where temperatures are low at least parts of the year, and uses windows to supply natural ventilation or ventilative cooling. A summary of the setpoint for opening windows is also included in this section.

2.5.1 Domestic buildings

Energy Flex House is a n-ZEB family house in Denmark that uses natural ventilation for parts of the year. Natural ventilation starts when indoor temperatures reach certain levels, 24 °C in summer and 25 °C in winter. When the house is unoccupied, the ventilation strategy is focused on saving energy, and when it is occupied the focus is to achieve a good indoor climate. The skylights close when it is raining, and the facade windows close when the wind velocity on the façade is above 7 m/s. (Kolokotroni and Heiselberg, 2015)

Home for Life is a low energy family house in Denmark, and has automatic windows that are used for ventilative cooling. Window are installed on the façades and in the roof, so both cross- and single sided ventilation is possible, and both the stack effect and wind pressure can drive the ventilation. Ventilative cooling is used in the summer, and indoor temperatures and outdoor climate determines the window positions. The system works well, and there is no occurrence of over-heating in summer. The month with the most over-heating is March – underling the importance of a sensitive control in the shoulder season. (Kolokotroni and Heiselberg, 2015)

Maison Air et Lumiere is a high-performance domestic building located in France and uses the same type of windows and control system as Home for Life. This building uses natural ventilation in summer and in cases of overheating in winter, and there was very little occurrence of over-heating in summer. (Kolokotroni and Heiselberg, 2015)

2.5.2 Schools and kindergartens

Mellomhagen school in Norway was retrofitted with a hybrid ventilation system in 2010. It switches to natural ventilation when the indoor temperature or CO_2-concentration is above certain levels - 21 °C in winter, 22 °C in summer and 1300 ppm all year. The ventilation is wind-driven. They found that the CO_2 levels had to be a higher priority than they first thought, and that they had to focus more on the IAQ than energy reduction. (Kolokotroni and Heiselberg, 2015)

Solstad kindergarten in Norway uses natural ventilation in the summer, and in winter when the mechanical ventilation system is unable to control the CO_2 concentration alone. Window operation is allowed at indoor temperatures above 19 °C in winter and 21 °C in summer. It has been reported that the mechanical ventilation system rarely operates in summer, because of the higher ventilation need for cooling than for removal of pollutants. (Kolokotroni and Heiselberg, 2015)

2.5.3 Office buildings

The Pihl & Son company headquarter in Denmark only has mechanical ventilation in meeting rooms, bathrooms and kitchens. The rest of the building is naturally ventilated - normally through window openings. The windows are open 10 to 60 minutes at the time depending on outdoor temperature. If the outdoor temperature exceeds 20 °C, the windows are automatically controlled by the indoor temperature. This is because the risk of undercooling is non-present when the outdoor temperature is so high. When the stack effect is not strong enough, fans assist the ventilation. Occupants are generally satisfied, but there have been complaints about draught on the bottom floor of the two-story atrium. Strong winds and rain overrules the system and the windows are closed. (Delsante and Vik, 2002)

The police station on Schoten, Belgium uses stack natural ventilation for cooling and hygienic ventilation. The windows open when the CO_2-concentration is above 900 ppm and closes at 600 ppm. The minimum outdoor temperature for opening windows is 12 °C. Ventilative cooling start when indoor temperatures exceed 24 °C. Exhaust opening in an atrium are opened whenever a window is opened in one of the offices. This cooling method gave good results. The windows are closed if there is rain or winds above 10 m/s. (Kolokotroni and Heiselberg, 2015)

The CIT ZERO 2020 office building in Cork uses single-sided natural ventilation. Windows are opened when indoor temperatures exceed 21 °C, as long as the outdoor temperature is above 15 °C. The natural ventilation system has gotten positive user feedback, even though the indoor temperatures often exceeded the recommendations from building standards. (Kolokotroni and Heiselberg, 2015)

2.5.4 Summary of setpoints for window ventilation in example buildings

All of these reference buildings used natural ventilation when the outdoor temperatures, indoor temperatures or CO_2-concentrations are above certain set points. Table (2.6) sums up these.

Table (2.6): Setpoints for natural ventilation controls in example buildings

	Required temperature for window openings		***Required CO_2-concentration for window openings***
	Outdoor	***Indoor (summer/winter)***	
Energy flex house	-	24 °C / 25 °C	None
Home for life	-	-	-
Maison air et lumiere	-	-	-
Mellomhagen school	-	22 °C / 21 °C	1300 ppm
Solstad kindergarten	-	21 °C / 19 °C	-
Pihl & Son	20 °C (total switch)	-	None
Police station Schoten	12 °C	24 °C	900 ppm
CIT ZERO 2020	15 °C	21 °C	None

None of the domestic buildings used CO_2-concentration to control windows. This is more important in schools and offices with high density of people. All the buildings with the possibility to use a mechanical ventilation system had an indoor temperature limit for when to open windows. These setpoints were higher in domestic buildings because of the higher heating need.

Chapter 3 Living Lab

This chapter presents Living Lab, focusing on the aspects of Living Lab most relevant for ventilative cooling, and is an edited version of the same chapter in Blandkjenn's project work from 2016. A more thorough description of the building can be found in *The ZEB Living Laboratory at the Norwegian University of Science and Technology: a zero emission house for engineering and social science experiments* by Goia et al. (2015), which most of this chapter is based on.

3.1 Background

Living Lab is a Zero Emission Building built on NTNU Gløshaugen university campus in Trondheim, as a part of the Research Centre on Zero Emission Buildings (ZEB). It is a single family home with a floor area of 100 m^2, and a gross volume of 500 m^3. Many state-of-the-art solutions are installed in the building to test different technologies for energy supply and conservation. The aim of Living Lab is to demonstrate how to realize a CO_2-neutral building in the cold, Norwegian climate. Test families have occupied the building, to study the interaction between the user and the building. (Goia et al., 2015)

Figure (3.1): Living Lab. Picture by Solveig Blandkjenn

3.2 Architecture and materials

The architect of Living Lab is Luca Finocchiaro, Associate Professor at NTNU (The Research Centre on Zero Emission Buildings (ZEB), 2017). The building has two bedrooms, an entrance, a bathroom and a large open living area consisting of a living room, a kitchen and a home office on the ground floor. The layout of the building is open, and organized in two zones – living area towards the south and sleeping/working area towards the north. A mezzanine is placed over the small bedroom, and can be used as a guest room. Figure (3.2) shows the layout of Living Lab's ground floor. (Goia et al., 2015)

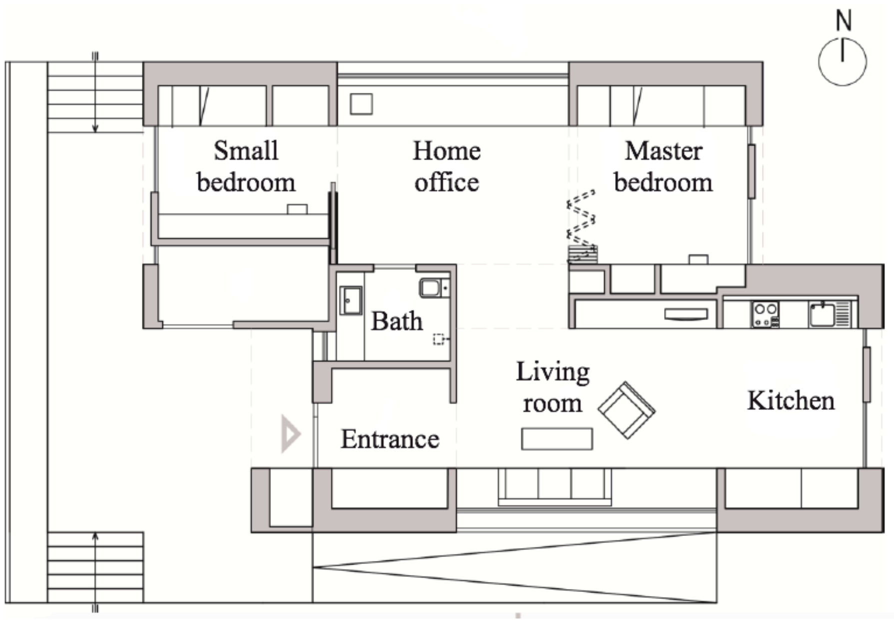


Figure (3.2): Floor plan of the ground floor of Living Lab.
Used with permission (Goia et al., 2015)

The main building material is wood, and the U-values of the walls, floor and roof are 0.11 W/m^2K, 0.11 W/m^2K and 0.10 W/m^2K, respectively. It is characterized as a construction with low thermal mass. (Goia et al., 2015) The roofs have a 30 ° slope, according to the architectural drawings (Bergersen Arkitekter, 2013).

3.3 Technical installations

A brine-to-water heat pump coupled with a ground heat exchanger supplies energy for heating and a water tank stores hot water to use for heating. Extra electric coils and a thermal collector on the south façade can be used in addition to the heat pump. PV-panels on the roof are designed to cover the energy need of the building and the energy embedded in the materials and components of the building, making Living Lab a ZEB. (Goia et al., 2015)

Two hydronic systems for space heating are installed, floor heating with a water temperature of 33 ^{o}C (Prosjektutvikling Midt-Norge AS, 2015), and a high-temperature (55 ^{o}C) radiator (Goia et al., 2015). It is also possible to use ventilative heating by supplying overheated air through the mechanical ventilation system. The reason for installing several solutions is to test the performance of different solutions in the same building. (Goia et al., 2015)

Living Lab has a balanced mechanical ventilation system with heat recovery from a rotary heat exchanger with 85 % nominal efficiency and additional electric heating coils. Supply units are placed in the living room and bedrooms and extracts are placed in the kitchen and bathroom. (Goia et al., 2015) Table (3.1) shows the airflow rates supplied and extracted from each room in Living Lab, these air flow rates were determined and validated in Blandkjenn's project work (2016).

Table (3.1): Airflow rates in Living Lab during normal occupancy

Supply	***Airflow rate [m³/h]***	***Extract***	***Airflow rate [m³/h]***
Small bedroom	52	Bathroom	78
Master bedroom	52	Kitchen	52
Living room	26		
Total supply	130	Total extract	130

3.4 Cooling strategies

3.4.1 Reducing solar gains

To reduce overheating, 90 m^2 of phase changing material (PCM) boards are installed in the sloped of the south-facing roofs of Living Lab. The purpose of the PCM-boards is to delay the entry of solar gains through the roof. (Goia et al., 2015) The PCM stores the extra energy as latent heat when temperatures in the roof are elevated, thus increasing the thermal mass of the structure. The heat is released when the temperatures decrease to normal levels. (Baetens et al., 2010)

In a large window in the living room there is installed solar shading to reduce solar gains. (Goia et al., 2015) In Risnes' master's thesis *Indoor Environment in ZEB Living Lab* from 2016 it was concluded that the solar shading was very effective in reducing the occurrence of overheating in Living Lab (Risnes, 2016).

3.4.2 Window ventilation

There is no mechanical cooling installed in Living Lab, and ventilative cooling is the chosen cooling strategy. Supplying it as natural window ventilation will keep the energy consumption low, compared to increasing the mechanical airflow rates. Some of the windows are equipped with electrical motors, making automatic window control possible. (Goia et al., 2015)

In the master's thesis "*Ventilative cooling in Living Lab*" from 2015, Kirkøen proposed a window ventilation strategy for Living Lab, based on IDA ICE simulations. Opening windows when the indoor temperature reached 24 ^oC and closing when it had decreased to 22 ^oC gave the least amount of undercooling and overheating. A PI-control did not improve the performance of the system, so the simpler on-off control principle was preferred. Solar radiation, outdoor temperature and occupancy was in that order the most determining factors of the cooling need in Living Lab. Wind did not have a big influence on the cooling effectiveness. Night-time ventilation was not found effective in reducing the hours of thermal discomfort, this is mainly because of the low thermal inertia of Living Lab. (Kirkøen, 2015)

In the fall of 2016, Blandkjenn carried out a project work to prepare for this master's thesis. The focus was to test the cooling effect of different window openings in Living Lab. Experiments were done for different weather conditions, and the conclusion was that using window ventilation was very effective for cooling even on warm days. Cross stack ventilation was more effective for lowering the indoor temperatures than cross wind ventilation, and opening the window on the north façade in combination with kitchen skylights gave the best cooling effect. The window in the south façade has a pre-heating function that reduced the cooling effect, and gave a negative effect on the warmest days. When the outdoor temperatures were low, only the skylights could be opened without causing local thermal discomfort. (Blandkjenn, 2016) In Risnes' master's thesis from 2016 it was concluded that the risk of draught is very high when the windows are opened in the shoulder season. (Risnes, 2016) The experiments done in Living Lab to date has mostly used large window opening sizes, so it is of interest to evaluate smaller window opening in a larger variation of weather conditions.

A presentation of the windows available for automatic control follows. The placements of these windows are shown in Figure (3.3). The heights above floor given in Figure (3.3) are the heights of the middle point of the windows. The areas and openable areas of the windows are presented in Table (3.2). As of today, there are only automatically controlled windows in the living areas and not in the bedrooms. There are large sliding doors in the bedrooms that cannot be included in an automatic control because of safety issues. (Goia et al., 2015)

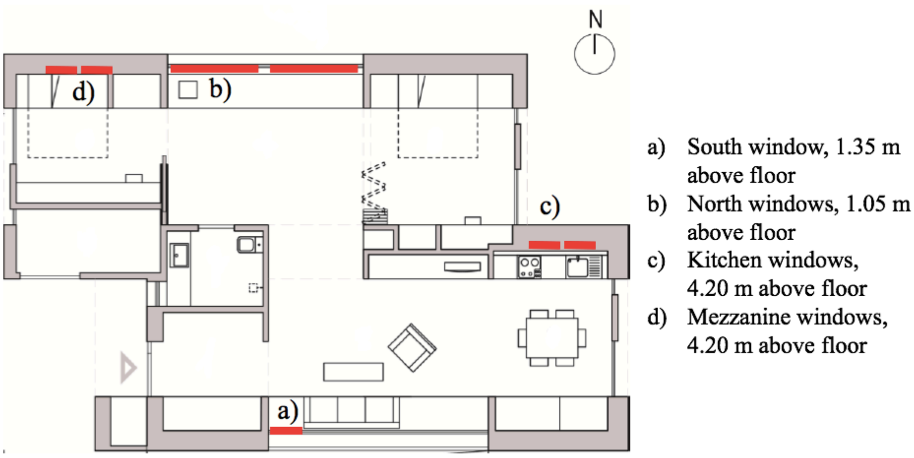


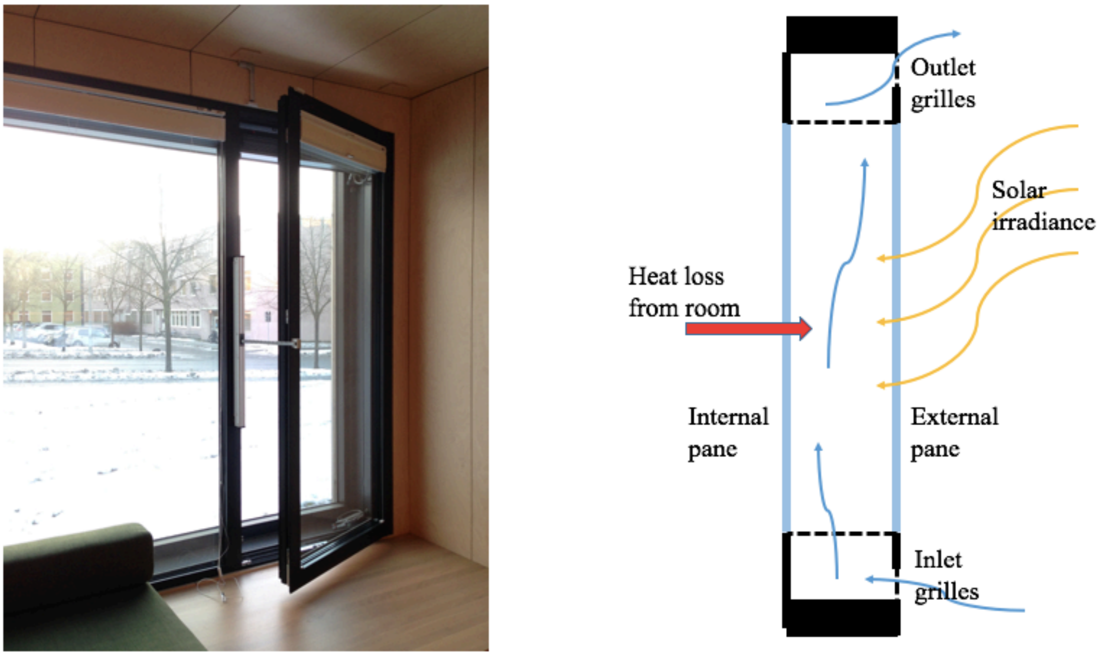
Figure (3.3): Position of automatically controlled windows in Living Lab

Table (3.2): Window areas and maximal openable areas

Window	***Number of windows***	***Area per window [m²]***	***Maximum openable area per window [m²]***
North	2	1.21	0.786
South	1	10.5	1.130
Skylights	4	0.484	0.338

3.4.2.1 South window

In the south façade in the living room there is a large ventilated double skin window (Goia et al., 2015). Double skin windows have two window panes, between which the outdoor air is heated by both the solar irradiance and the heat loss through the inner window pane, before it is mixed with the room air. This makes the double skin window a heat recovery system, utilizing heat that is otherwise lost through the window. (Carlos and Corvacho, 2013) Figure (3.4) shows a photo and a side view of the south window.



a) b)

Figure (3.4): The south window. a) During window opening, photo by Solveig Blandkjenn b) Sketch of how the outside air is heated between the two window panes when the window is closed (side view) (Carlos and Corvacho, 2013)

The window opening is controlled by a motor. Grilles at the top and bottom on the window let outdoor air into the double skin cavity, see Figure (3.4.b). In Blandkjenn's project work of fall 2016, it was found that the air entering the room from the double-skin window had been heated a few degrees compared to outdoor air. Those measurements were done in November, with outdoor temperatures below 0 °C and low solar irradiance. Experiments done on warm summer days indicated that air from the double-skin window was too warm to cool the building down (Blandkjenn, 2016). It is of interest to do further experiments on this window with higher temperatures and solar irradiance to determine when it can be used for ventilative cooling.

3.4.2.2 North window

Figure (3.5): North window.
Photo by Solveig Blandkjenn

In the north façade in the home office there are two top hung, outward opening windows right above a working station along the north wall. The two openable panes can be controlled separately by motors. Figure (3.5) shows one of the north windows. (Goia et al., 2015) This window type does not preheat the air so it gives a good cooling effect. However, this also leads to a high risk of draught.

3.4.2.3 Kitchen and mezzanine windows

Figure (3.6): Mezzanine windows
Picture by Solveig Blandkjenn

There are four pivot skylight windows in Living Lab, two in the kitchen and two on the mezzanine. The height difference between the skylights and the north and south windows mean that the stack effect can be utilized as a driving force for natural ventilation. Figure (3.6) shows the skylight windows on the mezzanine. (Goia et al., 2015)

3.5 Building management system and sensors in Living Lab

A LabVIEW program controls the data acquisition and building management system in Living Lab (Goia et al., 2015). This program can be used to control window openings, temperature set points, lights and many other things.

Integrated sensors in Living Lab measure indoor climate parameters like indoor temperatures, CO_2-concentration and relative humidity. Air temperatures in the rooms are measured by two sensors in the bedrooms, kitchen and bathroom – and by six sensors in the living room and in the home office. There are sensors in the ventilation system measuring temperatures of the air and air velocities. In the hydronic heating system, sensors measure temperatures, flow rates and energy delivered to the zones. The power supplied to each power outlet, as well as to fans, pumps and other equipment is logged. A weather station is placed on the roof of Living Lab. It measures wind speed and direction, air temperature, relative humidity, atmospheric pressure and global solar irradiance on the south façade and the PV panels. Air temperatures on the north and south façades are also measured. (Goia et al., 2015)

Chapter 4 Summary of findings from background study

Living Lab is a good subject for this thesis work because it is a zero-emission building with a large data acquisition system already in place – making it easy to conduct experiments and retrieve data. It has an open floor plan and height difference between the windows and the possibility to use cross ventilation, making it a good building to test natural stack ventilation. There are also different window types installed in the building, so it is possible to evaluate the performance of these windows against one another. (Goia et al., 2015) According to Perén et. al. (2015), the sloped roof of Living Lab will help to increase the air flow rates from natural ventilation.

It has been determined than comfort categories I and II are considered acceptable for Living Lab. This means that the indoor temperatures should be between 20 and 24 °C or as otherwise specified for a building without mechanical cooling in Figure (2.1). The draught rate should be below 20 %. Deviation from these requirements will only be accepted for 3 % of the hours of occupancy. NS-EN 15251 states that values outside of category III comfort are only accepted for 3 % of the time, so the requirements chosen for Living Lab are even stricter. Other parameters influencing thermal comfort will not be evaluated. Choosing these comfort criteria also means that the CO_2-concentration in the building should be less than 500 ppm above the outdoor air CO_2-concentration. It is more important that the building meets these comfort requirements than that the energy consumption is reduced.

Previous studies of Living Lab have shown that ventilative cooling is an effecting method of reducing the indoor temperatures (Kirkøen, 2015) (Blandkjenn, 2016). Stack ventilation was more effective than wind-driven ventilation (Blandkjenn, 2016), so the focus of this thesis will be to apply stack ventilation when outdoor conditions allow it. The air will be supplied to the living areas through the north or south window, and extracted through a kitchen skylight due to the stack effect. This is shown in Figure (4.1). When the outdoor temperatures are too low to supply air directly to the zone of occupancy, the two skylight windows in the kitchen will be opened to let out warm air from the south zone of Living Lab.

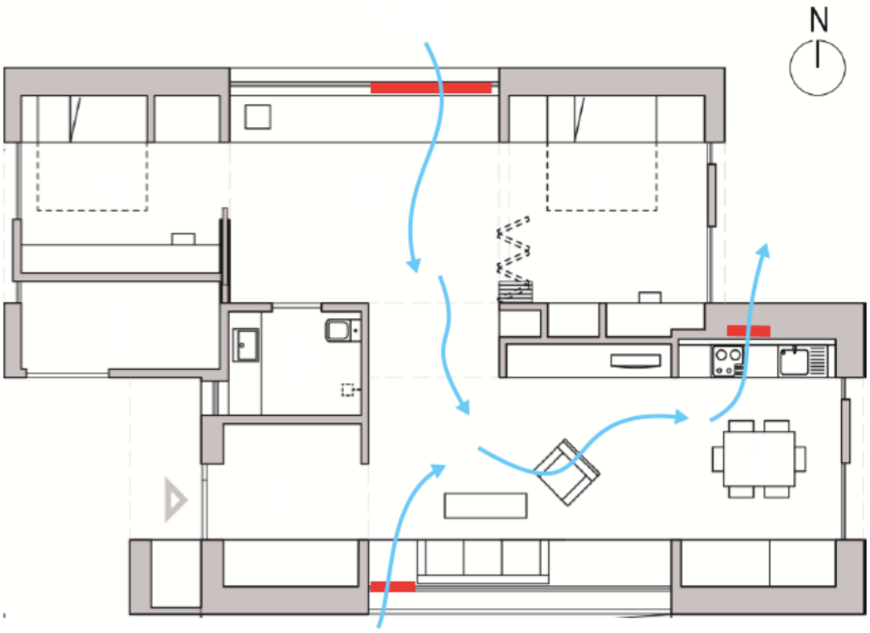


Figure (4.1): Air flows due to stack ventilation in Living Lab

Looking at the reference buildings presented in Chapter 2.5, most of them used indoor temperature, CO_2 concentration or both to determine the ventilation need in the building. Many of the buildings used simple control algorithms, like on-off controls or pulsed ventilation, while still achieving high user satisfaction. In Kirkøen's thesis from 2015 it was concluded that ventilative cooling in Living Lab should commence at 24 °C and stop at 22 °C, and that simple on-off control algorithms were as effective as more advanced controls. (Kirkøen, 2015). Based on Kirkøen's findings, it has been decided to move forward with an on-off control using daytime cooling, opening windows when indoor temperatures surpass 24 °C and close when the temperatures reach 22 °C. The shoulder season is the most critical season when there is both a cooling need and high risk of overcooling. Therefore, it was decided to do simulations primarily for the months of May and June in Trondheim. This means that the hours of thermal discomfort should be below 44 h for the two months combined.

There should be a limit for how low outdoor temperatures can be accepted during natural ventilation. The reference buildings in the literature review had different temperature limits, the lowest was 12 °C. It is of interest to find the climatic conditions that allow window ventilation from the different windows in Living Lab. Because of the heating capacity of the south window the limits will probably differ between the south and north windows. There will also be times when the south window has a negative cooling effect because of the pre-heating of air. Some of the reference buildings also had upper limits for wind speeds during window ventilation. The experiments done in Living Lab will be the basis for determining the limits for different climatic conditions during natural ventilative cooling. There has been measured high air velocities in Living Lab when the windows are open (Risnes, 2016), and the experimental work in this thesis focuses on finding window openings that keep the draught rates within the comfort requirements in different weather conditions.

Chapter 5 Setup for experiments in Living Lab

This chapter contains the details about the equipment used in the experiments in Living Lab, and the setup and execution of the experiments. The goal of the experiments was to find window openings that can be used for ventilative cooling without causing local thermal discomfort near the windows.

5.1 Equipment

The main measuring equipment used to evaluate local thermal discomfort was AirDistSys 5000 from Sensor Electronics. This equipment consists of a portable rig, see Figure (5.3), with omnidirectional transducers, see Figure (5.1), that measure the instantaneous speed of the air and the air temperature.

Figure (5.1): Transducer from AirDistSys 5000.
Picture by Solveig Blandkjenn

iButtons from Maxim Integrated Products were used to measure temperatures in the south window during some tests. Integrated sensors in Living Lab measured the indoor and outdoor temperatures, wind conditions and solar irradiance. See Table (5.1) for specifics on the equipment.

Table (5.1): Measuring equipment

Name	***Brand***	***Parameter***	***Range***	***Accuracy***
SensoAnemo5100SF	Sensor Electronic	Air temperature	-20 - +50 °C	±0.2 °C ±1% of readings
		Air speed	0.05 – 5.00 m/s	±0.02 m/s
DS 1920 iButton	Maxim Integrated Products	Air temperature	-55 - +100 °C	±0.5 °C
RTF-1 PT100 FRIJA II 1/3 DIN	S+S Regeltechnik	Indoor air temperature	0 – +50 °C	±0.2 °C at 25 °C
THERMasgard® RTF1 PT100	S+S Regeltechnik	Indoor air temperature	-30 - +70 °C	±0.1 °C
HD52.3D	Delta Ohm	Wind speed	0 – 60 m/s	±0.2 m/s
		Wind direction	0 – 360 °	±2 ° from 1 m/s
		Outdoor air temperature	-40 - +60 °C	±0.15 °C
LP PYRA 03 AC	Delta Ohm	Global solar irradiance	0 – 2000 W/m^2	±5 %

Sources: (Sensor Electronic, 2017), (Maxim Integrated, 2017), (S+S Regeltechnik, 2017), (Delta Ohm, 2016), (Delta Ohm, 2007) and (Goia, 2016).

5.2 Setup of equipment

5.2.1 South window

The experiments on the south window was done with the AirDistSys 5000 rig in different positions near the window to get a sense of the flow of air when the window is open. Figure (5.2) shows the points of measurements around the south window, seen from above. The gray area in Figure (5.2) is a 0.34 m high built-in bench under the window.

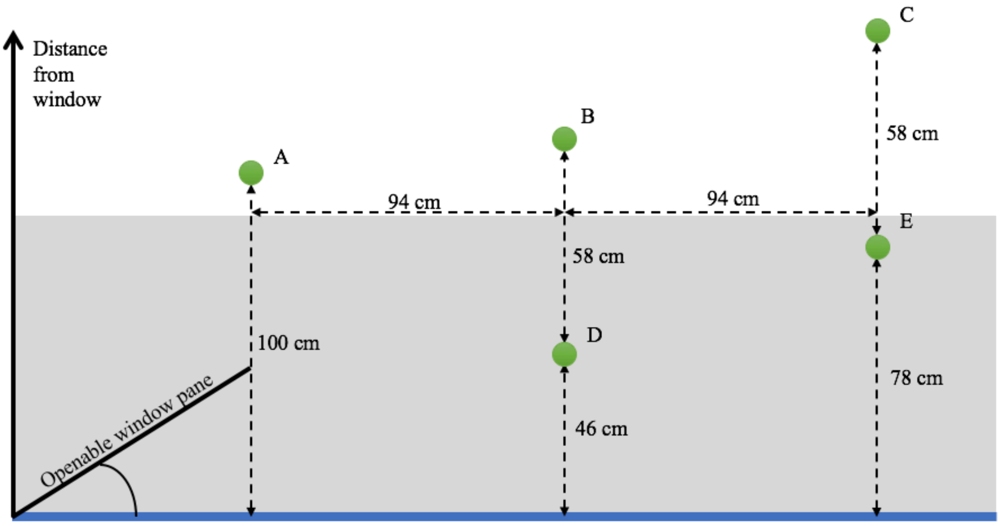


Figure (5.2): Points of measurements near the south window, seen from above

Transducers measured the air velocity and temperature at three heights in each point of measurement. The heights of the transducers were chosen to represent the ankles, abdomen and neck of a seated person - 0.1 m, 0.6 m and 1.1 m. Some of the points of measurements are on a bench under the window, so the air velocity at 0.1 m height was only measured in point C. In the other points, the lowest sensor was placed 5 cm above the bench because it was suspected that the air velocities were high along the bench. Measurements were also done in point D with five transducers instead of three. Table (5.2) shows the heights of the transducers. Figure (5.3) shows a photo of the experimental setup in point D.

Table (5.2): Height of sensors

Point of measurement	***Height above floor [m]***				
	Sensor 1	***Sensor 2***	***Sensor 3***	***Sensor 4***	***Sensor 5***
A	0.39	0.60	1.10	-	-
B	0.39	0.60	1.10	-	-
C	0.10	0.60	1.10	-	-
D	0.39	0.60	0.85	1.10	1.35
E	0.39	0.60	1.10	-	-

Figure (5.3): AirDistSys 5000 rig in point D in front of the south window.
Picture by Solveig Blandkjenn

In some of the experiments, iButtons were placed in the window cavity to study the preheating of air that takes place there. The temperature was measured before the air enters the window, and at the top and bottom of the window cavity. The placements of the iButtons are presented in Table (5.3).

Table (5.3): Placement of iButtons in south window

Sensor number	***Placement***
1	By the inlet grilles to the window cavity
2	At the bottom of the window cavity
3	At the top of the window cavity

5.2.2 North window

The experiments on the north window were done with the AirDistSys 5000 rig at different distances from the window, measuring air temperature and velocity at 3 or 6 different heights. Figure (5.4) shows the points of measurements in front of the north window, seen from west. The distance from the window and height above floor is indicated. The grey area in Figure (5.4) is a built-in work station under the window. All points of measurements were on the middle axis of the eastern of the two windows in the home office.

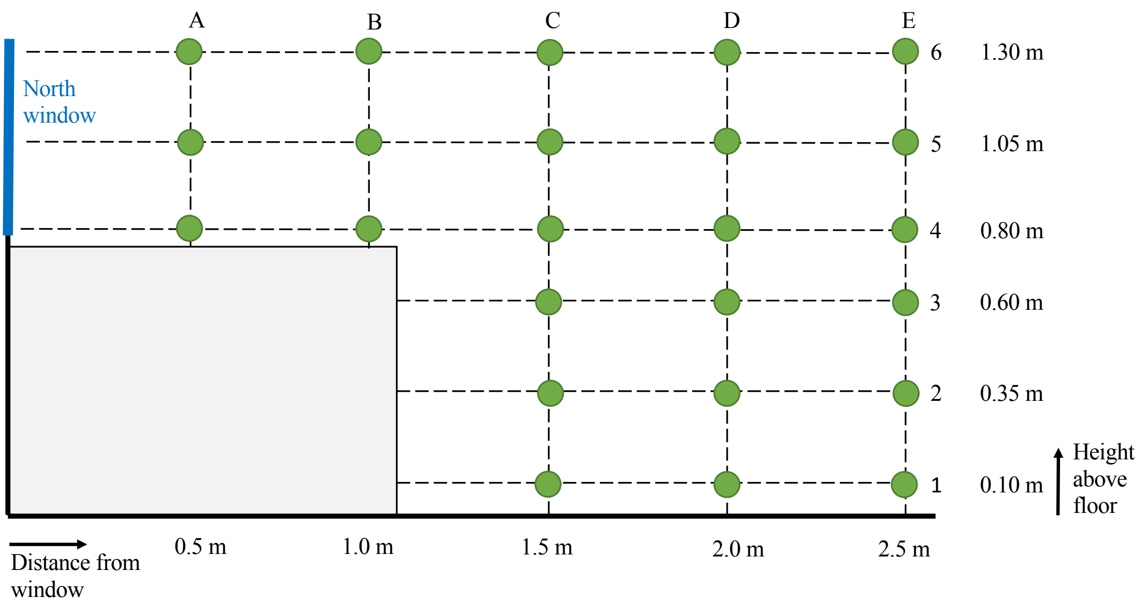


Figure (5.4): Points of measurements in front of the north window, seen from west

One of the experiments on the north window was done with an additional set of measuring points, located 3.0 m from the window, with the same transducer heights as those in Figure (5.4).

5.3 Execution of experiments

The goal of the experiment was to find relationships between the climatic conditions, window positions and the draught rate from the windows during stack ventilation. For the experiments done in this thesis, either one of the north or south windows were opened in combination with one kitchen skylight. Measurements were done with the window opening sizes presented in Table (5.4), at different temperature differences between indoor and outdoor temperatures. After the windows were opened the air velocities and temperatures were measured for 1 minute. The method for calculating the window opening size is presented in Appendix A.

Table (5.4): Window opening areas used in experiments

South window		*North window*		*Kitchen skylight*	
[%]	*[m^2]*	*[%]*	*[m^2]*	*[%]*	*[m^2]*
12.5	0.141	25	0.197	100	0.338
25	0.282	50	0.393		
37.5	0.424				
50	0.565				
75	0.848				

Most of the experiments were done in early spring, without an actual cooling need. To simulate a warmer outdoor environment, the indoor temperature in Living Lab was reduced. The floor heating was off, and the supply air temperature from the mechanical ventilation system was set to 10 °C. The mechanical air flow rates were as described in Table (3.1). For each tested window opening combination, the temperature difference between indoor and outdoor was measured, because the temperature difference is the main driving force of natural stack ventilation. The temperature difference was measured different for the experiments on the north window and on the south window. For the north window, the indoor temperature was the average of all the temperature sensors in the living room, kitchen and home office, and the outdoor temperature was the average of the temperature measured in the room, the south façade and the north façade. For the south window, the indoor temperature was the average of the temperature sensors in the living room and kitchen, and the outdoor temperature was the average of the temperature measured on the roof and on the south façade. For both windows, the temperature difference was calculated as the indoor temperature minus the outdoor temperature. The draught rate was calculated for a hypothetical scenario with an indoor temperature of 24 °C and the same temperature differences as during the experiments. The hypothetical outdoor temperature was calculated according to equation (7);

$$T_{out,hyp} = 24\,°C - T_{in,real} + T_{out,real}. \tag{7}$$

Chapter 6 Experiments in Living Lab

This chapter contains the results of the experiments done with window ventilation in Living Lab, and a discussion of the results. At the end of the chapter, the conclusions about acceptable window openings are presented.

6.1 South window

The experiments on the south window were done to determine when the window can be used for ventilative cooling. The pre-heating of the air has been studied to get a sense of when the window has a cooling effect or not. Also, the draught rates at different locations around the window has been used to evaluate how opening the window affects the thermal comfort.

6.1.1 Evaluating the cooling effect of the south window

The south window in Living Lab is a ventilated construction and the pre-heating function of this window is evaluated in this section. Figure (6.1) shows the temperatures in the south window cavity at night-time without solar gains on the 08.03.17, and the outdoor temperature, the temperature in the living room and the solar irradiance on the south façade.

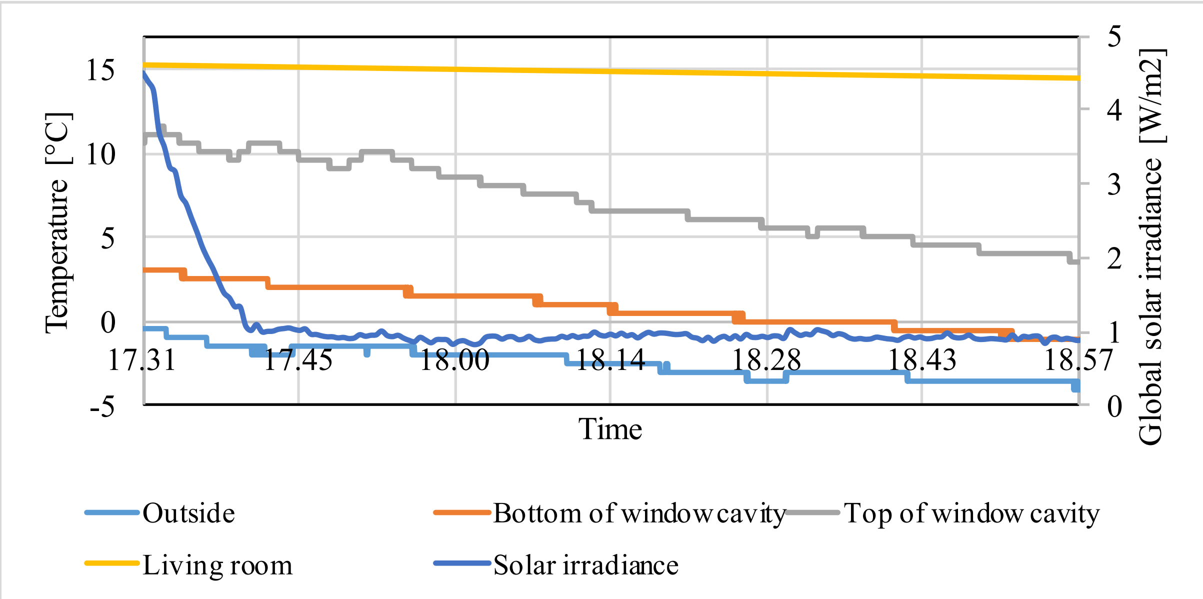


Figure (6.1): Temperatures in the south window 08.03.17

As seen in Figure (6.1), the air was heated both from the inlet to the bottom of the window cavity, and through the window cavity. Since there was no solar irradiance at this hour, the temperature increase in the window was due to the heat loss through the inner window pane and the mixing with the room air. In these weather conditions, the double skin window has a positive effect. The thermal discomfort is reduced because the air supplied to the room is warmer than the outdoor air, but the air is still cold enough to cool the building. Figure (6.2) shows the temperatures in the window on a sunny day, 09.03.17, the indoor and outdoor temperatures and the solar irradiance on the south façade.

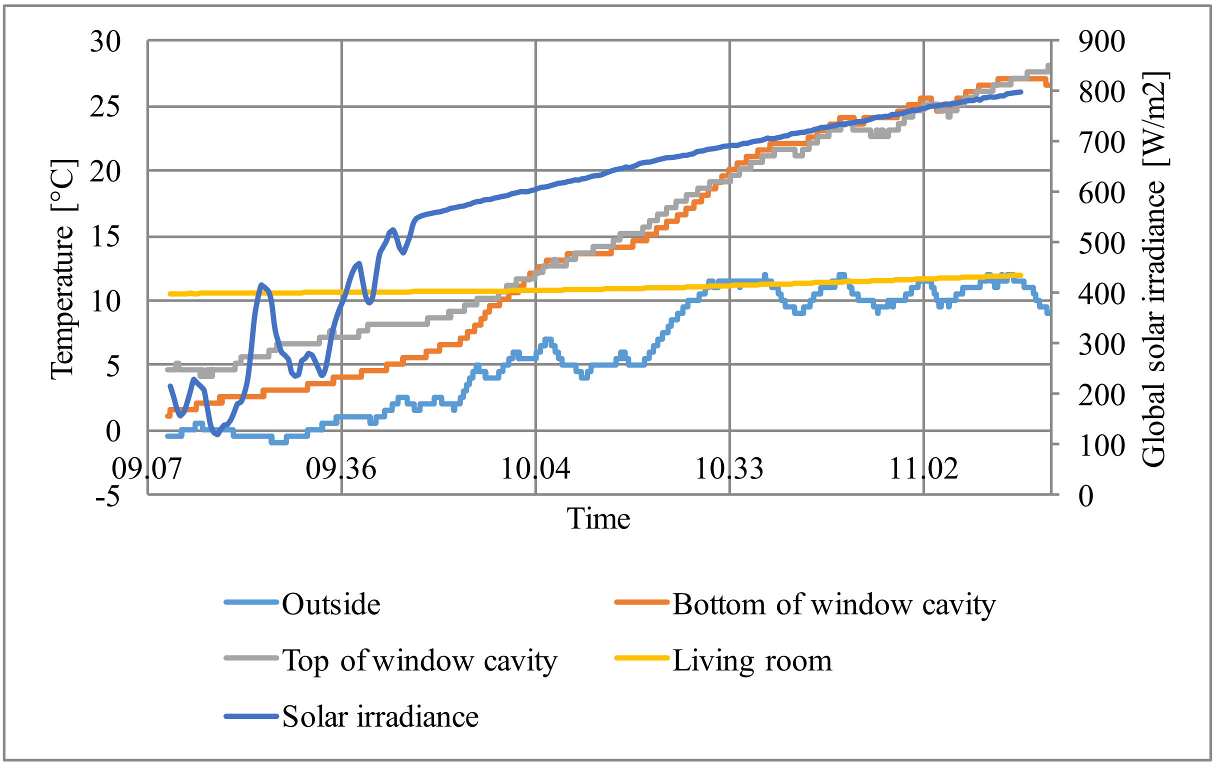


Figure (6.2): Temperatures in the south window 09.03.17

When the solar irradiance was high the air temperature in the window cavity became high. Even though the outdoor temperature stabilized at around 11 °C, the temperature in the window cavity reached 27 °C during the course of the experiment. Since the temperatures in the window cavity were much higher than both the indoor and outdoor temperatures, the heat must have come from the solar irradiance. Comparing the results in Figures (6.1) and (6.2) showed that solar irradiance has a much higher heating effect on the air in the window cavity than the heat loss through the inner pane.

One way to find out if the window has a cooling effect or not is to look at the temperature difference between the air coming from the window and the room air. If the air in the jet from the window is coldest, the room temperature will be reduced. The difference between the temperature measured 1 m from the window by the lowest transducer in point D in Figure (5.2) and the room air is presented in Figure (6.3). The room air is calculated as the average of all temperature sensors in the living room. This graph does not distinguish between different opening sizes, but between the different levels of solar irradiance during the window opening. The general temperature difference between the indoor and outdoor air is along the x-axis.

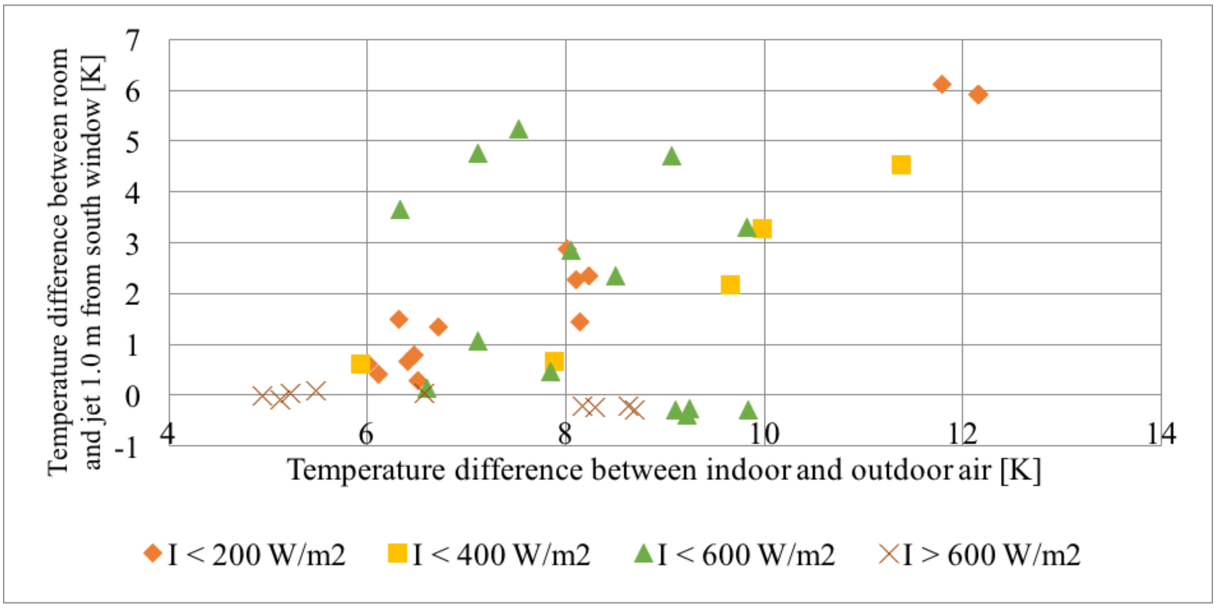


Figure (6.3): Temperature difference between air in the room and air in the jet 1 m from window, for different levels of solar irradiance.

This shows that when the solar irradiance is above 600 W/m^2, the pre-heating of the air is so substantial that the air 1 m from the window the same temperature as the rest of the room or warmer. For lower levels of solar irradiance, the temperature differences generally increase with the increase in overall temperature difference between indoor and outdoor air. It seems, however, that when the temperature differences are below 6 K between the indoor and outdoor air, the air from the jet will never cool the indoor air down. The average air velocity 1 m from the window is plotted against the temperature difference between the room and the jet in Figure (6.4).

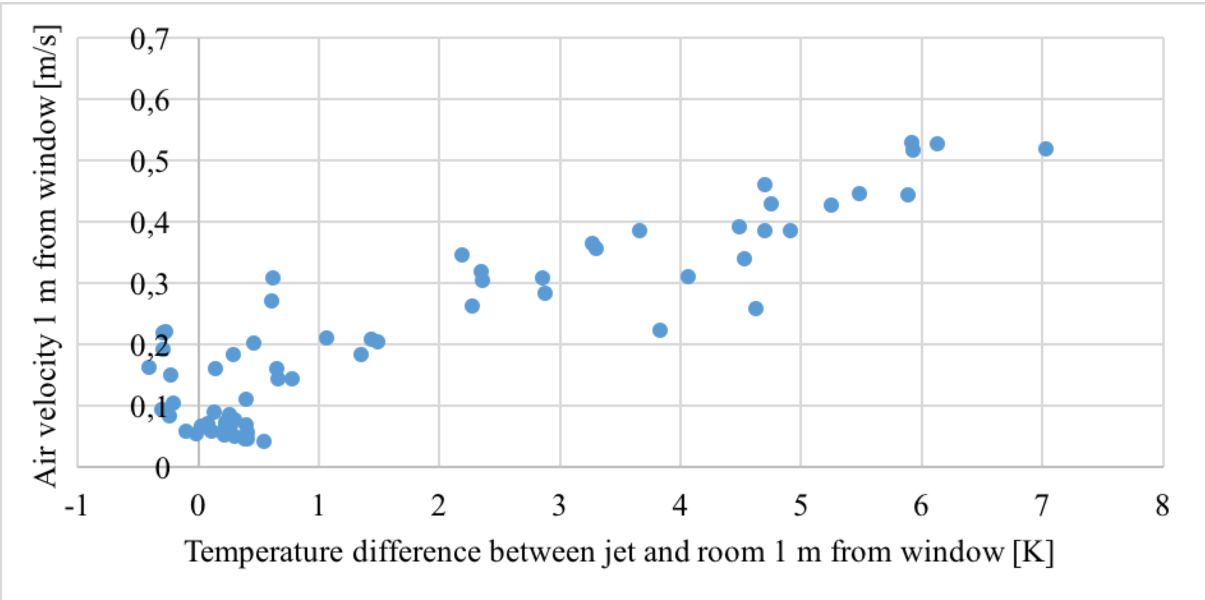


Figure (6.4): Air velocities measured by lowest transducer in point D plotted against the temperature difference between jet and room

Figure (6.4) shows that even when the air in the jet is warmer than the average temp of the room, the air velocities can exceed 0.2 m/s and cool the body of the occupants. This will have a cooling effect on the people sitting in the room, even if the air temperature is the same as before. The air still moves through the window because the room air and the air outside the inlet grilles to the window still has a temperature difference, and there is an under pressure from air exiting the building through the skylight in the kitchen. The temperatures of the air jet were never more than 0.4 K higher than the room air, and air velocities could be high even when the air jet was warm. This means that the south window can be opened in most weather conditions without risking to increase the overheating a lot, but the cooling capacity will be reduced.

The conclusion is that the pre-heating of air in the south window reduced the risk of undercooling on cool days, because the air was heated several degrees before entering the room even when there were no solar gains. This is in accordance with literature about double skin ventilated windows (Carlos and Corvacho, 2013). However, the pre-heating of air reduced the cooling effect on warm summer days. At temperature differences below 6 K or solar irradiance above 600 W/m^2, the cooling effect of the air from the window was low. Therefore, it is important to use the north window for cooling in warm weather. This confirms the results from previous studies of Living Lab, that showed that using the south window for cooling was less effective for reducing indoor temperatures, especially in warm weather.

6.1.2 Air flow from south window

Figure (6.5) presents the air velocities measured at five different heights at point D in Figure (5.2), 1 m from the window, with four different opening sizes. These results are the averages of all measurements done on the 26th of April. The experiments were done under different climatic conditions so the results are not entirely comparable. The average climatic conditions for each window opening size are presented in Table (6.1).

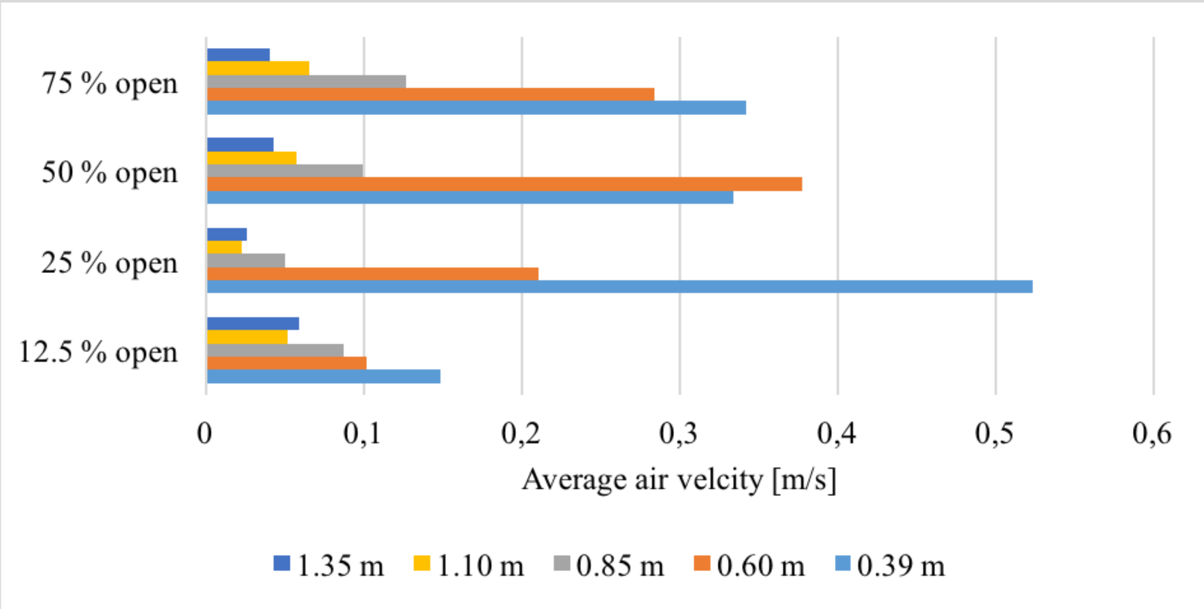


Figure (6.5): Velocity profiles from the south window

Table (6.1): Boundary conditions for the measurements in Figure (6.5)

	12.5 % opening	*25 % opening*	*50 % opening*	*75 % opening*
Temperature difference	7.0 K	12.0 K	9.7 K	9.4 K
Wind speed	1.18 m/s	1.40 m/s	0.92 m/s	0.85 m/s
Wind dir.	191 °	218 °	197 °	156 °
Solar irradiance	544 W/m^2	52 W/m^2	422 W/m^2	378 W/m^2

As seen in Figure (6.5), the air velocities were higher at the bottom of the window, meaning that most of the air entered the room at the bottom of the window. Because the air entered the window cavity through the inlet grilles at the bottom of the window, a lot of the air entered the room at the bottom of the window. This means that there will be higher risks of draught and other local thermal discomfort near floor levels. There was no occurrence of air velocities over 0.2 m/s at heights of 0.85 m and above. It was decided to focus on the draught rates caused at the lowest measuring point of 0.39 m in the further work, seeing as the highest air velocities were measured here for almost all cases.

The air velocities measured at different places around the south window are presented in Figure (6.6). Because of the high air velocities at the lowest measuring points, only the measurements done by the lowest transducer on the rig is shown.

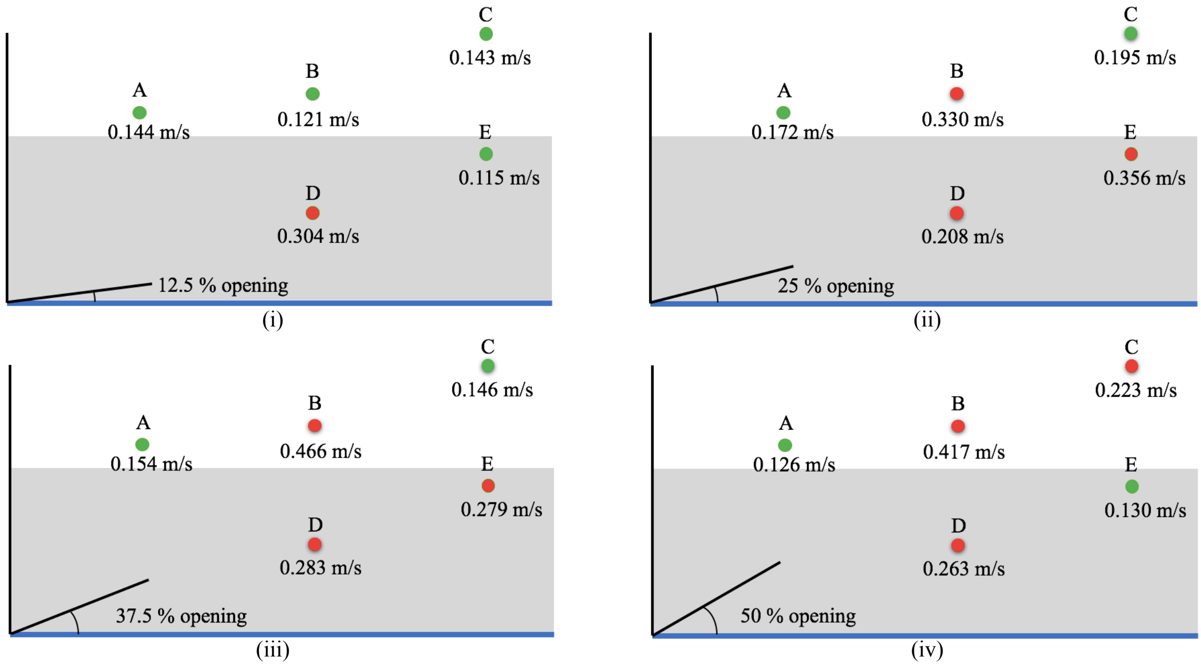


Figure (6.6): Air velocities at 5 cm height with i) 12.5 % window opening, ii) 25 % window opening, iii) 37.5 % window opening and iv) 50 % window opening.
Red indicates air velocities above the 0.2 m/s limit.

The measurements in each point of measurements are not done at the same time, so the real airflow pattern is not necessarily as indicated in the figures. The average climatic conditions for each measuring point are presented in Table (6.2).

Table (6.2): Weather conditions during measurements in the different points

	Point A	*Point B*	*Point C*	*Point D*	*Point E*
Temperature difference [K]	8.6	8.5	8.7	8.3	8.1
Wind speed [m/s]	0.97	2.71	1.61	1.75	1.72
Wind dir. [°]	211	231	266	230	226
Solar irradiance [W/m^2]	38	89	62	58	73

The climatic conditions were approximately the same for all measurements, but the significantly higher wind speed during the experiment in point B will have caused higher air velocities compared to the other measured points. The points with the highest risk of local thermal discomfort were the ones in direct extension in front of the window opening, points B through E. The air velocities measured in point D were higher than the recommended 0.2 m/s for all window opening sizes at this temperature difference. Therefore, it was concluded to do further measurements in this point to investigate the effect of different boundary conditions on the air velocities and draught rate. The air velocities in point B were also high for all window opening sizes except 12.5 %, but because of the atypically high wind speeds during that experiment it was decided to continue measurements in point D.

6.1.3 Draught rates under different climatic conditions

As discussed in Chapter 6.1.2, the point 0.05 m above the bench 1.0 meter from the window (point D) was chosen for further investigation because of a high risk of local thermal discomfort during window openings. The air velocities and temperatures were measured in that point with a variety of different combinations of window openings and climatic conditions. The draught rates were calculated using equation (2), with hypothetical outdoor temperatures as calculated in equation (7). In this chapter, draught rates in point D will be presented as functions of the temperature difference, solar irradiance and wind speed, to investigate the effect these boundary conditions had on the thermal comfort. Some of these weather parameters are co-related, but the effect of that has not been investigated in this work. To decide when window ventilation was allowed, it was decided to exclude the weather conditions that never produced draught rates below 20 %.

6.1.3.1 Temperature difference and draught rate

Figure (6.7) shows the draught rates measured 0.05 m above the bench in point D as a function of the temperature difference, with different window opening sizes.

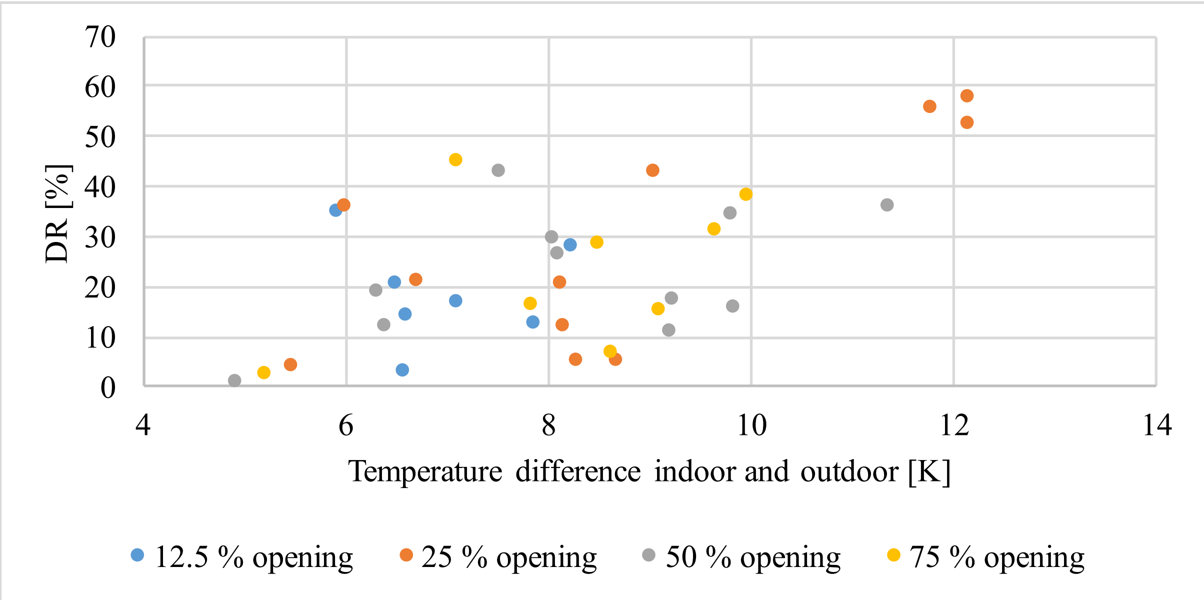


Figure (6.7): Draught rates as a function of temperature difference, for different window opening sizes

As seen in Figure (6.7), the draught rates generally increased with the temperature difference. However, there were many outlying measurements, especially when the temperature differences were low. This indicates that the temperature difference is the main driving force for natural ventilation at higher temperature differences, but at lower temperature differences wind and solar conditions will influence the air flow to a larger degree. There was no apparent relationship between the opening size and draught rate.

It will not be possible to establish rules for the use of this window using only the temperature differences, due to the large variation in draught rates at low temperature differences. However, it can be concluded that when the temperature differences were higher than 10 K, the draught rates always exceeded 20 %. Therefore, one rule to apply to the south window is that the temperature difference has to be below 10 K during window openings.

6.1.3.2 Solar irradiance and draught rate

Figure (6.8) shows the draught rates measured 0.05 m above the bench in point D as a function of the solar irradiance on the south façade for different opening sizes.

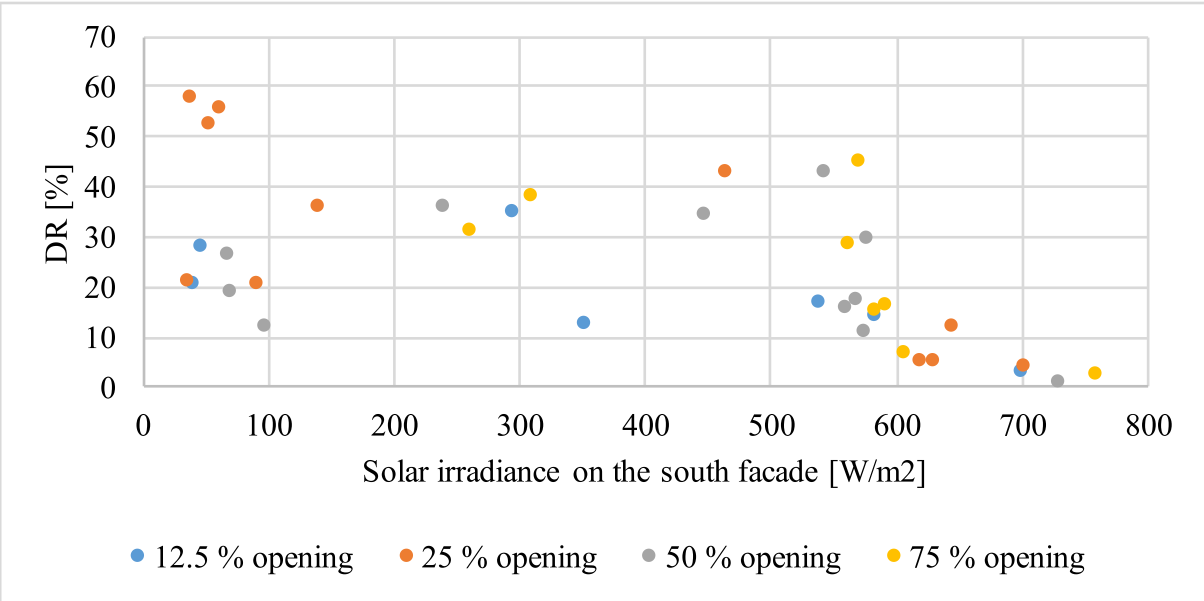


Figure (6.8): Draught rates as a function of solar irradiance, for different window opening sizes

The draught rates in front of the window were lower when the solar irradiance was high. This is because a high solar irradiance both indicates a lower temperature difference and cause more heating of the air in the window cavity. A lower solar irradiance gave higher variance within the measuring points, this can for instance be explained by sudden changes in cloudiness on warm days.

It is seen from Figure (6.8) that there is no occurrence of draught rates less than 20 % when the solar irradiance is below 70 W/m^2. This is therefore chosen as a lower limit for solar radiation to open the south window.

6.1.3.3 Wind conditions and draught rate

Figures (6.9) and (6.10) shows the draught rates measured 0.05 m above the bench in point D as functions of the wind speed and the wind direction, respectively.

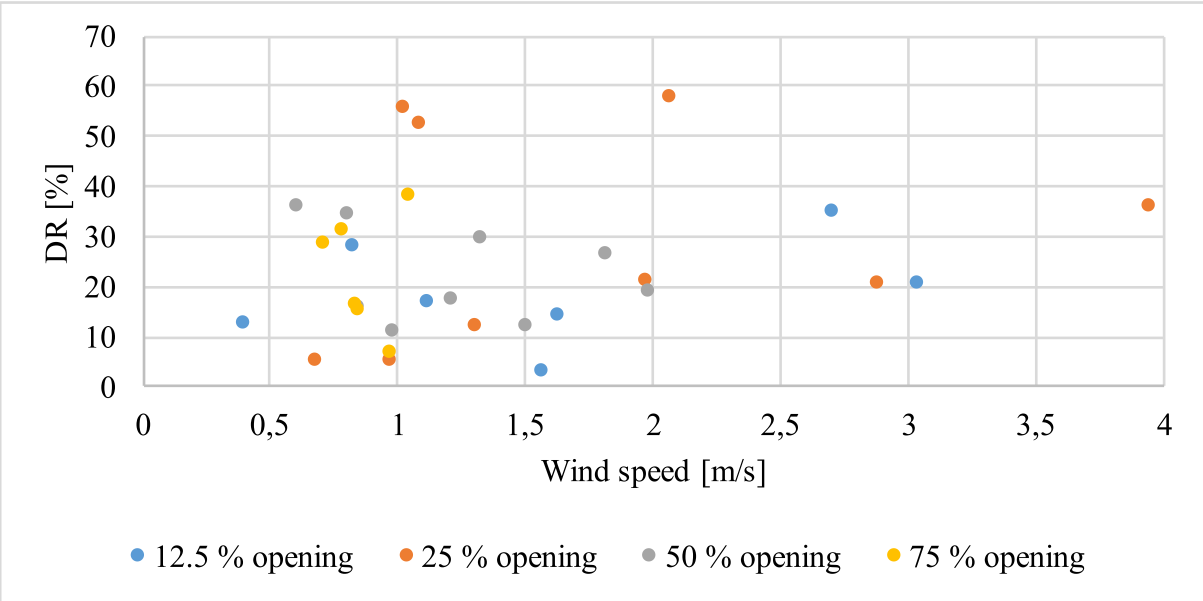


Figure (6.9): Draught rates as a function of wind speed, for different window opening sizes

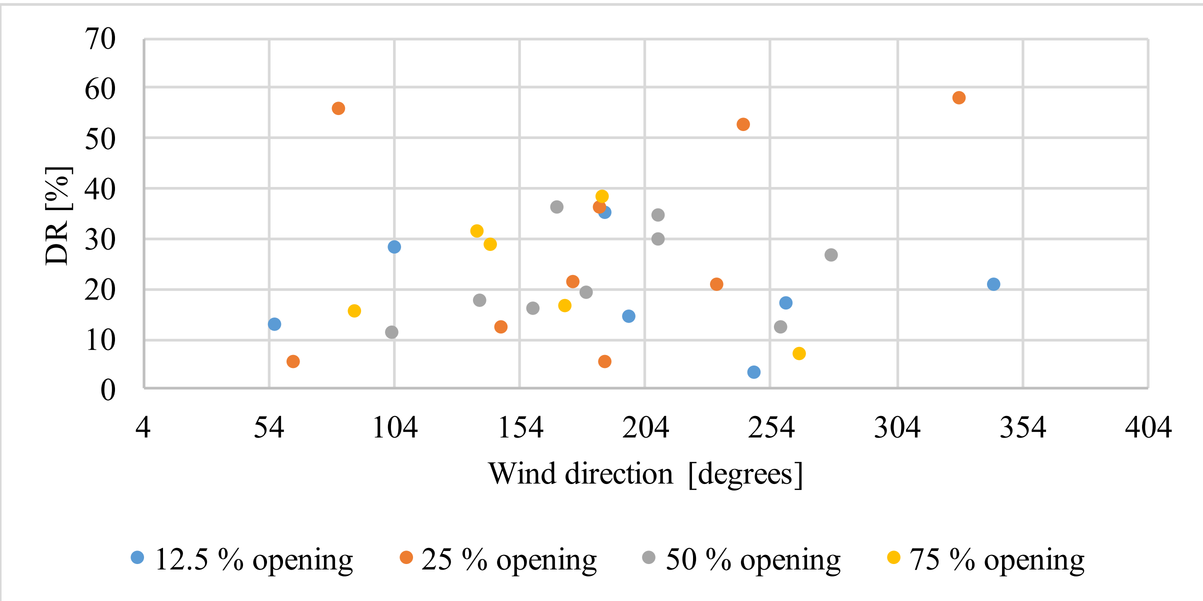


Figure (6.10): Draught rates as a function of wind direction, for different window opening sizes

Because of the double skin of the window, the wind will not be able to blow directly into the room. With wind from the south (180 °), there will be a wind over-pressure helping the natural ventilation through the south window. The prevailing wind direction on the site of Living Lab is from the south – with 50 % of the measurements having a wind direction from SE-S-SW (135 ° - 225 °). With draught rates ranging from 5 to 36 % for the same window opening when the wind direction is 180 °, there is no clear relationship between wind direction and draught rates.

The wind speed has a less obvious effect on draught rates than the temperature difference and the solar irradiation. However, when the wind speed was above 2.0 m/s, the draught rates were never below 20 %. This is therefore chosen as an upper limit for the wind speed during openings of the south window.

6.1.4 Limits for opening the double skin south window

To establish rules for the use of the south window, limits for temperature difference, wind speed and solar irradiance were chosen based on the measurements done 1.0 m from the window, 0.05 m above the bench. The upper limits for temperature difference is 10 K, the upper limit for wind speed is 2.0 m/s and the lower limit for solar irradiance is 70 W/m^2. The measurements adhering to these three rules are presented in Figure (6.11).

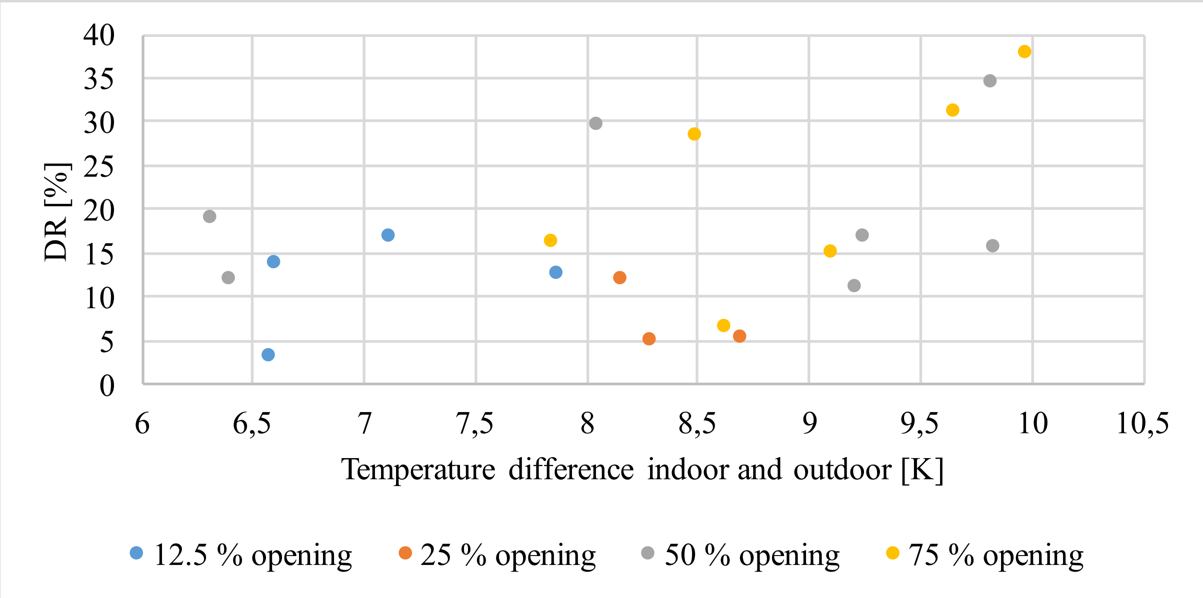


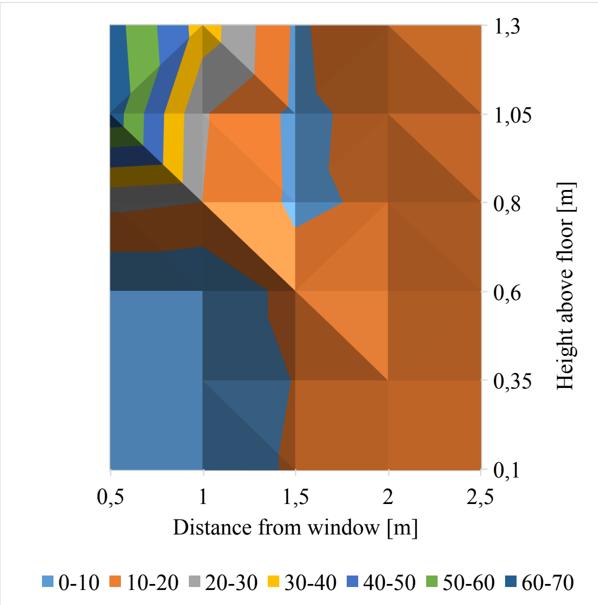
Figure (6.11): Measurements done with dT < 10 K, v < 2 m/s and I > 70 W/m^2

With these restrictions, draught rates above 20 % only occur with window opening sizes of 50 % and 75 %. Choosing to use window opening degrees of maximum 25 % with the three restrictions in place should therefore limit the local thermal discomfort in a satisfactory way. Because of the limited data from the experiments, draught might still occur. This will most likely be within the 3 % allowed deviation. With the possibility for the user to over-ride the system, the draught rates from the south window are considered acceptable.

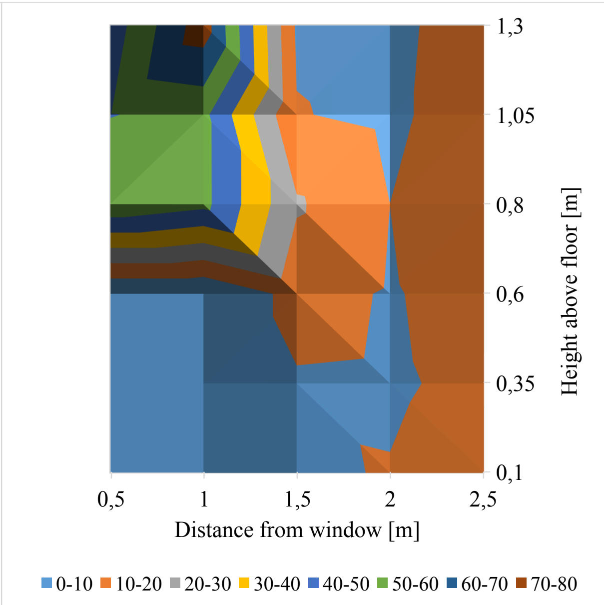
Because of the double skin, cooling will not always be achieved by opening the south window. It has been seen that the cooling effect of opening the south window has been near zero when the temperature difference between the indoor and outdoor air is below 6 K.

6.2 North window

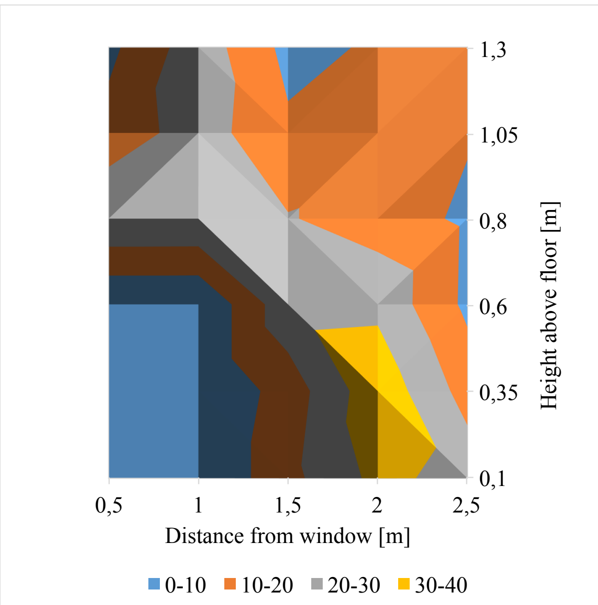
The results from the experiments with draught measurements in front of the north window are presented in Figure (6.12 a-f). Draught rates within chosen limits are colored light blue and orange in the figures. The weather conditions during the experiments on the north window are presented in Table (6.3).



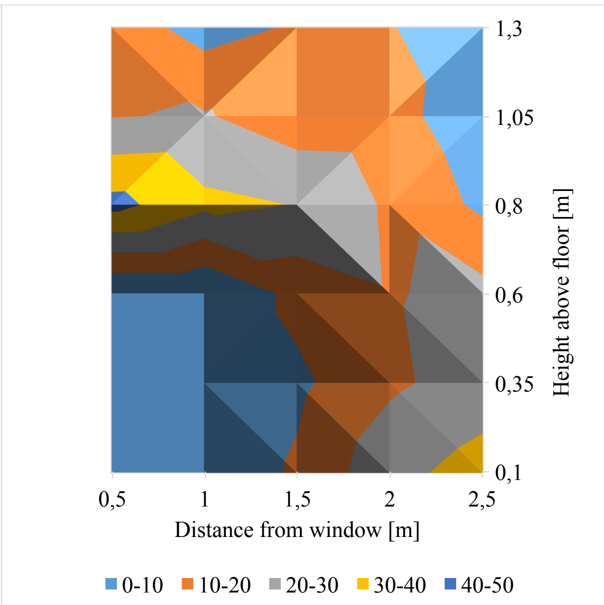
a) 25 % opening, dT=5.7 K



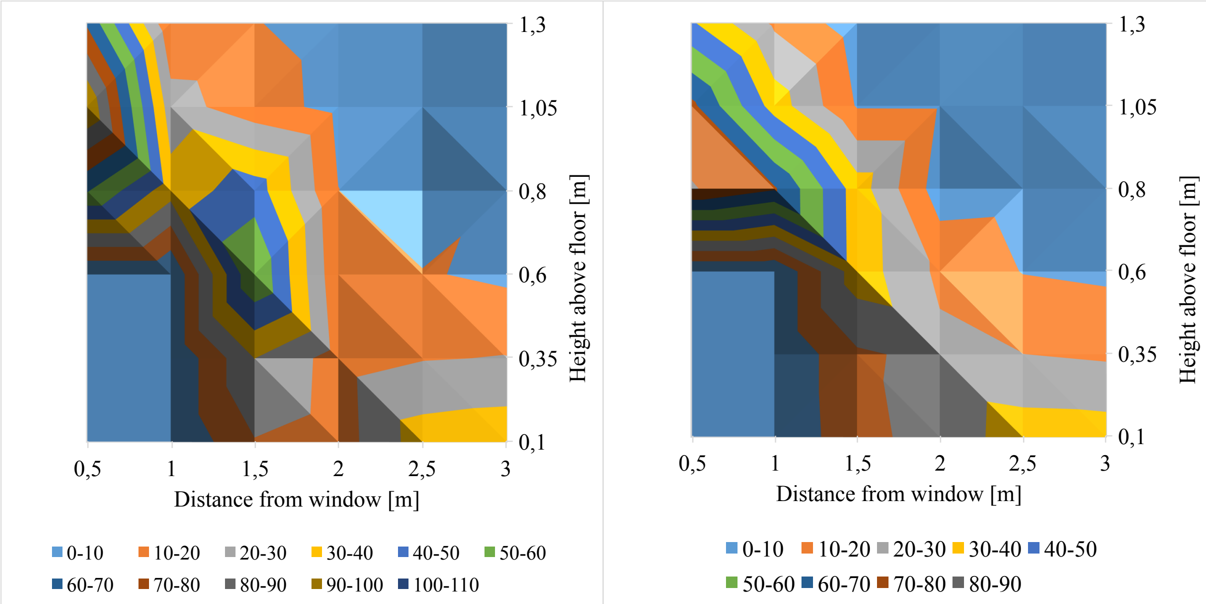
b) 50 % opening, dT=5.7 K



c) 25 % opening, dT=8.4 K



d) 50 % opening, dT=8.4 K



e) 25 % opening, dT=9.9 K

f) 50 % opening, dT=9.5 K

Figure (6.12): Surface plots of draught rate measured in front of the north window, with opening percentage and temperature difference indicated under each figure

Table (6.3): Weather conditions during north window experiments

	(a) and (b)	*(c) and (d)*	*(e) and (f)*
Temperature difference	5.7 K	8.4 K	9.4-9.9 K
Wind speed	2.32 m/s	2.25 m/s	1.50 m/s
Wind dir.	203 deg.	238 deg.	217 deg.
Solar irradiance	43.3 W/m^2	78.2 W/m^2	736.9 W/m^2

With a temperature difference of 5.7 K, as seen in Figures (6.12 a) and (6.12 b), there was only unacceptable draught rates within one meter's distance of the window, ergo outside the zone of occupancy. This indicates that the north window can be opened up to 50 % without thermal discomfort if the outdoor temperatures are high enough. The experiment was repeated with temperature differences of 8.4 K and 9.5-9.9 K, and these produced higher draught rates further into the room. As seen in Figures (6.12 c-f), the cold air from the window flows into the room and falls to the floor. This will cause local thermal discomfort to the head and torso of a person seated at the work station, and at ankle height further into the room. The draught rates increased when the north window was opened 50 % compared to when it was opened 25 %.

The high risk of local thermal discomfort was expected for the north window – and showed the drawbacks of using a window that delivers unheated outdoor air at body height. Due to the limited number of measurements it is hard to determine the exact temperature difference at which the north window can be opened without thermal discomfort. However, a limit of 6 K is proposed in this work, because a temperature difference of 5.7 K gave satisfactory comfort. This coincides nicely with the fact that the cooling effect of the south window is very low for temperature differences below 6 K. It might be possible to use the north window at even higher temperature differences, for instance by using smaller window opening percentages. More tests would have to be conducted to investigate this.

In the experiments on the north window, both the supply and extract windows face north so the wind pressure and the solar irradiance on the two windows are approximately the same. The wind speed was low during all experiments, and the prevailing wind direction was from south-west. It can therefore be assumed that the differences between the results are not influenced by changing wind conditions. The solar irradiance in the e) and f) measurements was much higher than for the other measurements. This can cause buoyancy plumes in the zones with high solar gains, and therefore affect the natural ventilation air flow. More experiments with a variety of wind and solar condition would have to be conducted to draw any conclusion about the effect of these phenomena on the draught rate.

6.3 Conclusion of experiments on window ventilation in Living Lab

The purpose of the experiments was to investigate the local thermal discomfort caused by window opening under different climatic conditions, and determine rules for when and how to use the windows for ventilative cooling. The rules established about the climatic conditions that allow for window ventilation in Living Lab are presented in Table (6.4).

Table (6.4): Climatic rules for ventilative cooling through windows in Living Lab

Window combination	***Temperature difference between indoor and outdoor***	***Wind speed***	***Solar irradiation***
South window and one kitchen skylight	6 K – 10 K	< 2 m/s	> 70 W/m^2
North window and one kitchen skylight	< 6 K	NA	NA

When these climatic requirements were satisfied, the draught rates 1.0 from the north and south windows were deemed satisfactory when the north window was opened up to 50 %, and when the south window was opened up to 25 %, both in combination with one kitchen skylight. These conclusions will be used in the following IDA ICE simulations to determine the resulting thermal climate and energy consumption when applying ventilative cooling.

6.3.1 Sources of error

The idea of reducing the indoor temperature to simulate a scenario with higher indoor temperature and lower temperature difference between indoor and outdoor is used in all the calculations of draught rates done in this chapter. These scenarios, with low temperature differences even when the solar irradiance is low might be unrealistic and can have led to some wrong conclusions. Living Lab has a complex geometry and the varying weather conditions will influence the measurements, making it hard to compare the measurements to each other without making errors.

It has later been discovered that three of the anemometers in the AirDistSys 5000 rig has some damages. It is uncertain when these damages happened - so either none, some or all of the measurements done for this thesis are affected by it. Otherwise, the AirDistSys 5000 rig and the sensors in Living Lab has not been calibrated during this work, so there might be systematic errors due to this. Additionally, there is always a risk of human error during experiments or analysis.

Chapter 7 Simulation model

This chapter presents the simulation model used for evaluating ventilative cooling in Living Lab. The software used for simulations is IDA Indoor Climate and Energy (IDA ICE) from EQUA Simulation. The IDA ICE software performs multi-zone, dynamic simulations, and delivers detailed results on thermal environment, energy consumption, indoor air quality and ventilation air flows, to name a few. IDA ICE is validated by different agencies, for instance ASHRAE, International Energy Agency and BREEAM, and is found to compute results that match measured data well. (EQUA Simulation, 2017)

7.1 The IDA ICE model of Living Lab

An IDA ICE model of Living Lab was established during Kirkøen's thesis work in 2015 and was continued in Risnes' master's thesis in 2016. The model is based on the architectural drawings of Living Lab and has been validated for both summer and winter conditions as a part of the work on this master's thesis.

Figure (7.1): 3D view of the IDA ICE model of Living Lab

The validation concluded that the indoor temperatures of the simulation model were quite accurate, especially during summer conditions. In winter, the simulations resulted in slightly higher temperatures than in reality. The simulations showed less temperature differences between rooms than the measured results. They also overestimated the cooling effect of window ventilation; this could be because the simulation model assumes total mixing of the air. The changes in CO_2-concentration when people entered the rooms were similar in the IDA ICE model and reality. The energy consumption for heating was 55 % larger in the simulated model than reality under summer conditions, and the energy consumption of the fan in the AHU was 109 % higher in the reality than simulation model under winter conditions. It was concluded that even though the energy consumption of Living Lab was not accurately calculated in IDA ICE, the results of different simulations can still be compared to each other. At the time of building the model, the actual installed heating effect in Living Lab was uncertain, so some of the error in winter temperatures and energy consumption can be attributed to this. All in all, the model is deemed acceptable to use in this thesis, but the indoor temperatures and CO_2-concentration are more accurate than the energy consumption. More details on the validation can be read in Appendix B.

The IDA ICE model of the building is divided into nine zones; living room, home office, kitchen, entrance, master bedroom, small bedroom, mezzanine, bathroom and technical room. A detailed description of the construction of the IDA ICE model can be read in Kirkøen's master's thesis (Kirkøen, 2015). Figure (7.2) shows the zones on the ground floor of Living Lab in IDA ICE. There is also a zone for the mezzanine over the small bedroom not shown in the figure.

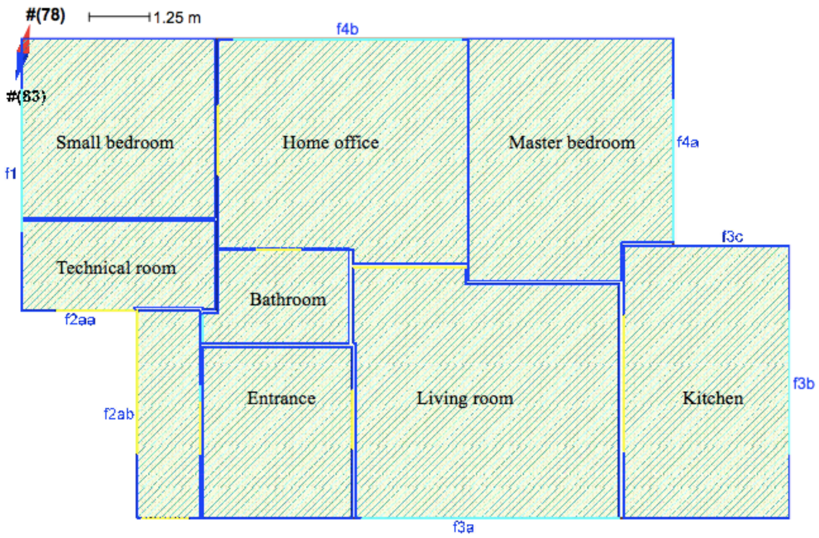


Figure (7.2): Zone layout of the Living Lab IDA ICE model

Living Lab is located on the university campus of NTNU Gløshaugen in Trondheim, and is shaded from the sun in parts of the day by hills, trees and buildings. Figure (7.3) shows an aerial photo of Living Lab and the shading objects added in IDA ICE to simulate these surroundings. The ambient CO_2-concentration was assumed to be 400 ppm, meaning that comfort category I limit for the building is 900 ppm, and comfort category II limit is 1200 ppm (NS-EN 15251:2007)

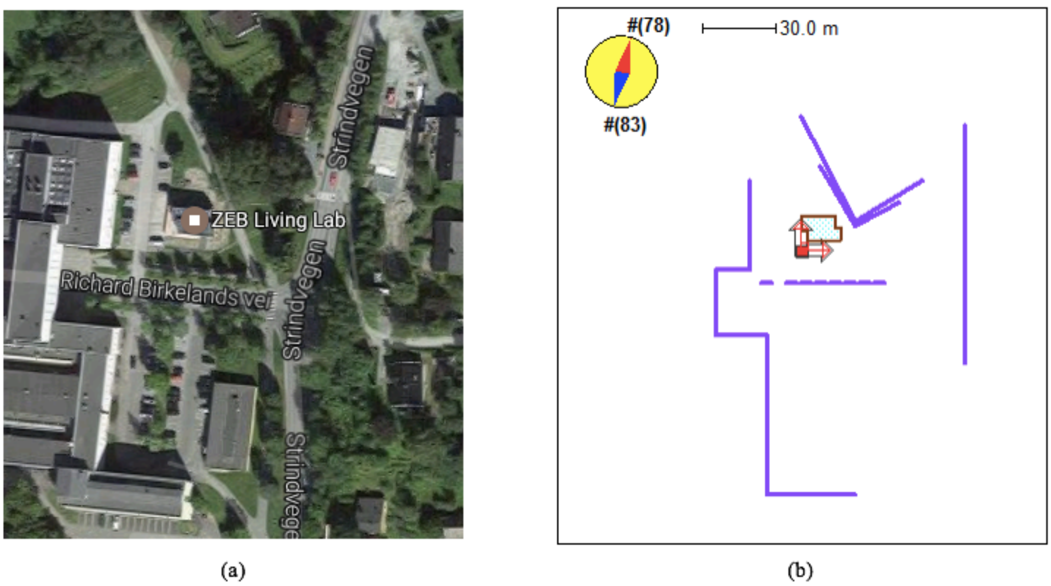


Figure (7.3): a) Aerial photo of Living Lab with surroundings, b) shading objects in IDA ICE

7.2 Specifics for the simulations of Living Lab

What follows are the specifics of the simulation model regarding technical installations and building use that are chosen for the scenarios simulated in this thesis.

7.2.1 Heating and ventilation

The simulation model has floor heating in all rooms except the technical room, and a heating setpoint of 22 °C. The total heating power installed in each room is presented in Table (7.1). In one case, mechanical cooling was used in a simulation to compare the energy consumption of window cooling to mechanical cooling. In that scenario, 2000 W ideal coolers were installed in each room. The modeled ventilation system supplied air to the rooms according to the values in Table (3.1).

7.2.2 Internal loads

Table (7.1) presents the internal heat loads from lights and equipment present in the simulation model of Living Lab. These are supposed to imitate the effect of lights, appliances and other technical equipment in Living Lab – and are rough estimates based on the measured power consumption in Living Lab. The equipment is on 24 hours a day; the lights are on when there are people in the building except from midnight to 7 AM.

Table (7.1): Installed heating and internal heat loads in Living Lab simulation model

	Floor heating [W]	***Equipment [W]***	***Lights [W]***
Living room	526.0	60	100
Home office	454.6	20	98.7
Kitchen	321.7	90	37.7
Bathroom	110.0	-	10.8
Master bedroom	396.9	-	40.0
Small bedroom	287.6	-	29.0
Technical room	-	200	14.4

7.2.3 Occupancy

The simulations were done for a scenario where four people live in Living Lab, leading a normal family life with work or school on week-days. The detailed schedule of the presence of people is shown in Figures (7.4) and (7.5).

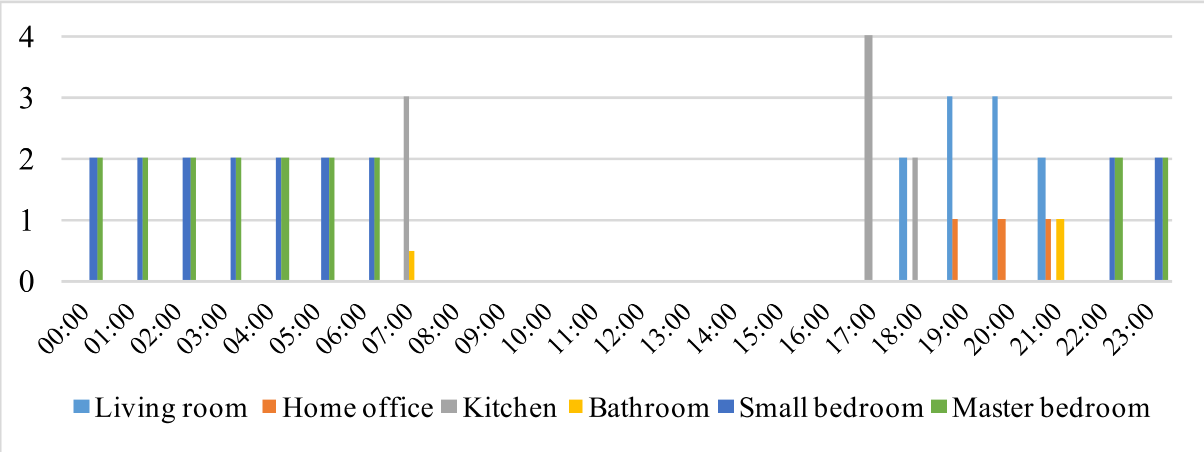


Figure (7.4): Number of people in each room from Monday to Friday

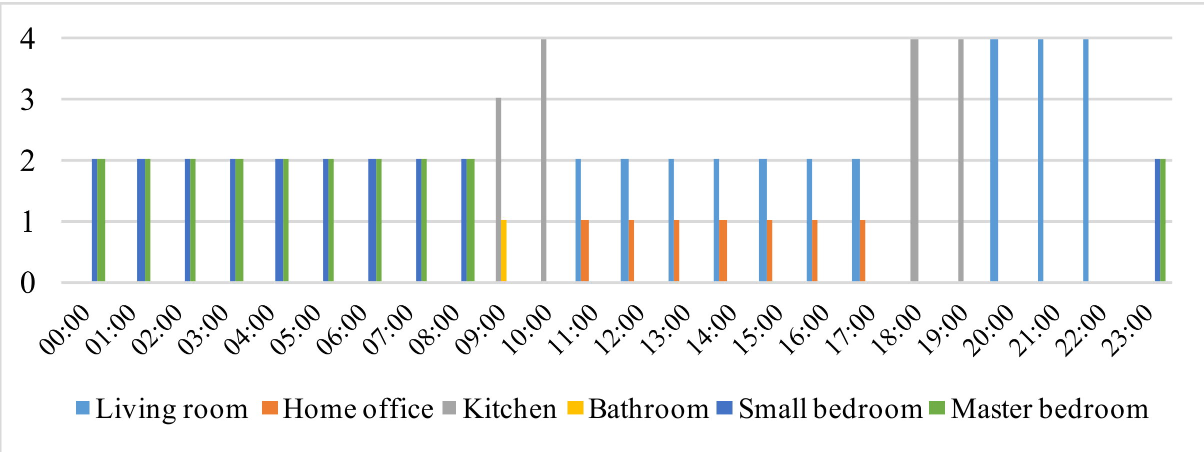


Figure (7.5): Number of people in each room on Saturdays and Sundays

The occupants have an activity level of 1.2 met in the daytime and 0.8 met at night. Clothing levels are 0.5 clo in the bedrooms and bathroom and 1.0 clo in the other rooms. Total hours of occupancy in the living room, kitchen, home office and bedrooms were 11 613 h per year. The bedroom doors are closed when people are in the bedrooms.

7.2.4 Control algorithm for window openings

The control algorithm for the windows in the IDA ICE model was based on findings from literature and the rules for each window combination established in Chapter 6. The chosen control is an on-off control, cooling the building from 24 °C to 22 °C. Cooling is allowed from 06 AM to 22 PM every day. The rules regarding the use of window combinations from Table (6.4) were applied in IDA ICE as presented in Table (7.2). A more detailed explanation of the window control algorithm is given in Appendices B and C.

Table (7.2): IDA ICE rules for window combinations

	Determined by	***South window and one kitchen skylight***	***North window and one kitchen skylight***
Temperature difference	Difference between average temp. in living room, home office and kitchen and outdoor dry bulb temp.	6 K – 10 K	0 K – 6 K
Wind speed	Wind velocity on the south façade	< 2 m/s	NA
Solar irradiance	Direct normal irradiance	> 70 W/m^2	NA

7.3 How the results of simulations will be evaluated

Simulations will be carried out to determine the best way to apply ventilative cooling in Living Lab. The results will be evaluated based on the thermal comfort, indoor air quality and energy consumption. Simulation will be done with closed windows as well, to compare against the results with ventilative cooling and be able to quantify the decrease in hours of thermal discomfort and change in energy consumption. The first priority was to achieve the requirements set for the thermal and atmospheric environments, and the second to keep the energy consumption to a minimum.

The thermal comfort will be measured by the total hours of occupancy outside of comfort categories I and II as defined by NS15251 in a building without mechanical cooling. The results from these zones will be used; living room, kitchen, home office, master bedroom and small bedroom. Some temperature graphs from warm days will also be used to compare the cooling effect of the different window ventilation scenarios.

The draught rates from the original window design are assumed to be acceptable when the rules decided in chapter 6 are followed. With new window design, draught rates will be estimated by calculation and used to evaluate the thermal comfort with the different ventilative cooling strategies.

The energy consumption will be measured by the energy supplied to all zones through the floor heating system. In the scenarios where the use of mechanical ventilation is reduced, both the energy consumption for the heating and the ventilation will be used to evaluate the simulations.

CO_2-concentrations in the living room, kitchen, home office and bedrooms will be used to evaluate the hygienic ventilation efficiency of the natural ventilation. The limits for categories I and II were 900 and 1200 ppm. The hours of CO_2-concentrations above these levels in the living areas and the bedrooms will be used to compare the strategies, as well as the peak CO_2-level from the simulation.

More details about the simulated scenarios will be presented in Chapter 8, in parallel to the results of the simulations and discussion of the results.

Chapter 8 Simulations

This chapter contains description of the IDA ICE simulation scenarios, and the results of the simulations with discussion. The purpose of the simulations was to investigate the ventilative cooling potential in Living Lab and evaluate ways of applying ventilative cooling and hygienic ventilation through window ventilation. The results regarding hours of thermal discomfort in each individual zone are presented in Appendix E.

8.1 Choice of sensors for window control

Previous studies of Living Lab have concluded that the best way to apply ventilative cooling is to cool the building from 24 °C to 22 °C, so the temperatures measured in the zones will determine the window position. Simulations were done to investigate how the choice of temperature sensors influenced the thermal climate and energy consumption. The zones where ventilative cooling is applied are the living room, home office and kitchen, so it was decided to use the temperatures in these zones to determine the cooling need. This means that over-temperatures might occur in the bedrooms without a window response, but the alternative is to risk undercooling in the other zones. Three different sensor choices were tested for the months of May and June in the Trondheim location, as presented in Table (8.1).

Table (8.1): Sensor scenarios

	Windows open when	***Windows close when***
I	Average temperature is above 24 °C	Average temperature is below 22 °C
II	Average temperature is above 24 °C	Minimum temperature is below 22 °C
III	Maximum temperature is above 24 °C	Minimum temperature is below 22 °C

Average temperature means the average temperature in the living room, home office and kitchen, weighted by volume. The window control was as described in chapter 7.2.4, the window openings were 25 % in the south window and 50 % in the north window. The results of these simulations will determine the best sensor choice, which is used in the rest of the simulations.

8.1.1 Results and discussion

Table (8.2) presents the results of the three simulations; the hours of occupancy with thermal discomfort – i.e. outside comfort categories I and II - and the energy consumption of the floor heating system.

Table (8.2): Thermal comfort and energy consumption of different sensor scenarios

	Hours of thermal discomfort [h]	***Heating energy [kWh]***
I	38	153.1
II	38	145.1
III	36	149.9

As seen in Table (8.2), the thermal comfort is essentially the same for all three scenarios – with Scenario III having 2 more hours of occupancy within comfort categories I and II. Additionally, there was very little change in comfort for each individual zone. Scenario III starts cooling at a lower average temperature, and was able to reduce the hours of overheating by a small margin. Category I comfort is between 21 °C and 23 °C, so cooling some zones slightly below 22 °C will not affect thermal comfort as defined by NS15251. The allowed deviation of 3 % means that 44 hours of thermal discomfort is allowed for the two months combined – so all sensor scenarios are within this limit.

The energy consumption varied more between the three scenarios. Scenarios I and III had 5.5 % and 3.3 % higher energy consumptions for heating than scenario II, respectively. It was suspected that scenario I would cause an increase in energy consumption because the coldest zone would be cooled to a temperature below 22 °C, and that is confirmed in these results. Starting the ventilative cooling when the warmest zone reaches 24 °C meant that cooling happened more frequently, increasing the energy consumption slightly compared to starting ventilative cooling when the mean temperature reached 24 °C.

Based on the results of these simulations, it was decided to perform the remaining simulations with sensor scenario II, where cooling starts when the mean temperature in the zones reaches 24 °C, and stops when the minimum temperature in the affected zones reaches 22 °C. Scenario III was also a good choice, but the energy consumption was given the most weight in the evaluation – because all scenarios yielded very good and nearly identical thermal comfort.

8.2 Window opening sizes

As discussed in Chapter 6, opening the north window up to 50 % in combination with one skylight window is acceptable when the temperature difference is below 6 K. Opening the south window up to 25 % in combination with one skylight is acceptable when the temperature difference is between 6 K and 10 K. Simulations were carried out with the maximum opening size and half of the maximum opening size, to evaluate different choices. Table (8.3) shows the simulations carried out. The window control was as described in 7.2.3, and the sensors used were as presented in Chapter 8.1. Simulations were run for May and June in the Trondheim location.

Table (8.3): Simulations with different opening sizes

Simulations	*South window*		*North window*		*Kitchen skylight*	
	[%]	*[m²]*	*[%]*	*[m²]*	*[%]*	*[m²]*
S12.5%, N25%	12.5	0.141	25	0.197	100	0.338
S12.5%, N50%	12.5	0.141	50	0.393	100	0.338
S25%, N25%	25	0.282	25	0.197	100	0.338
S25%, N50%	25	0.282	50	0.393	100	0.338

8.2.1 Results and discussion

The thermal comfort and energy consumption for the different window opening sizes are presented in Table (8.4). Results of simulations without window openings and with mechanical cooling are also shown for comparison.

Table (8.4): Thermal comfort and energy consumption with different window opening sizes

	Hours of thermal discomfort				*Heating and cooling energy*	
	Living room [h]	*Building total [h]*	*Decrease living room*	*Decrease building total*	*Value [kWh]*	*Increase compared to closed windows*
No cooling	105	303			126.2	
Mech. Cooling	0	0	100 %	100 %	341.8	171.8 %
S12.5%, N25%	17	57	83.8 %	81.2 %	139.4	10.5 %
S12.5%, N50%	15	47	85.7 %	84.5 %	144.9	14.8 %
S25%, N25%	15	48	85.7 %	84.2 %	138.9	10.1 %
S25%, N50%	13	38	87.6 %	87.5 %	145.1	15.0 %

The results in Table (8.4) show that all the window opening sizes were able to increase thermal comfort significantly in the simulated period, but that the hours of overheating was within the 44 h limit only when the largest window opening percentages were used. For the building as a whole, the hours of thermal discomfort decreased at least 81.2 % compared to not applying any cooling. Generally, larger window openings gave better thermal comfort, because larger openings resulted in larger airflows that cooled the building quicker. Opening the north window 50 % decreased the hours of thermal discomfort by 10 h compared to opening it 25 %. Opening the south window 25 % decreased the thermal discomfort by 9 h compared to opening it 12.5 %. Therefore, it is concluded that larger window opening degrees in both windows will give higher thermal comfort. To maximize the thermal comfort in Living Lab and comply with thermal comfort requirements, the north window should be opened 50 % and the south window opened 25 %, in combination with one kitchen skylight.

The living room was the warmest zone in the building, with the lowest thermal comfort according to NS15251, and about one third of the hours of thermal discomfort happened here. Similar to the building as a whole, the thermal comfort in the living room increased with the window opening size. With the largest allowed window openings, only 13 hours of occupancy were outside the requirements set for the building. These simulations assume no solar shading, and previous studies have shown the positive effects of solar shading in Living Lab. The thermal climate can therefore be improved further by applying solar shading and manually opening larger windows and doors when necessary.

The energy consumption for heating increased about 10 % in the scenarios where the south window was opened 12.5 %, and ca 15 % in the scenarios where the south window was opened 25 % (compared to when the windows were closed). The size of opening in the south window was a bigger influence on the energy consumption than the opening in the north window. This is because the south window was used at lower outdoor temperatures and therefore more cold air had to be heated when the opening degree was larger. Using larger window openings will generally change the air faster and reduce the cooling in surfaces that are the main reason for increased energy consumption after window ventilation. This was not true for the south window, which could be explained by the double-skin function that pre-heats the air before it enters the room. When the window opening is smaller, the airflow through the window is smaller, and will be heated more from the solar gains and heat loss through the inner pane than a larger airflow. The lowest energy consumption is for opening the north window 50 % and the south window 12.5 %. This means that you have a small opening in the cooler periods, and large openings when the heating demands are low. All the window ventilation scenarios had a much lower energy consumption than the scenario with mechanical cooling.

Figures (8.1) and (8.2) shows the indoor air temperatures in the living room and small bedroom during a cooling load simulation for 15th July. These zones were typically the warmest zones in the building, due to large solar gains in the day and evening.

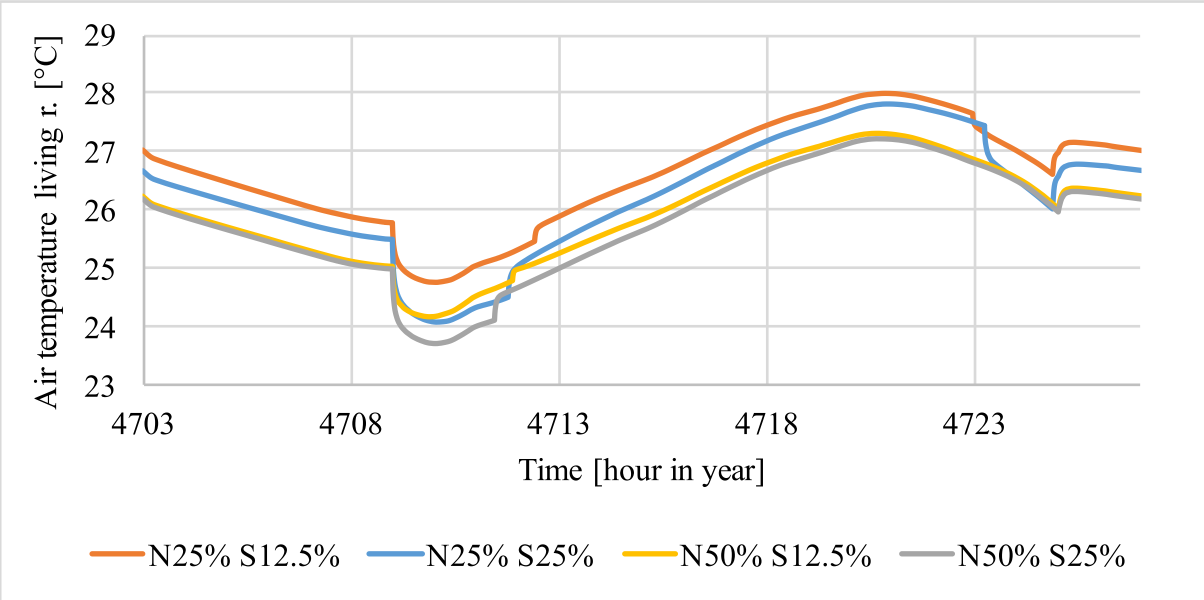


Figure (8.1): Temperatures in the living room in a cooling load simulation
on the 15th July with different window opening sizes

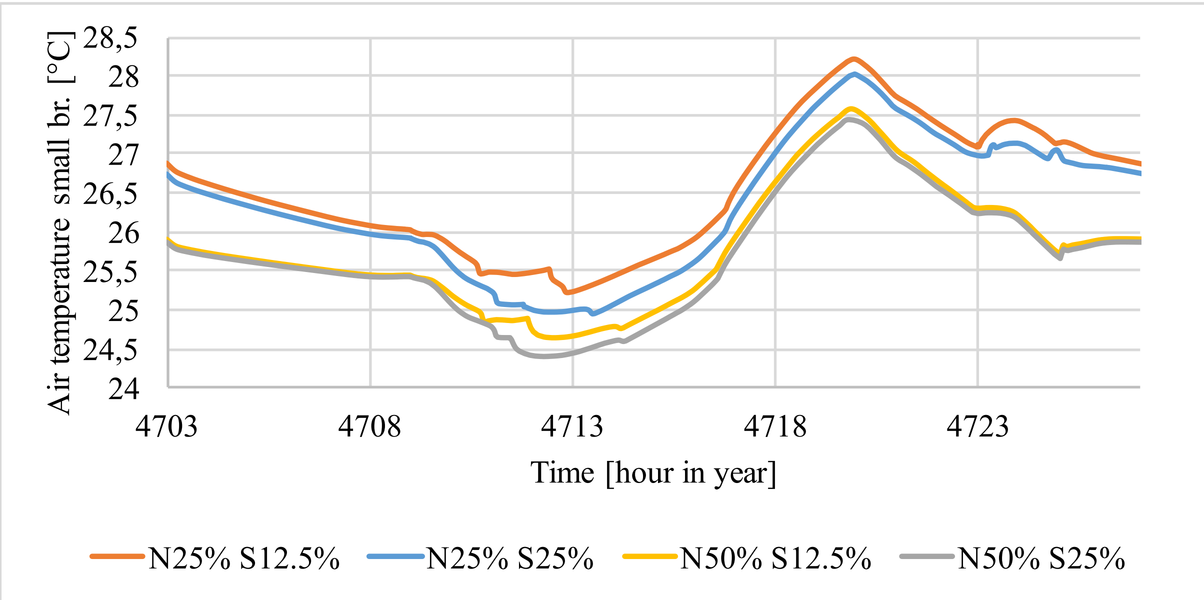


Figure (8.2): Temperatures in the small bedroom in a cooling load simulation
on the 15th July with different window sizes

As seen in Figures (8.1) and (8.2), using the largest possible window openings gives the best thermal comfort in warm periods. This will reduce the temperature with 1 °C throughout the day compared to using smaller openings. The cooling effect in the small bedroom is not as good as in the living room, because the cooling is not directly applied there. This room would benefit from having windows that could be included in the automatic ventilative cooling control.

8.2.2 Conclusion on window opening sizes

The conclusion drawn from the simulations with different window sizes is that a good thermal climate can be achieved with window ventilation without a high increase in energy consumption for heating. Generally, increased openings in the north window gave better thermal comfort - without increasing the energy consumption. Increased openings in the south window gave increased thermal comfort – while increasing the energy consumption. According to the simulations, the operative temperatures can be kept within comfort categories I and II more than 97 % of the time by using the largest allowed window openings. Table (8.5) presents the results of full-year energy simulations for this alternative.

Table (8.5): Full year simulation

	Hours of thermal discomfort		***Heating energy***	
	Value [h]	***Decrease***	***Value [kWh]***	***Increase***
No cooling	664		5361.0	
N 50 %, S 25 %	134	79.8 %	5392.4	0.6 %

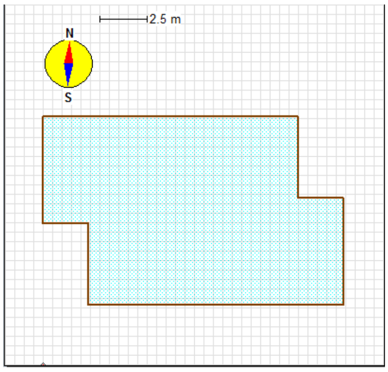
The allowed number of hours of thermal discomfort is 259 h, so the chosen solution gives thermal comfort within the limits. When only 134 h of occupancy are outside of category II comfort, it means that 98.9 % of the hours of occupancy are within the chosen limits. The energy for heating increases with only 31.4 kWh per year, and about 86 % of this difference occurs in April and May.

8.3 Sensitivity of ventilative cooling solution in different scenarios

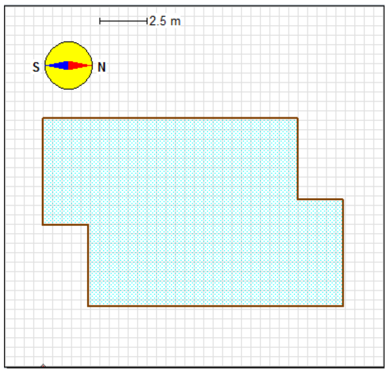
Simulations were done with the chosen window openings of 25 % in the south window and 50 % in the north window for different scenarios. The object was to test the sensitivity of the chosen solutions to these three variables; cardinal direction, level of insulation and climate.

8.3.1 Cardinal direction

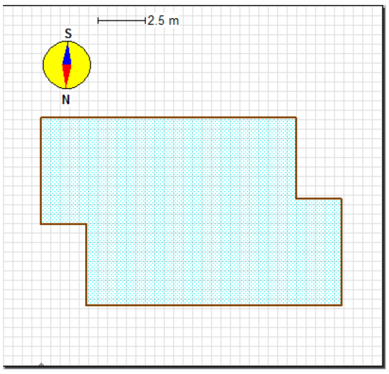
Today, the living room in Living Lab is in the south of the building – and the site shading is as shown in Figure (7.3). To investigate the sensitivity of the ventilative cooling solution when the living room faces different cardinal directions, simulations were done with and without ventilative cooling in the Trondheim location with the building facing four different ways. This is illustrated in Figure (8.3). In these four simulations, all site shading was deleted.



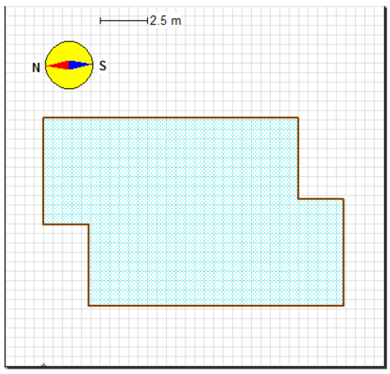
Living room facing south



Living room facing east



Living room facing north



Living room facing west

Figure (8.3): Living Lab turned to different cardinal directions

8.3.1.1 Results and discussion

The hours of thermal discomfort in May and June are presented in Table (8.6) for each cardinal direction. Results are shown for each zone individually and for the building in total.

Table (8.6): Hours of thermal discomfort with double skin window facing each direction

	Hours of thermal discomfort [h]			
Zone	***South***	***East***	***North***	***West***
Living room	18	19	24	21
Home office	9	17	26	13
Kitchen	10	12	16	12
Master bedroom	13	13	15	5
Small bedroom	15	14	33	20
Building total	65	75	114	71

These results indicate that shading from nature and buildings surrounding Living Lab had a good effect on the thermal climate in Living Lab. With the living room facing south, the hours of thermal discomfort increased from 38 to 65 hours when the shading from other structures was deleted. Turning the building 180 ° so that the living room faced north resulted in the worst thermal comfort. This is most likely due to the low g-factor of the windows in the kitchen and home office that normally face north. The double skin window is large, but well insulated and has a high g-factor that helps reduce solar gains. Figures (8.4), (8.5), (8.6) and (8.7) show the indoor temperatures on a warm day, Saturday June 11th, in all zones for each cardinal direction.

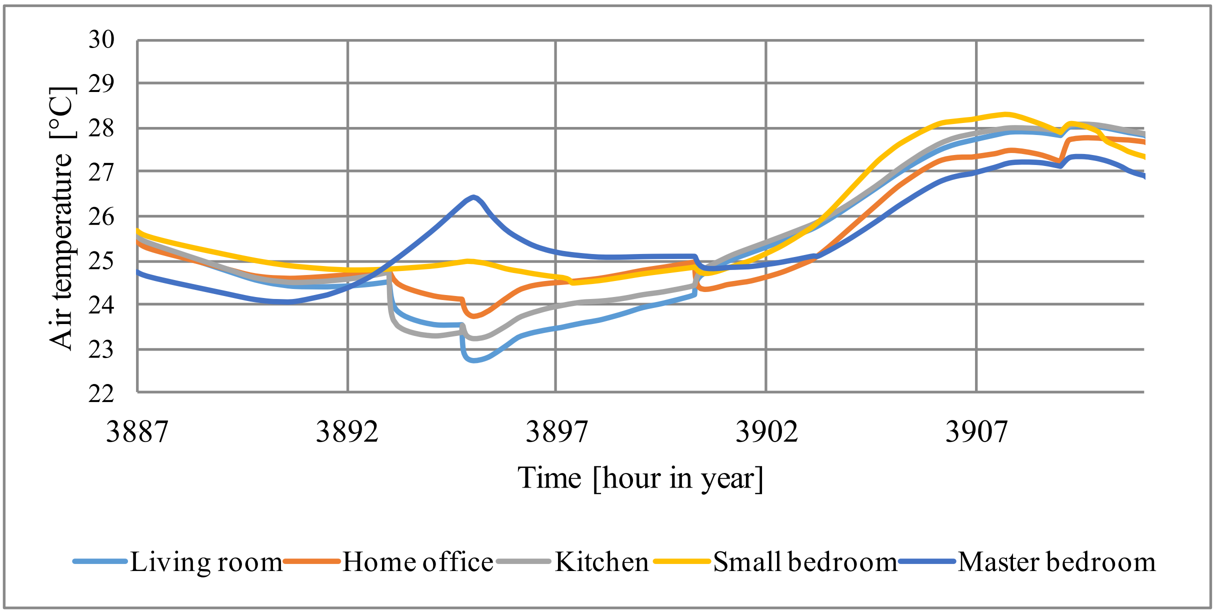


Figure (8.4): Temperatures on June 11th with living room facing south

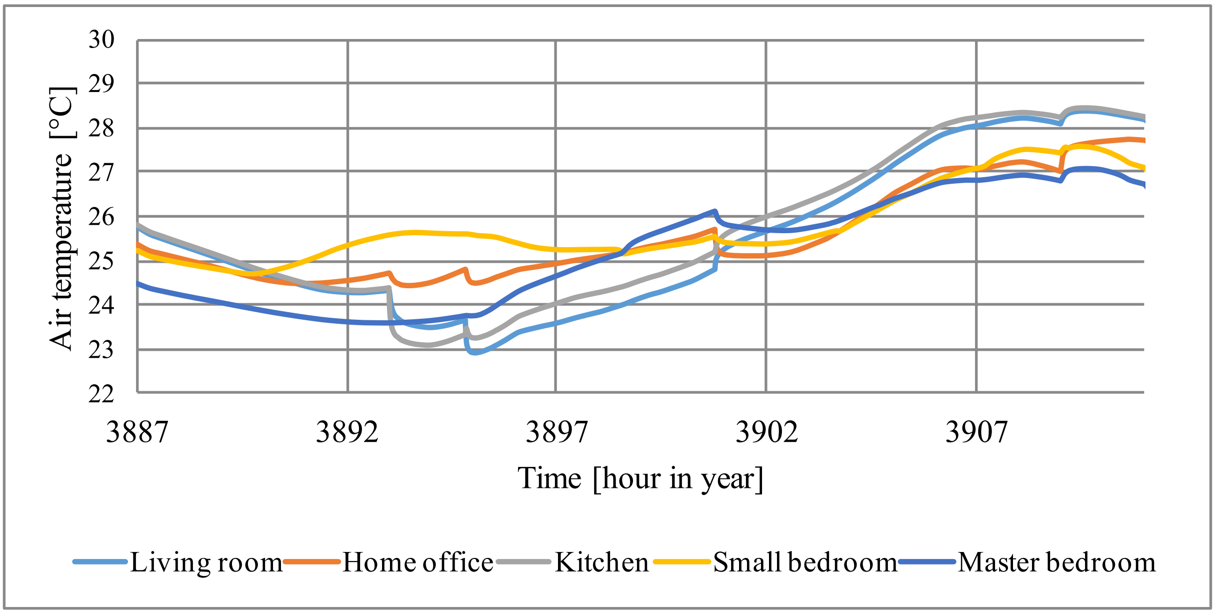


Figure (8.5): Temperatures on June 11th with living room facing west

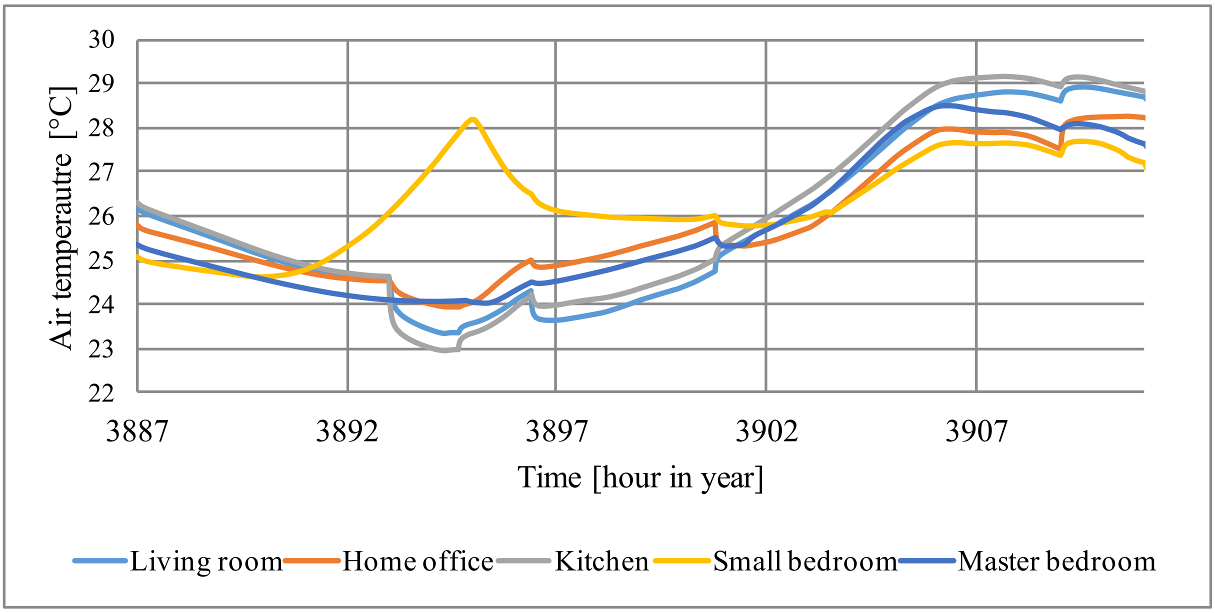


Figure (8.6): Temperatures on June 11th with living room facing north

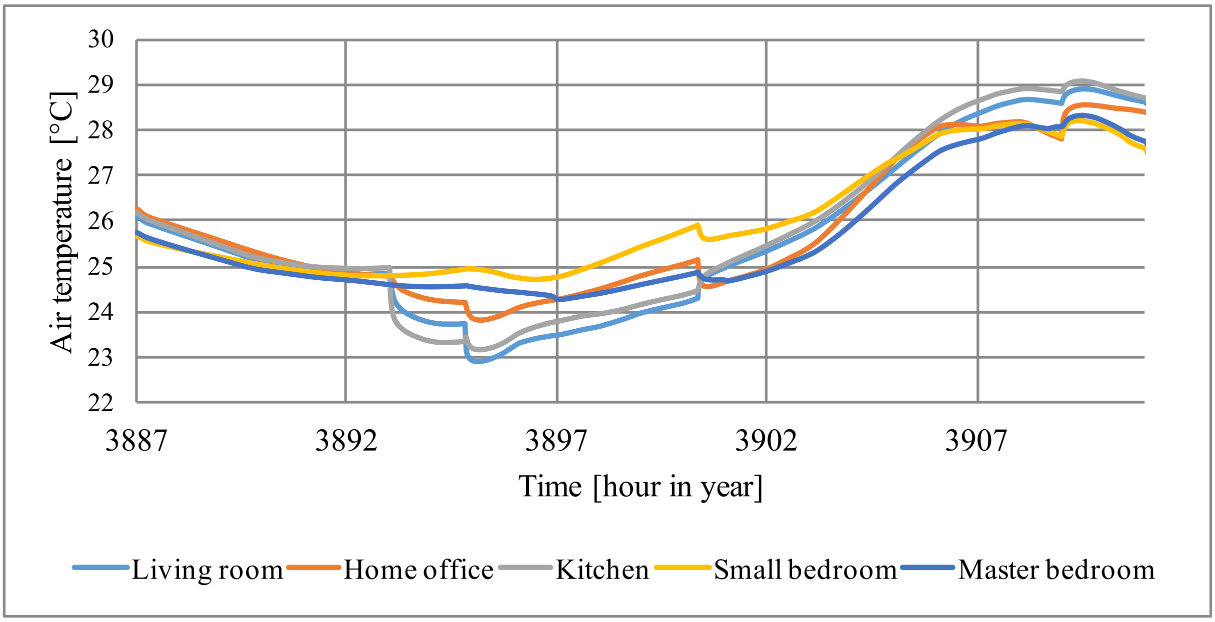


Figure (8.7): Temperatures on June 11th with living room facing east

The temperature graphs above show that the bedrooms varied the most in temperature when the building was turned. The day shown is a Saturday, so people were in their beds until 09 AM. This caused a large temperature increase in the bedroom facing the morning sun, as seen in Figures (8.4) and (8.6). The zones exposed to sun in the daytime or evening did not experience the same temperature increase, so it was the combination of a closed room with people in it, solar gains and no possibility for ventilative cooling that caused the increase. Today, the master bedroom of Living Lab is shielded from morning sun by a hill east of the building. In other locations, one should be careful to apply ventilative cooling in all rooms people occupy that has solar gains. Another thing to note is that when the living room faced east or north the general indoor temperatures in the evening were higher. This can be explained by the high solar gains through the windows in the kitchen and home office in the daytime and afternoon.

Table (8.7) shows the change in total thermal comfort and energy consumption when ventilative cooling is applied versus when all windows are closed. The total hours of window openings are also presented for both the window in the living room and the window in the home office.

Table (8.7): Increase in thermal comfort and energy consumption

	South	***East***	***North***	***West***
Decrease in hours of thermal discomfort	90.4 %	89.3 %	86.0 %	90.7 %
Increase of energy consumption	38.4 %	60.1 %	93.1 %	74.3 %
Hours of opening living room window [h]	167.9	151.8	178.6	188.2
Hours of opening office window [h]	67.0	64.4	57.0	69.7

There was no clear relation between decrease in hours of thermal discomfort an increase in energy consumption. The effect on the thermal comfort was largest when the building was turned to the west, and lowest when it was turned to the north. The energy consumption increased the most when the living room faced north. The hours of window openings are not higher than for other directions, so an explanation for the large increase in energy consumption could be that there is less pre-heating of air in the double skin window. When the building faced south and west it had solar irradiance on the double skin window during the window openings, and that helped keeping the energy consumption for heating low even though the hours of window openings were many. This highlights the positive effect of having the double skin window for natural ventilation when outside temperatures are cooler.

It is clear that having Living Lab with the living room facing south is by far the best choice for this window control algorithm. That resulted in the best total thermal comfort, the best or close to the best thermal comfort in each individual zone, and the lowest energy consumption for heating. Turning the building so that the living room faced north reduced the hours of thermal comfort by 49 h, and increased energy consumption for heating by 13.0 % compared to having the building facing the way it does today. Note that these numbers are for the months of May and June, not a whole year.

8.3.2 Level of insulation

Simulations were done with different insulation levels to investigate the effect of this natural ventilative cooling control in different types of buildings. It was decided to do simulations with three insulation levels; a building meeting the TEK10 U-value requirements, a low-energy building and a passive house. Insulation levels for the low-energy building and passive house were chosen as the lowest value in the range of typical values given in NS3700:2013. Table (8.8) shows the U-values of walls, roof and floor for the different simulations, and the average U-values of the building body including windows and doors. These simulations were done for May and June in Trondheim.

Table (8.8): U-values for simulation scenarios

	U-value walls [W/m^2]	***U-value floor [W/m^2]***	***U-value roof [W/m^2]***	***Average U-value [W/m^2]***
TEK10	0.18	0.15	0.13	0.20
Low-energy building	0.15	0.10	0.10	0.18
Passive house	0.10	0.08	0.08	0.15

8.3.2.1 Results and discussion

Table (8.9) presents the thermal comfort and energy consumption when applying ventilative cooling in buildings with different insulation levels.

Table (8.9): Thermal comfort and energy consumption with and without window cooling

	Hours of thermal discomfort in building		***Floor heating energy***	
	Value [h]	***Decrease***	***Value [kWh]***	***Increase***
TEK10 no cooling	193		282.4	
TEK10 ventilative cooling	33	82.9 %	327.7	16.0 %
Low-energy no cooling	280		155.1	
Low-energy ventilative cooling	41	85.4 %	176.9	14.1 %
Passive house no cooling	452		57.5	
Passive hours ventilative cooling	44	90.3 %	72.3	25.7 %

Without window cooling the thermal comfort was worse for lower U-values, because the heat got trapped within the building. However, when applying window cooling the thermal comfort is almost the same in the three simulated scenarios. This means that even though the result after applying ventilative cooling is nearly the same, the increase in thermal comfort is greater when the U-value of the building is low. This corresponds to the findings in literature that the potential of ventilative cooling is larger in well-insulated buildings (Finocchiaro et al., 2010). With this particular control, the hours of thermal discomfort decreased by 82.9 % in a building with TEK10 requirements, but decreased by 90.3 % in a passive house. This difference is explained by the large cooling potential in a well-insulated house where over-heating occurs more frequently.

The absolute increase in energy consumption is lowest when the U-value is lowest. Interestingly, the percentage increase in energy consumption when applying ventilative cooling is the smallest in a low-energy building. This can be explained by the very low energy consumption with passive house standard, where even the small amount of 14.8 kWh is a 25.7 % increase. Figures (8.8), (8.9) and (8.10) presents the temperatures in the living room and small bedroom in a cooling load simulation on the 15.07 with and without window cooling.

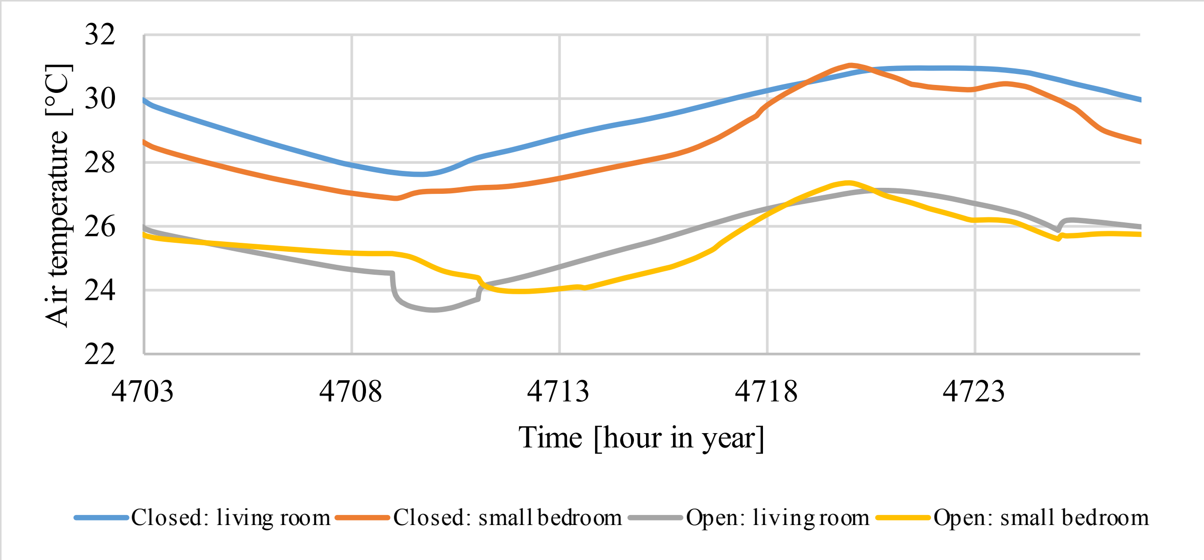


Figure (8.8): Temperatures in living room and small bedroom with and without ventilative cooling, TEK10 insulation levels. Cooling load simulation for 15th July.

Figure (8.9): Temperatures in living room and small bedroom with and without ventilative cooling, low-energy building insulation levels. Cooling load simulation for 15th July.

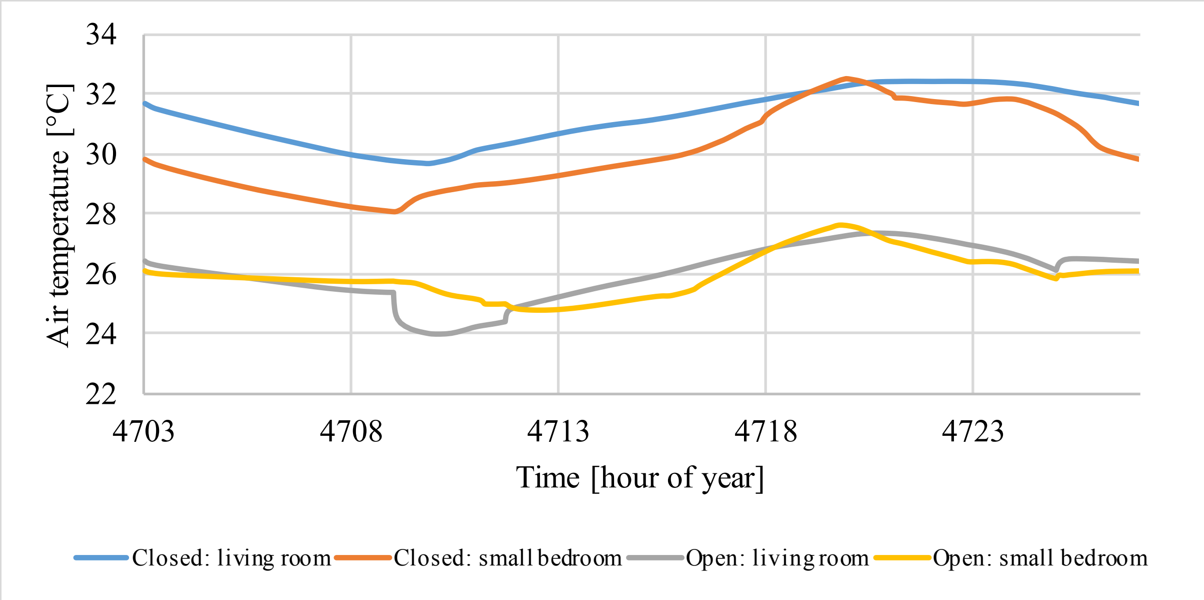


Figure (8.10): Temperatures in living room and small bedroom with and without ventilative cooling, passive house insulation levels. Cooling load simulation for 15th July.

As seen in Figures (8.8), (8.9) and (8.10), the temperatures are higher when the U-values are lower. Applying ventilative cooling will reduce the temperatures with about 4 °C with TEK10 or low-energy insulation levels, and with about 5 °C for a passive house. This is explained by the higher indoor temperatures with a passive house, which gives a higher cooling potential. In these simulations, the upper temperature limit for comfort category II is 27.9 °C. This means that ventilative cooling with 50 % and 25 % opening in the north and south windows is able to keep the temperatures at comfortable levels on a warm summer day for all three levels of insulation.

8.3.3 Location and climate

To investigate the effect of the chosen ventilative cooling control in different climates, full-year energy simulations were done for the five different locations and climates presented in Table (8.10). The ASHRAE IWEC2 weather files were downloaded from the EQUA Climate Data Download Center. Simulations were done with closed windows and with an on/off window control as described in Chapter 7.2.4. The reason for doing full-year simulations is that the heating, cooling and shoulder seasons are not the same months in the different locations.

Table (8.10): Locations and climate for different simulations

Location	***Latitude [°]***	***Elevation [m]***	***Average dry-bulb temperature [°C]***	***Average solar irradiance [W/m²]***
Trondheim Værnes	63.5	17	6.2	166.0
Oslo Gardermoen	60.2	204	4.7	188.5
Copenhagen Kastrup	55.6	5	8.8	146.4
Paris Orly	48.7	90	11.5	168.5
Rome Fiumicino	41.8	3	15.9	236.7

It was of interest to find the type of climate in which this ventilative cooling strategy has the most potential, therefore cities with different latitudes were chosen. Higher latitudes generally mean lower average temperatures, but also long, sunny days in summer.

8.3.3.1 Results and discussion

Table (8.11) shows the thermal comfort and energy consumption of the simulations done in the different locations.

Table (8.11): Thermal comfort and energy consumption in different climates

	Hours of thermal discomfort			***Heating and cooling energy***	
	Building total [h]	***Decrease [h]***	***Decrease [%]***	***Value [kWh]***	***Increase compared to closed windows***
Trondheim closed	664			5361.0	
Trondheim open	134	530	79.8 %	5392.4	0.6 %
Oslo closed	771			6350.7	
Oslo open	82	689	89.4 %	6392.3	0.7 %
Copenhagen closed	632			3909.4	
Copenhagen open	55	577	91.3 %	3933.0	0.6 %
Paris closed	1533			2456.2	
Paris open	461	1072	69.9 %	2522.0	2.7 %
Rome closed	3453			560.8	
Rome open	703	2750	79.6 %	638.6	13.9 %

The results showed that this type of window control would be able to keep thermal comfort within category I and II with less than 3 % error in Trondheim, Oslo and Copenhagen. For these three locations, the total thermal comfort in the building got higher the further south the building was located – although the variations were small. This could be due to warmer weather increasing the allowed indoor temperatures, or increasing the period of high outdoor temperatures that allows window cooling. Trondheim can get solar gains far into the evening while outdoor temperatures drop to below acceptable temperatures for window operation. Of the three cities, a building located in Copenhagen would have the largest decrease in hours of thermal discomfort percentagewise, but Oslo had the largest decrease when counting hours. the

For the locations further south – Paris and Rome – the hours of thermal comfort with window ventilation was less than 97 % of the hours of occupancy. Still, the ventilative cooling resulted in a larger absolute reduction of hours of thermal discomfort compared to the cooler climates. This means that a building in Rome would save more energy on ventilative cooling than a building in Copenhagen, even though Copenhagen has a larger decrease percentagewise. The increased potential of ventilative cooling in warmer climates corresponds to the findings in literature (Finocchiaro et al., 2010).

The energy consumption for heating of buildings located in Trondheim, Oslo and Copenhagen increased very little when ventilative cooling was applied, less than 1 % per year. Locations of Paris and Rome gave a slightly higher increase in energy consumption. Rome had the largest increase of 77.8 kWh/year, and Copenhagen the smallest of 23.6 kWh. These small differences suggest that the reason Rome and Paris had so large percentages of increase is because of the low energy consumption in the first place. Assuming an energy cost of 1 NOK/kWh, none of the locations would have increased the energy bill by more than 77.8 NOK/year when applying ventilative cooling with the chosen control. Essentially, applying ventilative cooling through windows is a cheap solution in all of the tested climates, once the investment of automatically controlled windows has been done.

The conclusion drawn from this comparison of building locations is that a Living Lab located in Copenhagen would have the best thermal comfort, with Living Labs in Oslo and Trondheim also performing very well. In all these locations, ventilative cooling using the chosen control would result in thermal comfort fulfilling the requirements in NS15251. Living Labs located in Paris and Rome would get more overheating than building standards allow with this control strategy – so other means of cooling would have to be applied. Another possible solution is to increase the window opening sizes, and open more of the windows in the building. It has not been evaluated whether passive cooling methods like solar shading and thermal inertia would lead to a satisfactory thermal climate.

8.4 New window design

It was decided to test another window design in the IDA ICE model to see if other windows would improve the performance of the ventilative cooling in Living Lab. Long, narrow windows were placed 2.9 m up on the wall in the living room and home office, and in each of the bedrooms, see Figure (8.11).

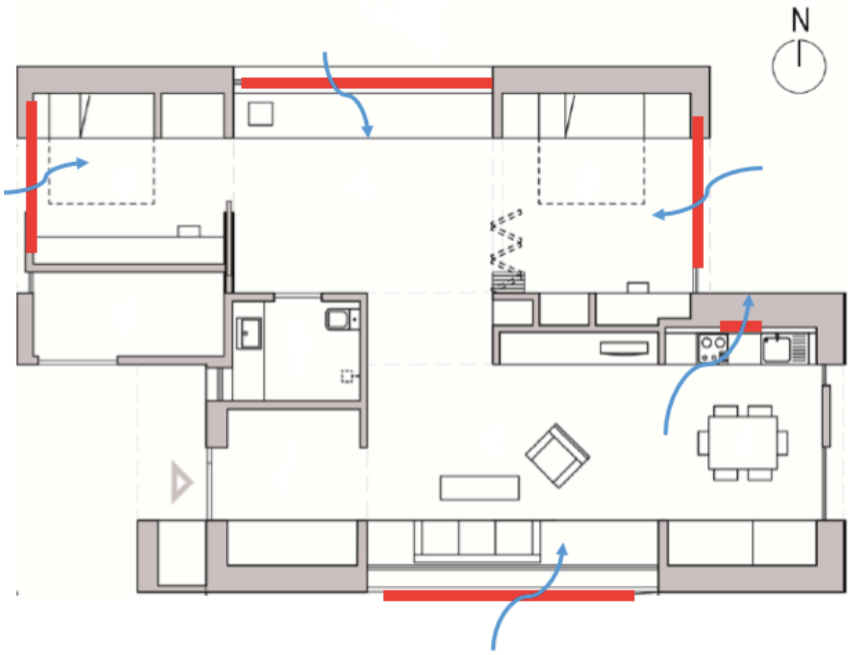


Figure (8.11): Placement of new windows in Living Lab

The windows in the living room and home office were 5 m wide and 0.1 m high, and the windows in the bedrooms were 3 m wide and 0.1 m high. These windows were supposed to imitate long and narrow bottom-hung windows, commonly used for natural ventilation. This type of window placed high on the wall should be better for the indoor climate because the air mixes with the room air like a jet before it enters the zone of occupancy (Heiselberg et al., 2001).

All scenarios used one kitchen skylight as outlet. Simulations were done using supply windows in different numbers of rooms, to see how this affects the thermal climate and energy consumption. Table (8.12) shows the simulated scenarios with this window design. A simulation with closed windows was also done for comparison.

Table (8.12): Scenarios with new window design

	Zones with inlet openings	***Control level***
1	Living room	Central
2	Living room and home office	Central
3	Living room, home office and both bedrooms	Central
4	Living room, home office and both bedrooms	Zonal
5	Living room and small bedroom	Zonal

Window ventilation was allowed when the temperature difference between the indoor and outdoor air was between 0 K and 10 K. These limits were chosen to easily compare the performance of the new windows to the original windows. The control algorithm was almost the same as the one presented in Appendix C, but the criteria for solar irradiance and wind speed were removed, and the opening percentage was 100 % for all windows.

For the first three scenarios, the average temperatures in the rooms with inlet openings are used to determine the start and finish of cooling, dubbed a central control. In the two last scenarios, the temperature in the individual zone will determine whether the window is opened or not, dubbed a zonal control. Findings in the literature review stated that the air flow from these types of windows are well approximated using the equations for a line jet flow (Heiselberg et al., 2001). IDA ICE calculates the air flow through a window, so the local air velocities and temperatures were calculated using the jet equations (6), and thereby the draught rates can be found with equation (2).

8.4.1 Results and discussion

Table (8.13) shows the thermal comfort and energy consumption of the different control strategies with new windows. Simulations were done for May and June in Trondheim. The results of the best window openings for the existing windows are shown for comparison.

Table (8.13): Thermal comfort and energy consumption with new window design

	Hours of thermal discomfort				***Heating and cooling energy***	
	Living room [h]	***Building total [h]***	***Decrease living room***	***Decrease building total***	***Value [kWh]***	***Increase compared to closed windows***
N50 %, S25 % (old windows)	13	38	69.7 %	87.5 %	145.1	15.0 %
No openings	129	372			126.2	
Living room	11	50	91.5 %	86.6 %	147.5	25.4 %
Living room and office	14	44	89.1 %	88.2 %	144.3	22.7 %
All rooms, central control	15	34	88.4 %	90.9 %	125.7	6.9 %
All rooms zonal control	14	31	89.1 %	91.7 %	162.5	38.2 %
Living room and small bedr.	14	49	89.1 %	86.8 %	161.3	37.2 %

The performance of the new windows was quite similar to that of the best option for the original windows. The total thermal comfort in the building decreased somewhat, except for the scenarios with window openings in all rooms. But, adding the new windows gave 69 h more overheating without window ventilation because of the increase in solar gains. This means that the ventilative cooling potential was higher, and the decrease in hours of thermal discomfort was higher.

The total thermal comfort increased when the number of zones with ventilative cooling inlets increased. Applying cooling in the warm zones only, living room and small bedroom, gave less thermal comfort than applying cooling in the living room and home office. This could be because of the smaller window size in the bedrooms. The simulations done with window openings in all rooms gave the best total thermal comfort of all scenarios with ventilative cooling. This was expected because cooling is applied to more zones.

The thermal comfort in the living room increased if cooling was only applied in the living room. When the cooling is only applied there, the temperature in the living room decides the window position, so the living room is always cooled to 22 °C, even if it means that temperatures drop in the other rooms. The thermal comfort in the bedrooms was very good when window ventilation was applied there.

The energy consumption was lower with the new windows than with the original design because of the increased solar gains, but the increase in energy consumption was – with one exception - higher with the new windows. A possible reason for this is that there is no longer any pre-heating of air before it enters the room. Also, when cooling is applied to more zones the need for heating in these zones will increase. Having ventilative cooling inlets in all rooms with a central control only gave a 6.9 % increase in energy consumption for heating compared to closed windows. The reason for this is that the windows are open for short periods of time, and the air in the building changes quickly before the surfaces in the rooms cool down. Because of the long window opening times, the zonal controls performed worse than the central controls in terms of energy consumption. The trend was that more hours of window ventilation resulted in higher heating demand. This is illustrated in Figure (8.12) that plots the energy consumption for heating against the total hours of window ventilation.

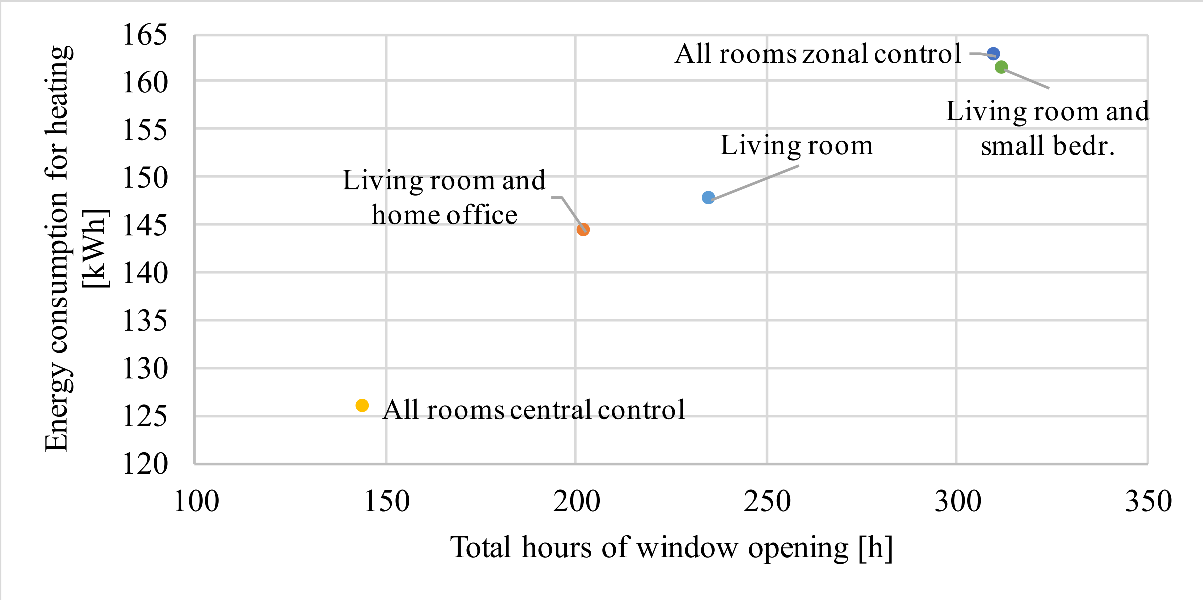


Figure (8.12): Energy consumption for floor heating against hours of window openings

Table (8.14) shows the mean and maximum draught rates in each room with the new window design. Using jet equations (6), the draught rates were calculated 1 m from each of the inlet windows.

Table (8.14): Mean and maximum draught rates with new window design

	DR in living room		***DR in home office***		***DR in small bedroom***		***DR in master bedroom***	
	Mean [%]	***Max [%]***	***Mean [%]***	***Max [%]***	***Mean [%]***	***Max [%]***	***Mean [%]***	***Max [%]***
Only living room	17.6	25.8						
Living room and home office	9.0	17.3	12.7	17.9				
All rooms, central control	4.1	13.5	9.8	14.8	13.1	20.2	13.2	18.3
All rooms, zonal control	13.2	25.1	9.0	22.6	10.5	24.8	7.4	12.9
Living room and small bedroom	13.4	30.2			10.3	22.0		

All the mean draught rates were within the chosen limit of 20 %, but the maximum draught rates exceeded the limit when cooling could be applied in one zone at the time – i.e. the zonal controls. The draught rates were lower when more windows were opened at the same time; for instance, the draught rates were significantly reduced when cooling was applied in both the living room and the home office compared to when it was applied in the living room alone.

This also means that the central control gave much lower maximum draught rates than the zonal control. The lower draught rates using the new window design backs up the findings in literature that bottom-hung windows gives low draught rates (Heiselberg et al., 2001).

8.4.2 Conclusion on new window design

The conclusion from the simulations with new window designs is that the best choice was to apply ventilative cooling to all rooms via a central control. This gave the second best total thermal comfort according to NS15251, the lowest draught rates as well as the lowest energy consumption. Using a higher number of windows for cooling increased the thermal comfort, both by comparing the room temperature with the NS15251 standards, and when calculating draught rates. The differences were largest when looking at the draught rates, for instance the average draught rate from the south window was reduced by 77 % when all windows were used compared to when only the south window was used.

Compared to the existing window design in Living Lab, the new window design performed roughly the same in most scenarios. When the new windows were installed in the living room and home office, the total thermal comfort decreased a little, but also the energy consumption. When new windows were installed in the bedrooms as well, the thermal comfort increased slightly, and the draught rates were kept low. The real benefit was that when all windows were controlled by a central control, the energy consumption only increased 6.9 % in May and June compared to keeping the windows shut at all times. This was the only window design and control principle with the new windows that outperformed the existing window design on all fronts.

A year-long simulation was done with the ventilative cooling option of a central control on windows in all rooms. The results of this is presented and compared to the best control with the original windows in Table (8.15).

Table (8.15): Year simulation

	Decrease in thermal discomfort living room	***Decrease in thermal discomfort total***	***Increase in energy consumption heating***
S25%, N50%	84.3 %	79.8 %	0.6 %
All rooms, central	84.7 %	82.9 %	0.4 %

As seen in Table (8.15), using the new windows in all rooms with a central control decreased the hours of thermal discomfort more while increasing the annual energy consumption less than the original windows. Now, the energy consumption for heating increased by 23.5 kWh per year. Given that there is no preheating of air with the new windows, it can be concluded that applying ventilative cooling this way is more energy efficient, and still gives a better thermal comfort. Per the validation of the IDA ICE model, the energy consumption for zone heating is overestimated in the model. This means that the energy consumption and increase in energy consumption in Living Lab will be lower than these numbers suggests.

8.5 Supplying hygienic ventilation through windows

The previous results in this chapter unanimously show that using natural ventilation for ventilative cooling will increase the energy consumption for heating of the building. It will therefore only increase the thermal comfort, not the energy efficiency of the building, unless mechanical cooling is installed. One possibility for reducing energy consumption is to turn off the mechanical ventilation system when it is possible to use only natural ventilation. Several of the example buildings studied in the literature review used this type of change-over hybrid ventilation, where natural ventilation is used alone if outdoor temperatures exceed a certain set point.

It was decided to test the energy saving potential of turning off the mechanical ventilation when outdoor conditions allowed it, and using the new windows in all rooms to supply hygienic ventilation. The central control using windows in all rooms had the lowest energy consumption in the ventilative cooling scenarios, so this control was chosen as the basis for the hygienic ventilation control as well. An on-off CO_2-control was added to this window control algorithm. In addition to cooling the building from 24 °C to 22 °C, the windows would now also open when the highest CO_2-concentration of any zone exceeded 800 ppm. The windows closed when the highest CO_2-concentration in any zone was below 700 ppm. These limits were chosen to keep CO_2-concentration below 900 ppm.

To simplify the algorithm, the previous requirement of a temperature difference below 10 K was changed. Now, window openings were allowed when the outdoor temperature was above 14 °C, which is 10 °C below the cooling start point. Window ventilation was also allowed at night in these scenarios, to maximize the possible hours of only natural ventilation. The ventilation system turned off when the outdoor temperatures were above a certain set point, which varied between the simulations. The detailed control algorithm is presented in Appendix D. Energy simulations were done for a year with the scenarios presented in Table (8.16). To evaluate the CO_2-removal efficiency of the windows, the scenarios with switch-over between mechanical and natural ventilation are compared to the scenario using concurrent mechanical and natural ventilation.

Table (8.16): Simulation scenarios to evaluate natural hygienic ventilation

		Ventilative cooling with windows if…	***Hygienic ventilation with windows when…***
1	AHU on	T_{out} > 14 °C	never
2	AHU off if T>14	T_{out} > 14 °C	T_{out} > 14 °C
3	AHU off if T>16	T_{out} > 14 °C	T_{out} > 16 °C
4	AHU off if T>18	T_{out} > 14 °C	T_{out} > 18 °C

8.5.1 Results and discussion

Table (8.17) compares the hours of CO_2-concentrations above 900 ppm and 1200 ppm in the living areas and bedrooms for the scenarios with window ventilation.

Table (8.17): Hours of CO_2-levels above 900 and 1200 ppm

	Hours above 900 ppm [h]		***Hours above 1200 ppm [h]***		***Highest***
	Living areas	***Bedrooms***	***Living areas***	***Bedrooms***	***CO_2-level***
AHU on	621	2172	1	0	1262 ppm
AHU off if T_{out} > 14 °C	490	2097	1	17	1335 ppm
AHU off if T_{out} > 16 °C	567	2162	1	16	1342 ppm
AHU off if T_{out} > 18 °C	605	2191	1	15	1335 ppm

When mechanical ventilation was on all the time, the CO_2-levels reached approximately 930 ppm every night in the bedrooms. This is the reason for the high number of hours with CO_2-concentration above 900 ppm. The number of hours of CO_2-levels above 900 ppm decreased when the hygienic ventilation was applied through windows. This is because the air flows from the windows exceeded the air flows from the mechanical ventilation most of the time, and removed CO_2 faster. However, the hours of CO_2-concentrations above 1200 ppm increased when the mechanical ventilation system was turned off for parts of the year. This happened on the warmest days when the buoyancy forces were unable to produce satisfactory air flow rates. The peak CO_2-concentration increased about 6 % when the mechanical system turned off, this also happened during the warmest days. This indicates that the mechanical ventilation system is necessary on the warmest days of the year. But, the natural ventilation system gives better indoor air quality on most days.

The energy consumption for heating and ventilation was the same for all scenarios from October to April, but using the windows for hygienic ventilation decreased the energy consumption in the summer months. Figure (8.13) shows the energy consumption for heating and ventilation for each scenario from May to September. More detailed results regarding thermal comfort, change in energy consumption and window opening duration are presented in Table (8.18).

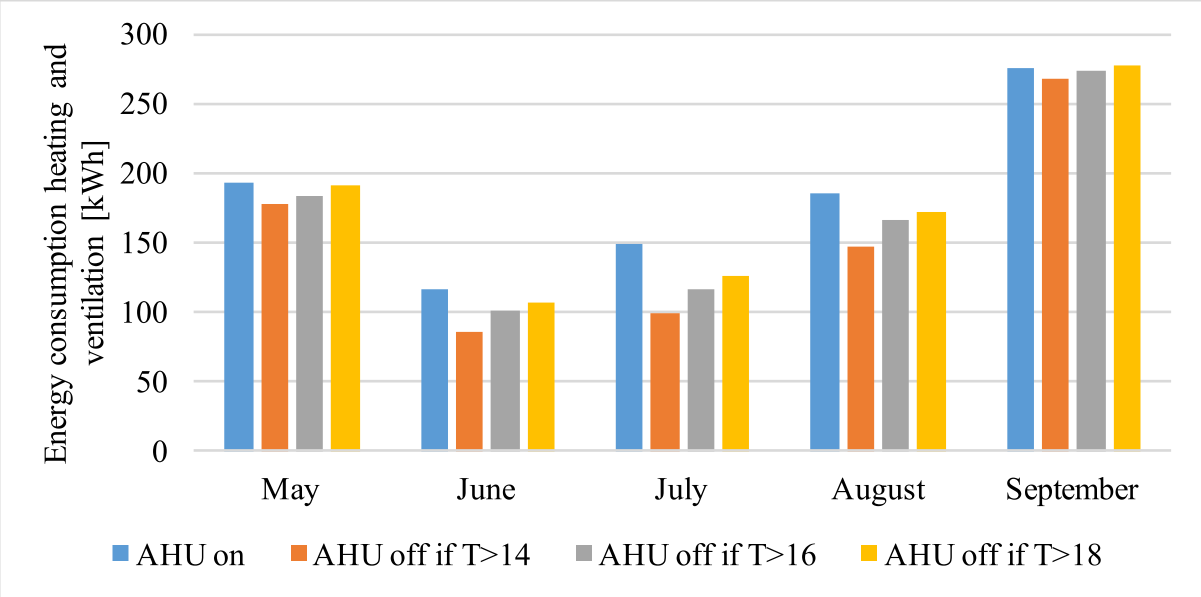


Figure (8.13): Energy consumption for summer months

Table (8.18): Hours of thermal discomfort and change in annual energy consumption

	AHU on	*AHU off if T_{out}>14°C*	*AHU off if T_{out}>16°C*	*AHU off if T_{out}>18°C*
Hours of thermal discomfort per year	81 h	104 h	104 h	105 h
Annual energy consumption for heating and ventilation	6750 kWh	6601 kWh	6670 kWh	6704 kWh
Change in annual energy consumption for heating	-	- 0.2 %	- 0.1 %	- 0.1 %
Change in annual energy consumption for ventilation	-	-12.9 %	-7.7 %	-4.2 %
Change in total annual energy consumption	-	-2.2 %	-1.2 %	-0.7 %
Hours of window openings per year	576 h	687 h	642 h	595 h

As seen in Figure (8.13), the energy consumption decreased when the mechanical ventilation was turned off at lower outdoor temperatures. The energy consumption for both space heating and the AHU fan decreased. An explanation of the decrease in energy consumption for heating is that when the CO_2-concentration exceeds 800 ppm the windows open, even if the indoor temperatures are low. This means that if the mechanical ventilation is on during window openings, the air change rate will be much higher than necessary to control CO_2-concentration and cause undercooling of the building. Therefore, it is more energy efficient to turn the mechanical ventilation off if window ventilation is needed to control CO_2-levels. The thermal comfort was the same with switch-over temperatures at 14 °C, 16 °C and 18 °C, but the energy consumption decreased when the mechanical ventilation was turned off at lower temperatures. The scenario where the mechanical ventilation was turned off at 14 °C gave the lowest energy consumption in all the months. When the windows ware used for hygienic ventilation in addition to ventilative cooling, the hours of window openings increased, and peaked at 687 h per year when the AHU turned off at 14 °C. So, in this case increased hours of window openings lead to reduced energy consumption.

All the simulations resulted in thermal comfort within the chosen acceptable limit of 259 hours of thermal discomfort per year. The hours of thermal discomfort increased by approximately 28 % when the mechanical ventilation was turned off for parts of the year. This is because the total airflow is reduced, meaning that the warm air in the room is replaced at a slower pace. Also, the mechanical ventilation system is a reliable source of ventilation when the outdoor temperatures are high and the stack effect inefficient. This shows the necessity of the mechanical ventilation system when natural forces are unable to drive ventilation.

The draught rates in front of the windows in the three scenarios with window operation are presented in Table (8.19).

Table (8.19): Mean and maximum draught rates

	DR in living room		***DR in home office***		***DR in small bedroom***		***DR in master bedroom***	
	Mean [%]	***Max [%]***	***Mean [%]***	***Max [%]***	***Mean [%]***	***Max [%]***	***Mean [%]***	***Max [%]***
AHU on	9.0	16.9	12.0	20.0	8.2	14.1	7.7	11.9
AHU off if T_{out} > 14 °C	7.2	17.3	11.6	19.9	8.2	14.2	8.0	12.0
AHU off if T_{out} > 16 °C	8.4	16.9	12.0	20.1	8.1	14.1	7.7	11.9
AHU off if T_{out} > 18 °C	8.4	16.9	11.9	20.0	8.1	14.1	7.8	11.9

As seen in Table (8.19), both the mean and maximum draught rates were within the 20 % limit for all windows in all scenarios, ignoring the 20.1 % maximum DR in the home office when mechanical ventilation turns off at 16 °C. Additionally, the draught rates were approximately the same for all scenarios. On basis of this, the draught rates will not limit or differentiate the scenarios.

Turning the mechanical ventilation system off when the outdoor temperature exceeded 14 °C was the most energy efficient solution and gave the least number of hours with CO_2-concentration above 900 ppm. With this solution it is possible to apply ventilative cooling to achieve thermal comfort and at the same time reduce the annual energy consumption for heating and ventilation by 2.2 %, or 149 kWh/year. However, this solution gave a small increase in hours of thermal discomfort, and hours of CO_2-concentration above 1200 ppm. Both of these can be compensated for by turning on the mechanical ventilation when indoor temperatures or CO_2-concentrations get very high, but that will in turn increase the energy consumption.

In the validation of the IDA ICE model it was concluded that the simulations underestimated the energy consumption of the AHU and overestimated the energy consumption for zone heating. This means that reducing the use of mechanical ventilation will be even better for the energy efficiency than these simulations suggests.

Chapter 9 Conclusion

Cross-stack natural ventilation through automatically controlled windows was chosen as the best way to apply ventilative cooling in Living Lab. The preferred control algorithm was an on-off control that used indoor temperatures, CO_2-concentration and weather conditions to determine the window openings. This type of ventilative cooling system had been used in other highly insulated buildings with good results.

Experiments with stack ventilation in Living Lab were conducted, using the south or north window to supply cool air, and one kitchen skylight to extract warm air. The results showed that the south window could be used to supply natural ventilation at lower outdoor temperatures than the north window, because of the preheating of air in the window cavity. The draught rate in front of the south window increased with temperature difference and wind speed, and decreased with solar irradiance, but there were still large variances. Window opening percentages up to 25 % were deemed acceptable at climatic conditions where the temperature differences were below 10 K, the solar irradiance above 70 W/m^2 and the wind speed below 2 m/s. The draught rates in front of the north window increased with the temperature differences. When the temperature difference was below 6 K the window could be opened up to 50 % while still keeping draught rates in the zone of occupancy low. The north window was more efficient than the south window for cooling the building when outdoor temperatures were high.

IDA ICE simulations were done with ventilative cooling from the acceptable window openings, and showed good results in terms of thermal comfort. The total hours of thermal discomfort decreased from 303 h/year to 38 h/year in the best option, which was using the largest allowed window opening sizes of 25 % in the south window and 50 % in the north window. That meant that thermal comfort was achieved for 98.9 % of the hours of occupancy. The energy consumption increased when ventilative cooling was applied, but only by 31.4 kWh/year using the largest allowed window openings.

Simulations showed that this ventilative cooling strategy worked best when the living room faces south, as it does today. This gave the best utilization of the pre-heating in the south window. The solution gave good thermal comfort in both highly insulated buildings and buildings meeting TEK10 requirements, but the effect of the ventilative cooling was higher in highly insulated buildings because of the high occurrence of overheating. The chosen solution worked best in cool climates, giving thermal comfort within requirements. However, the number of hours of thermal discomfort was reduced more in warmer climates. Out of the tested locations, the control strategy gave the best thermal comfort in Copenhagen.

Changing the windows to narrow, bottom-hung windows, and adding windows in the bedrooms, resulted in slightly improved cooling efficiency compared to the existing windows. The energy consumption for heating increased more with the new windows than with the old windows, except for when all windows were opened at the same time using a central control. That gave the lowest increase in energy consumption, 23.5 kWh/year, while still maintaining good thermal comfort. It was found that more hours of window openings lead to higher energy consumption, so using the new windows with the central control was more effective and needed less hours of opening to cool the building to the same temperatures.

If the mechanical ventilation system was turned off when the outdoor temperatures were high, it was possible to reduce the energy consumption of the building while still applying ventilative cooling and hygienic ventilation through the windows. The most energy-efficient option was to turn the mechanical ventilation off when the outdoor temperatures were above 14 °C. This could save 2.2 % of the annual energy for heating and ventilation, 149 kWh/year, and still keep hours of thermal discomfort within the accepted limits. It also gave sufficient hygienic ventilation for most days, but the mechanical ventilation system should be used on the warmest days when the buoyancy effect is weak.

Chapter 10 Suggestions for further work

Ventilative cooling strategies could be tested in Living Lab by programming the windows, so that the real performance of the system could be evaluated both in terms of thermal comfort and energy consumption. This could also be done while people occupy Living Lab to get used feedback on the ventilative cooling system.

Studies can be done to evaluate the combination of using both active solar shading and ventilative cooling in Living Lab at the same time, in terms of thermal comfort and energy consumption.

The ventilation efficiency of both the mechanical and natural ventilation systems in Living Lab should be experimentally tested, to find dead zones where it is important to supply air.

A similar ventilative cooling strategy could be tested, experimentally or via simulations, in different buildings. This will determine if the solution is particularly suited to Living Lab, or if it applies well to different buildings types and geometries.

The solution could be tested with different levels of thermal mass, especially in warmer regions, and in combination with night-time ventilation.

Chapter 11 Bibliography

ALLARD, F. 1998. *Natural ventilation in buildings - a design handbook,* London, James & James.

BAETENS, R., JELLE, B. P. & GUSTAVSEN, A. 2010. Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings,* 42**,** 1361-1368.

BERGE, M. & MATHISEN, H. M. 2016. Perceived and measured indoor climate conditions in high-performance residential buildings. *Energy and Buildings,* 127**,** 1057-1073.

BERGERSEN ARKITEKTER 2013. rev E Snitt D A30-103 ZEB Living Lab. *Unpublished drawings.* Trondheim.

BLANDKJENN, S. 2016. Ventilative cooling of Zero Emission Buildings (ZEB). *Unpublished work.* Trondheim: NTNU.

BRAGER, G. S. & DE DEAR, R. J. 1998. Thermal adaptation in the built environment: a literature review. *Energy and Buildings,* 27**,** 83-96.

CARLOS, J. S. & CORVACHO, H. 2013. Ventilated Double Window for the Preheating of the Ventilation Air Comparison of Its Performance in a Northern and a Southern European Climate. *Journal of Renewable Energy,* 2013**,** 11.

COOLVENT. 2017. *Basics of Natural Ventilation* [Online]. Available: http://coolvent.mit.edu/intro-to-natural-ventilation/basics-of-natural-ventilation/ [Accessed 07.06.2017].

DE DEAR, R. J. & BRAGER, G. S. 2002. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings,* 34**,** 549-561.

DELSANTE, A. & VIK, T. A. 2002. Hybrid Ventilation State-of-the-art Review. http://www.hybvent.civil.aau.dk/index.htm: International Energy Agency.

DELTA OHM. 2007. *LP PYRA 03 Piranometers* [Online]. Available: http://www.deltaohm.com/ver2012/index.php?main_page=product_info&cPath=1_17&products_id=212 [Accessed 30.05.2017].

DELTA OHM. 2016. *HD 52.3D Two axis ultrasonic anemometer* [Online]. Available: http://www.deltaohm.com/ver2012/index.php?main_page=product_info&cPath=1_17&products_id=106 [Accessed 30.05.2017].

DHALLUIN, A. & LIMAN, K. 2012. Comparison of natural and hybrid ventilation strategies used in classrooms in terms of indoor environmental quality, comfort and energy savings. *Indoor and Built Environment,* 23**,** 527-542.

DIREKTORATET FOR BYGGKVALITET 2010. TEK 10 Veiledning til tekniske krav i byggverk.

EQUA SIMULATION. 2017. *IDA Indoor Climate and Energy* [Online]. Available: http://www.equa.se/en/ida-ice [Accessed 31.05.2017].

FAGGIANELLI, G. A., BRUN, A., WURTZ, E. & MUSELLI, M. 2014. Natural cross ventilation in buildings on Mediterranean coastal zones. *Energy and Buildings,* 77**,** 206-218.

FINOCCHIARO, L., WIGENSTAD, T. & HESTNES, A. G. Potential of passive cooling, natural ventilation and solar control in cold climates office buildings. Renewable Energy Conference, 2010 Trondheim.

FRACASTORO, G. V., MUTANI, G. & PERINO, M. 2002. Experimental and theoretical analysis of natural ventilation by windows opening. *Energy and Buildings,* 34**,** 817-827.

GOIA, F. 2016. LIVING-LAB_Monitoring_and_control_systems.xlsx. Private communication 29.11.2016.

GOIA, F., FINOCCHIARO, L. & GUSTAVSEN, A. 2015. The ZEB Living Laboratory at the Norwegian University of Science and Technology: a zero emission house for engineering and social science experiments. *7PHN Sustainable Cities and Buildings.* Copenhagen: The Research Centre on Zero Emission Buildings

GOIA, F., GRYNNING, S., FINOCCHIARO, L. & GUSTAVSEN, A. 2014. The ZEB Living Lab: a multi-purpose experimental facility. *IEA EBC Annex 58 Expert Meeting.* Ghent: The Research Centre on Zero Emission Buildings.

HEISELBERG, P. 2002. PRINCIPLES of HYBRID VENTILATION. *In:* AGENCY, I. E. (ed.) *Annex 35: Hybrid Ventilation in New and Retrofitted Office Buildings.*

HEISELBERG, P., SVIDT, K. & NIELSEN, P. V. 2001. Characteristics of airflow from open windows. *Building and Environment,* 36**,** 859-869.

HERKEL, S., KNAPP, U. & PFAFFEROTT, J. 2008. Towards a model of user behaviour regarding the manual control of windows in office buildings. *Building and Environment,* 43**,** 588-600.

HUMPHREYS, M. A. & NICOL, J. F. 1998. Understanding the Adaptive Approach to Thermal Comfort. *ASHRAE Transactions,* 1998**,** 991-1004.

KIRKØEN, C. 2015. *Ventilative cooling in Living Lab.* Master's thesis, Norwegian University of Science and Technology.

KLEIVEN, T. 2007. Brukerundersøkelse i Husby Amfi. *SINTEF Report SBF BY A07022.* Trondheim: SINTEF Byggforsk.

KOLOKOTRONI, M. & HEISELBERG, P. 2015. Annex 62 Ventilative cooling state-of-the-art review. http://venticool.eu/annex-62-publications/: International Energy Agency.

LARSEN, T. S. 2006. *Natural Ventilation Driven by Wind and Temperature Difference.* Ph.d.-afhandling, Aalborg University.

MATH OPEN REFERENCE. 2011. *Heron's Formula for the area of a triangle* [Online]. Available: http://www.mathopenref.com/heronsformula.html [Accessed 07.06.2017].

MAXIM INTEGRATED. 2017. *DS1920 iButton Temperature Logger* [Online]. Available: https://www.maximintegrated.com/en/products/digital/ibutton/DS1920.html [Accessed 30.05.2017].

MICHAEL, A., DEMOSTHENOUS, D. & PHILOKYPROU, M. 2017. Natural ventilation for cooling in mediterranean climate: A case study in vernacular architecture of Cyprus. *Energy and Buildings,* 144**,** 333-345.

MISHRA, A. K., LOOMANS, M. G. L. C. & HENSEN, J. L. M. 2016. Thermal comfort of heterogeneous and dynamic indoor conditions — An overview. *Building and Environment,* 109**,** 82-100.

MLECNIK, E., SCHÜTZE, T., JANSEN, S. J. T., DE VRIES, G., VISSCHER, H. J. & VAN HAL, A. 2012. End-user experiences in nearly zero-energy houses. *Energy and Buildings,* 49**,** 471-478.

NILSSON, P.-E. & THE COMMTECH, G. 2003. *Achieving the desired indoor climate : energy efficiency aspects of systems design,* Lund, Studentlitteratur.

NORTHERN REGIONAL BUILDING RESEARCH INSTITUTE 2015. Design guideline of window for outdoor air cooling. Unpublished report: Northern Regional Building Research Institute, Building Research Department, Local Independent Administrative Agency Hokkaido Research Organization.

NOVAKOVIC, V., HANSSEN, S. O., THUE, J. V., WANGENSTEEN, I. & GJERSTAD, F. O. 2012. *TEP 4235 Energy Management in Buildings,* Trondheim, Norwegian University of Science and Technology.

OROPEZA-PEREZ, I. 2015. Assessment of Natural Ventilation within Buildings Located on Hot-temperate and Mild-temperate Regions. *Energy Procedia,* 78**,** 1513-1518.

OROPEZA-PEREZ, I. & ØSTERGAARD, P. A. 2014. Potential of natural ventilation in temperate countries – A case study of Denmark. *Applied Energy,* 114**,** 520-530.
PERÉN, J. I., VAN HOOFF, T., LEITE, B. C. C. & BLOCKEN, B. 2015. CFD analysis of cross-ventilation of a generic isolated building with asymmetric opening positions: Impact of roof angle and opening location. *Building and Environment,* 85**,** 263-276.
PROSJEKTUTVIKLING MIDT-NORGE AS 2015. Systemskjema Living Lab NTNU. Unpublished technical drawing of heating plant.
RISNES, A. 2016. *Indoor Environment in ZEB Living Lab.* Master's thesis, Norwegian University of Science and Technology.
ROETZEL, A., TSANGRASSOULIS, A., DIETRICH, U. & BUSCHING, S. 2010. A review of occupant control on natural ventilation. *Renewable and Sustainable Energy Reviews,* 14**,** 1001-1013.
S+S REGELTECHNIK. 2017. *RTF1 PT100* [Online]. Available: https://spluss.de/en/products/temperature/temperature-passive/room-temperature-sensor/1101-40a0-1003-000-rtf1-pt100/ [Accessed 30.05.2017].
SARTORI, I., WACHENFELDT, B. J. & HESTNES, A. G. 2009. Energy demand in the Norwegian building stock: Scenarios on potential reduction. *Energy Policy,* 37**,** 1614-1627.
SCHULZE, T. & EICKER, U. 2013. Controlled natural ventilation for energy efficient buildings. *Energy and Buildings,* 56**,** 221-232.
SENSOR ELECTRONIC. 2017. *AirDistSys 5000 air distribution measuring system* [Online]. Available: http://www.sensor-electronic.pl/pdf/KAT_AirDistSys5000.pdf [Accessed 30.05.2017].
SKÅRET, E. 2000. *Ventilasjonsteknisk Håndbok,* Oslo, Byggforsk.
SPINDLER, H. C. & NORFORD, L. K. 2009. Naturally ventilated and mixed-mode buildings—Part II: Optimal control. *Building and Environment,* 44**,** 750-761.
STANDARD NORGE 2006. NS-EN ISO 7730:2005. *Ergonomi i termisk miljø - Analytisk bestemmelse og tolkning av termisk velbefinnende ved kalkulering av PMV- og PPD-indeks og lokal termisk komfort.*
STANDARD NORGE 2013. NS 3700:2013 *Kriterier for passivhus og lavenergibygninger Boligbygninger.*
STANDARD NORGE 2014. NS-EN-15251:2007 + NA:2014 *Inneklimaparametere for dimensjonering og vurdering av bygningers energiytelse inkludert inneluftkvalitet, termisk miljø, belysning og akustikk.*
THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION. 2012. *DIRECTIVE 2012/27/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (Text with EEA relevance)* [Online]. Available: http://eur-lex.europa.eu/legal-content/en/TXT/?uri=celex%3A32012L0027 [Accessed 15.12.2016].
THE RESEARCH CENTRE ON ZERO EMISSION BUILDINGS (ZEB) 2017. ZEB Final Report 2009–2017. Trondheim.
UNITED NATIONS CENTRE FOR HUMAN SETTLEMENTS 1990. *National design handbook prototype on passive solar heating and natural cooling of buildings*, United Nations Centre for Human Settlements (Habitat).
VON GRABE, J., SVOBODA, P. & BÄUMLER, A. 2014. Window ventilation efficiency in the case of buoyancy ventilation. *Energy and Buildings,* 72**,** 203-211.

Appendix A Calculating window opening percentage

See methods for calculating the window opening areas below.

A.1 South window

The double skin window in the south façade opens as a casement window. The opening area is calculated using the following equations

$$A_{opening} = a * H + 2 * \sqrt{p(p-a)(p-B)(p-B)}, \quad \text{where } p = (B + B + a)/2. \tag{A.1}$$

The triangles on the top and bottom of the window opening is calculated using Heron's formula for area of a triangle with three known sides (Math Open Reference, 2011). Figure (A.1) shows the parameters in equations (A.1).

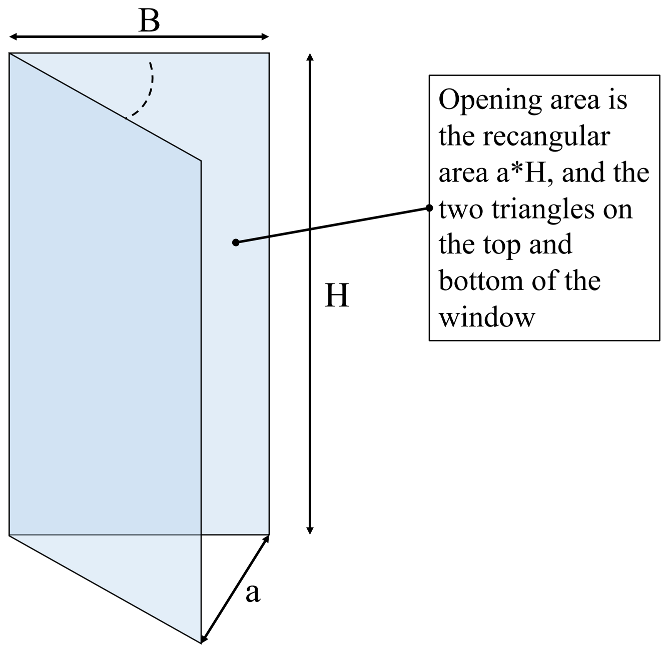


Figure (A.1): Parameters for calculating the opening area of the south window

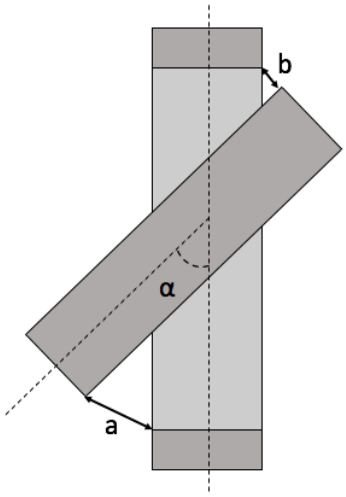
With B equal 0.85 m, H equal 1.965 m and a_{max} equal 0.405 m, the maximum window opening area of the south window is 1.13 m^2. The opening areas in Table (5.4) are found by multiplying the maximum area with the window opening percentage.

A.2 North window

The north window is a top-hung outward opening window. The opening area is calculated as follows

$$A_{opening} = L * (a + b) + \frac{a^2}{\sin(\alpha)} + \frac{b^2}{\sin(\alpha)}, \tag{A.2}$$

where the first part calculates the area of the long, rectangular part of the opening, and the two last parts estimate the area of the triangular openings on the sides of the window. Figure (A.2) illustrates the parameters in equation (A.2).



It has been measured that for maximum window opening, α is 51 °, a is 0.23 m and b is 0.09 m. The length of the window, L, is 2.21 m. The maximum opening area of the north window is then 0.786 m^2. The opening areas in Table (5.4) are found by multiplying the maximum area with the window opening percentage.

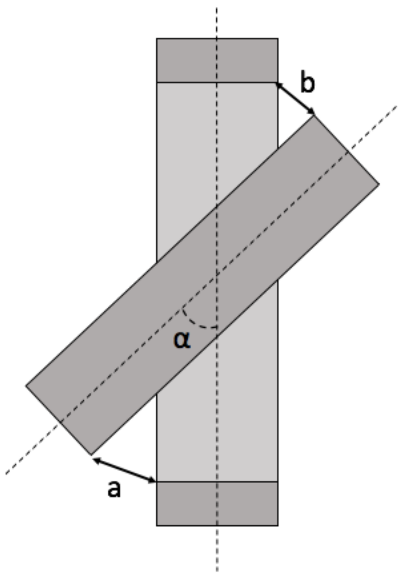
Figure (A.2): North window in side view

A.3 Skylight windows

The skylight windows are calculated using equation (A.3);

$$A_{open} = L * (a + b) + \frac{a^2}{\tan(\alpha)} + \frac{b^2}{\tan(\alpha)}, \tag{A.3}$$

where the first part calculates the area of the long, rectangular part of the opening, and the two last parts estimate the area of the triangular openings on the sides of the window. The parameters in equation (A.3) are indicated in Figure (A.3).



It has been measured that for maximum window opening, α is 32 °, a is 0.205 m and b is 0.22 m. The length of the window, L, is 0.455 m. The maximum opening area of a skylight window is then 0.338 m^2.

Figure (A.3): Skylight window in side view

Appendix B Validation of the IDA ICE model of Living Lab

The IDA ICE model of Living Lab has been validated to make sure that it is accurate enough to use in further work. The validation periods are 23.08.16, 24.08.16 and 09.11.16. These days were chosen to represent both summer and winter conditions, and the summer days contained window experiments so that the cooling effect of the windows could be validated as well. Table (B.1) contains some of the important input to the simulation model for the days of validation. Table (B.2) shows the window opening schedule of the days of validation.

Table (B.1): IDA ICE input for validation

	23.08.16 to 24.08.16	***09.11.16***
Lights	200 W in the living room from 10.00 to 15.00 on the 24.08.16	Off
Occupants	One person present in living room 10.00-15.00 the 24.08.16, 1 MET and 0.85 clo.	One person present in living room 15.00-16.00, 1 MET and 1.0 clo.
Equipment	Constant heat load of 20 W in entrance, 200 W in tech. room, 20 W in home office, 90 W in kitchen, 15 W in living room. Additional 45 W in living room 10.00-15.00 the 24.08.16.	Same constant heat load as the 23.08.16 and 24.08.16.
Heating power	20 W/m^2 floor heating	20 W/m^2 floor heating
Heating setpoint	Home office and bedrooms: 22 °C at all times Living room, kitchen, entrance and bathroom: 22 °C before 12.30 on the 23.08.16, and 28 °C after 12.30 the 23.08.16	22 °C in all rooms
Mechanical ventilation	Off from 10.30 the 23.08.16 to 15.30 the 24.08.16. On otherwise, with supply air temperature of 22 °C.	Always on with supply air temperature of 19 °C.
Natural ventilation	A natural ventilation experiment was conducted from 10.00 to 15.00 on the 24.08.16. More details in Table (B.2).	None.

Table (B.2): Window sequence for natural ventilation experiment on the 24.08.16

Window combination	***Time opened***	***Time closed***
Two north 100 %	10.09	10.27
Two north and one south 100 %	11.40	12.00
Two north and two kitchen 100 %	10.47	11.10
Two north, two kitchen and two mezzanine 100 %	13.12	13.34
Two north and two mezzanine 100 %	12.35	12.51
All windows 100 %	14.21	14.39
Two north and kitchen door 100 %	15.00	15.10

Outdoor temperature, relative humidity, wind conditions and global solar irradiance were measured by the weather station on the roof of Living Lab, and these values were used as the climate file for the validation periods.

B.1 Sources of error in the IDA ICE model of Living Lab

The climate file is a source of error because the measuring equipment in the weather station could be uncalibrated, and the local climatic conditions on the roof of Living Lab could be different than the average conditions on the site of the building. Also, the global solar irradiance is measured in the south façade and not on a flat surface, with the climate file in IDA ICE treats it as. The solar shading and internal gains are approximations made from the data in the BMS system, and could cause systematic errors in the simulation model.

The installed heating system in Living Lab is most likely not as good as the planned system, indicated by lower indoor temperatures than setpoint temperatures even in the summer. As long as the installed power in Living Lab is uncertain it is hard to get a very accurate IDA ICE model of the building.

Other sources of errors are the sensors in Living Lab measuring temperatures, power consumption etc. These have not been calibrated and have their own margins of error. Also, total mixing of the air is assumed in IDA ICE, while the real values for temperature and IAQ are only measured at certain points in each room. This is accounted for by using an average of all temperatures measured in a room to compare with the IDA ICE value. The CO_2-concentration is only measured in one point in the zone of occupancy in each room and that the measured value is assumed to be higher than the IDA ICE value.

B.2 Comparison of real measurements and simulations

B.2.1 Indoor air temperatures

Figure (B.1) shows the real and simulated indoor air temperatures on the 23.08.16 and 24.08.16.

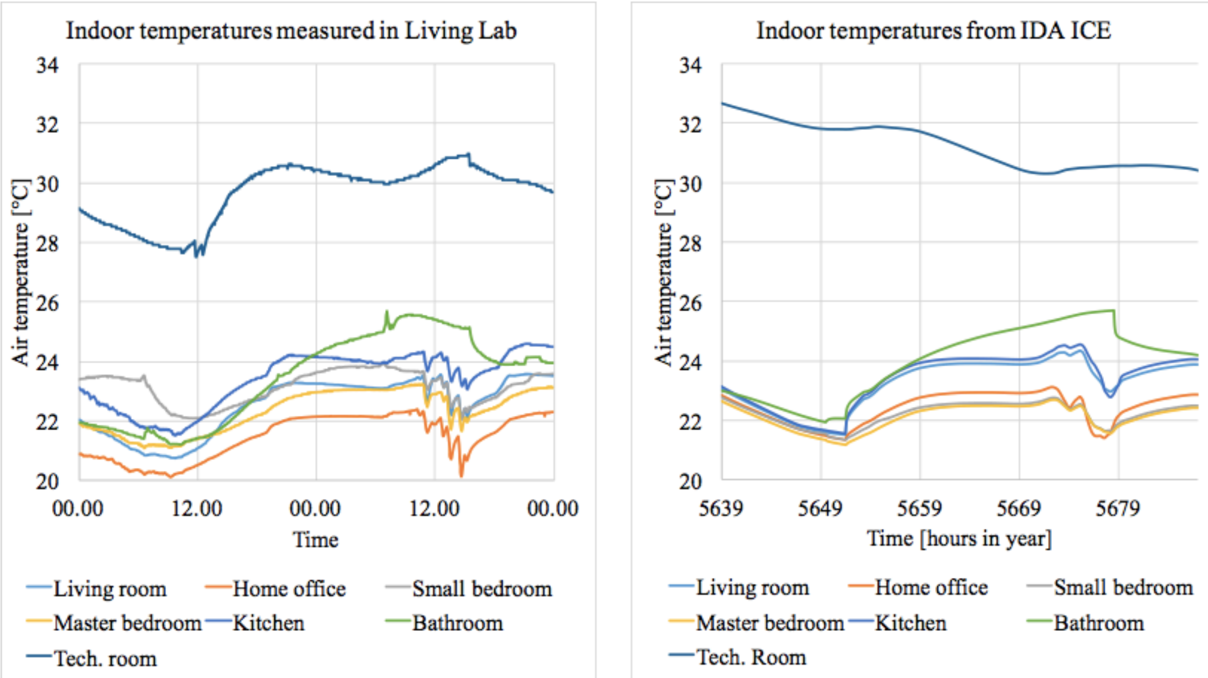


Figure (B.1): Real and simulated indoor air temperatures 23.08.16-24.08.16

Under summer conditions, IDA ICE simulated the indoor air temperatures with good accuracy. The general trends of the temperature graphs are very similar, and the range of temperatures as well. IDA ICE underestimates the temperature in the west bedroom by about 1 °C, this means that the west bedroom is more at risk for overheating than the IDA ICE simulation suggests. On the other hand, IDA ICE overestimates the temperatures in the living room and home office by about 1 °C, meaning that these rooms have a higher risk of undercooling than the simulation suggests. At the start of the validation period, when the ventilation system is running and the heating setpoints are the same in all zones, the temperatures from IDA ICE are nearly the same in all rooms. The measured temperatures have a 2 °C range during the same period, making the thermal environment in Living Lab less homogenous in reality than in simulation. It is apparent that IDA ICE underestimates the cooling effect of window openings. But at least part of this difference can be explained by the fact that IDA ICE assumes total mixing of the air. In reality, the necessary hours of window openings might be less than indicated by IDA ICE, because thermal comfort in the zone of occupancy will be reached faster than thermal comfort in the whole volume of the room.

Figure (B.2) presents the indoor temperatures measured and simulated on the 09.11.16.

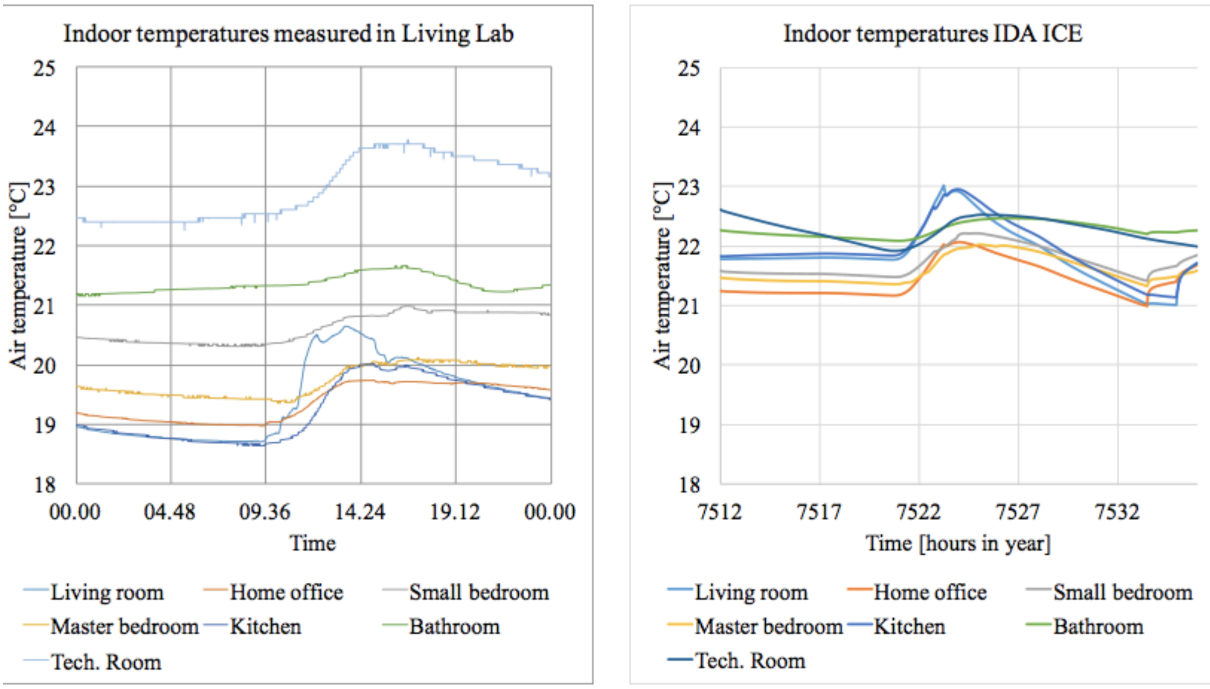


Figure (B.2): Real and simulated indoor air temperatures 09.11.16

Under winter conditions, the IDA ICE simulation overestimates all the indoor temperatures by 1-3 °C. This is likely due to the low heating effect installed in Living Lab. However, the general trends of the temperature graphs are similar, and the simulated temperatures are in the range of the measured temperatures. This IDA ICE model is to be used for evaluating ventilative cooling and natural ventilation – so it is more important that the model is accurate under summer conditions. Therefore, the IDA ICE model is assumed validated for indoor air temperatures.

A.2.2 CO_2-concentration

Figure (B.3) shows the real and simulated CO_2-concentrations on the 09.11.16.

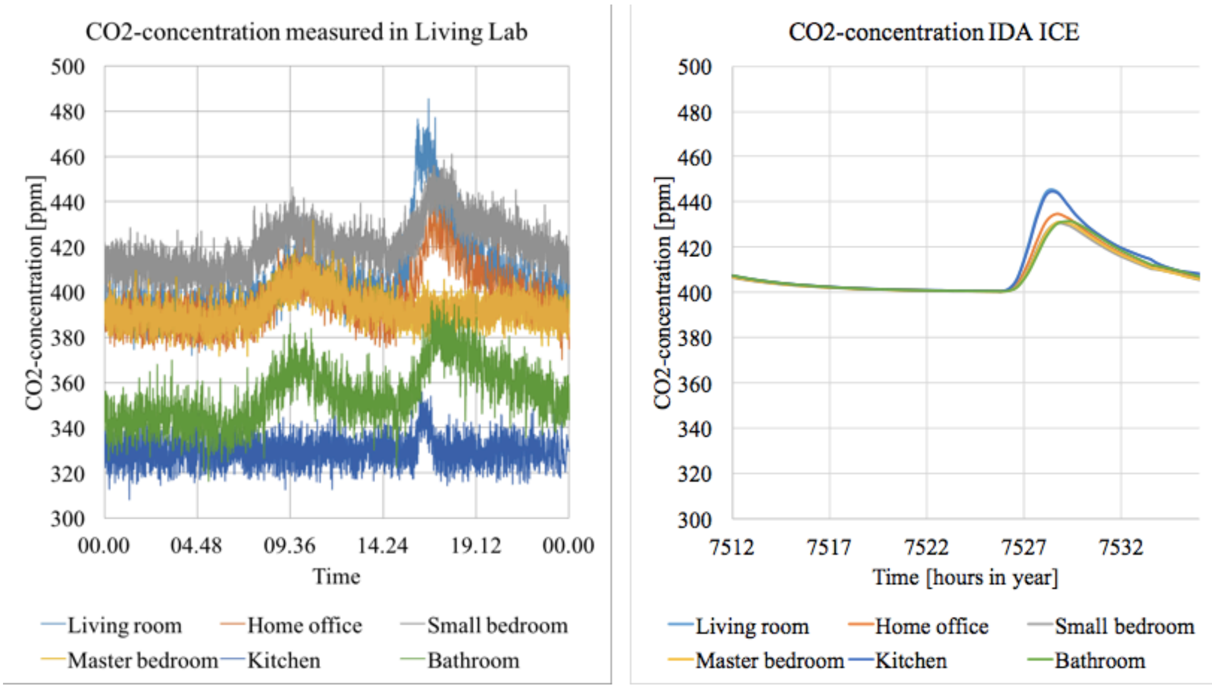


Figure (B.3): Real and simulated CO_2-concentrations 09.11.16

As seen in Figure (B.3), the CO_2-concentration in the simulation program is the same in all rooms, but in reality there were a range of 100 ppm in variations between the rooms. When a person entered the building, the increase in CO_2-concentration was smaller in the simulation than in reality, 30-40 ppm in simulation and 0-70 ppm in reality. As discussed in section A.1, this is expected because of the total mixing assumption in IDA ICE. All in all, the CO_2-concentrations from IDA ICE give a realistic representation of reality.

B.2.3 Energy for heating

Figures (B.4) and (B.5) shows the power for floor heating and the AHU hydronic coil the 23.08.16-24.08.16 and 09.11.16.

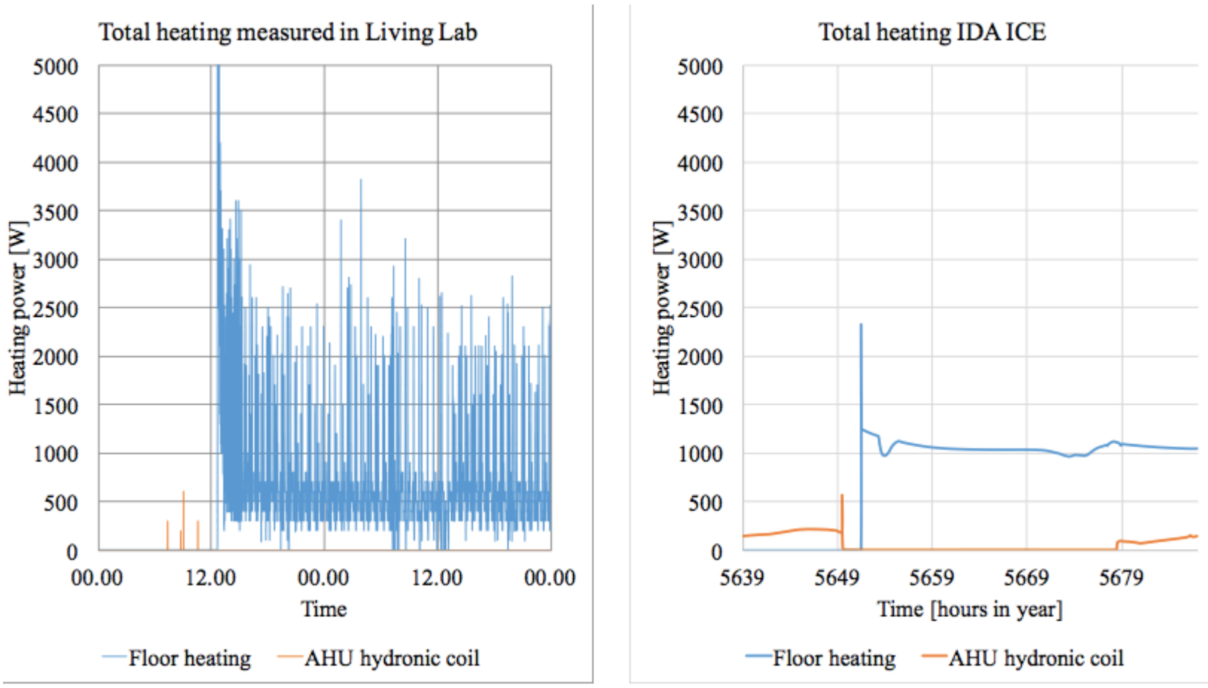


Figure (B.4): Real and simulated heating power 23.08.16-24.08.16

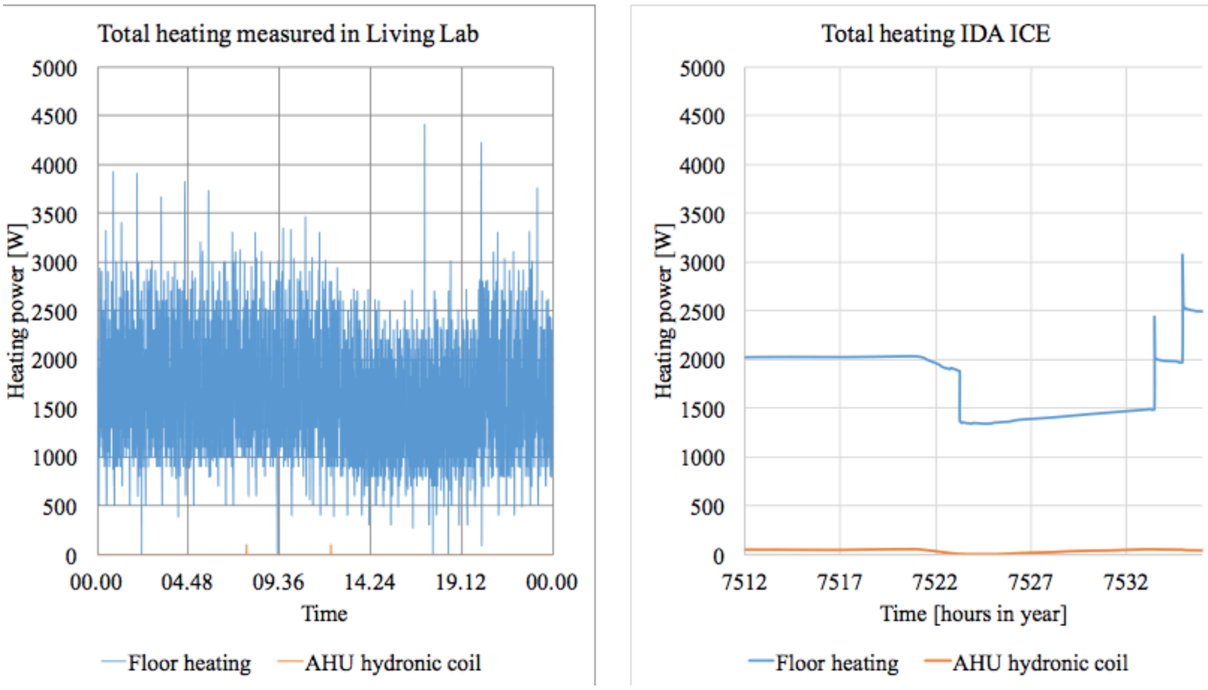


Figure (B.5): Real and simulated heating power 09.11.16

Table (B.3) presents the total energy consumption for heating and ventilation in the validated periods, and the average power consumption for floor heating.

Table (B.3): Real and simulated energy consumption

	23.08.16 to 24.08.16		***09.11.16***	
	Real value	***IDA ICE value***	***Real value***	***IDA ICE value***
Total floor heating	24.2 kWh	37.6 kWh	38.7 kWh	42.6 kWh
Total AHU heating	0.01 kWh	2.8 kWh	0.002 kWh	0.9 kWh
Average power floor heating	684 W (after 12.35 28.08.16)	1070 W (after 12.30 28.08.16)	1615 W	1803 W
AHU fan	4.6 kWh	3.5 kWh	4.6 kWh	2.2 kWh

As seen in Figures (B.4) and (B.5), the simulated heating power is a smooth line, whereas the real heating power varies all the time. The average simulated power consumption for heating was 56 % larger than reality in summer and 12 % larger in winter. That the values are wrong is unsurprising when the real installed power in Living Lab was uncertain when building the model. The total simulated energy consumption was 55 % too large in summer and 10 % too large in winter. This could be because of the low installed power in Living Lab.

The energy consumption in the AHU war significantly lower in simulation than in reality, 24 % in summer and 52 % in winter. This could be due to losses in the ventilation system like friction or pressure losses. Another factor is that the fan in the ventilation system is running on approximately 50 % of maximum fan power, which might not be the most energy efficient option.

The results of simulation will give too high energy consumption for floor and AHU heating, and too low energy consumption for the fan in the AHU, compared to real measurements in Living Lab.

Appendix C Window control for ventilative cooling

Figure (C.1) shows the control algorithm implemented in IDA ICE on the south window of Living Lab. This is the algorithm for ventilative cooling alone, not hygienic ventilation.

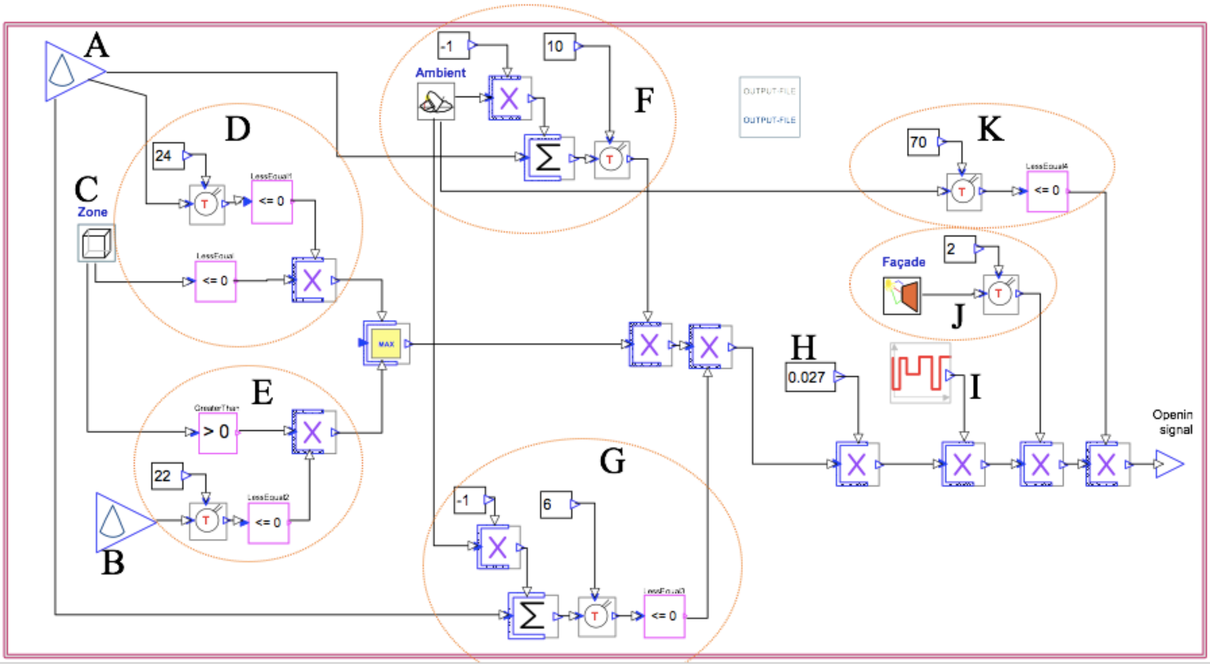


Figure (C.1): Window control algorithm for the south window of Living Lab

Below follows a step-by-step description of the control algorithm.

A. Sends the average air temperature of the living room, home office and kitchen
B. Sends the minimum air temperature of the living room, home office and kitchen
C. Sends 1 if the window is open, 0 if the window is closed
D. Sends 1 if the window is closed and the average air temperature above 24 °C, that means that windows should open
E. Sends 1 if the window is open and the minimum air temperature is above 22 °C, that means that windows shall remain open. Either D or E has to send 1 for windows to open/remain open.
F. Sends 1 if the temperature difference between indoor and outdoor air is under 10 K
G. Sends 1 if the temperature difference is above 6 K
H. Window opening percentage (of total window area in IDA ICE)
I. Sends 1 if window ventilation is allowed at that time of day (schedule)
J. Sends 1 if wind speed on the façade is below 2 m/s
K. Sends 1 if solar irradiance is above 70 W/m^2

The same algorithm is applied to the north window, but without steps J and K. The limits of the temperature differences and the window opening percentage is also changed for the north window, according to Table (7.2). This algorithm is also applied to the wide, narrow windows – but without steps H, J and K.

Appendix D Window control for cooling and CO_2-control

Figure (D.1) shows the control algorithm implemented in IDA ICE on the new window design for both ventilative cooling and hygienic ventilation. The same algorithm is applied to all windows.

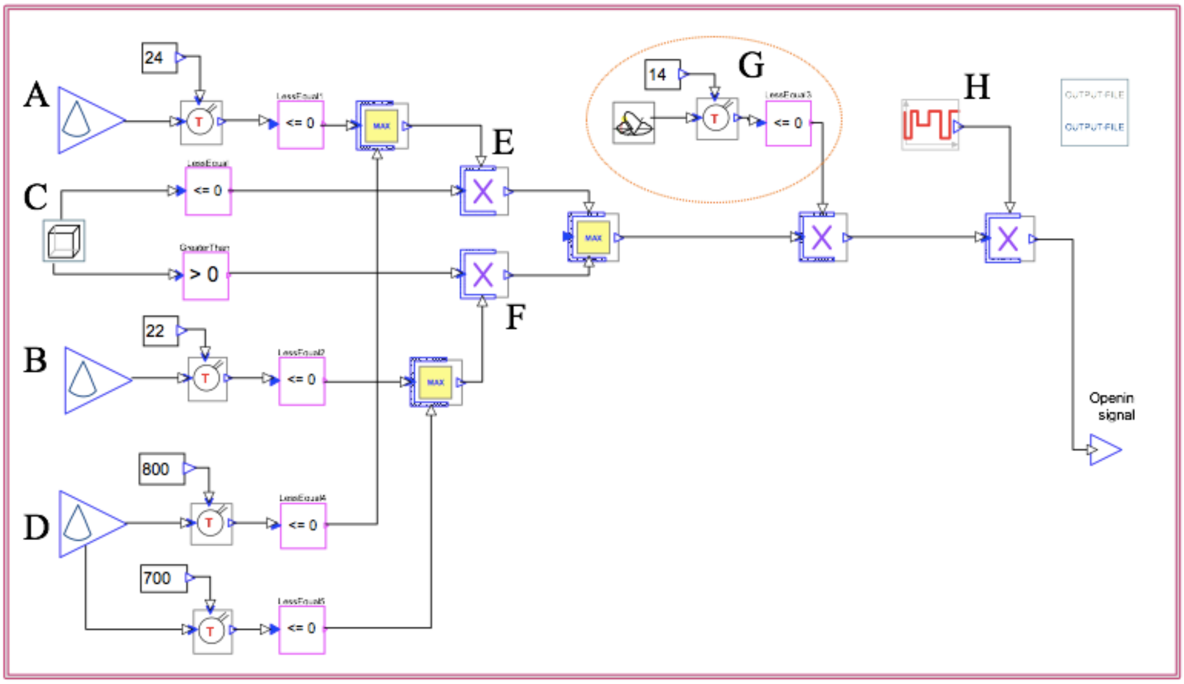


Figure (D.1): Window control algorithm for the south window of Living Lab

Below follows a step-by-step description of the control algorithm.

A. Sends the average air temperature of the living room, home office, kitchen and bedrooms
B. Sends the minimum air temperature of the living room, home office, kitchen and bedrooms
C. Sends 1 if the window is open, 0 if the window is closed
D. Sends the maximum CO_2-concentration of the living room, home office, kitchen and bedrooms
E. Sends 1 if the window is closed and the average air temperature above 24 °C or the maximum CO_2-concentration is above 800 ppm, that means that windows should open
F. Sends 1 if the window is open and the minimum air temperature is above 22 °C or the maximum CO_2-concentration is above 700 ppm, that means that windows should remain open. Either D or E has to send 1 for windows to open/remain open.
G. Sends 1 if the outdoor temperature is above 14 °C
H. Sends 1 if window ventilation is allowed at that time of day (schedule)

Appendix E Thermal comfort results for each zone

E.1 May and June simulations

Table (E.1): Hours of thermal discomfort in each zone for the simulations done for May and June in Trondheim

Old windows	Windows closed	Sensor scenario I	Sensor scenario II	Sensor scenario III	S12.5%, N25%	S12.5%, N50%	S25%, N25%	S25%, N50%
Living room	105	13	13	12	17	15	15	13
Home office	51	6	6	6	10	9	8	6
Kitchen	50	6	6	6	11	7	8	6
Small bedroom	57	9	9	8	13	11	12	9
Master bedroom	40	4	4	4	6	5	5	4
Total	303	38	38	36	57	47	48	38

Old windows	South closed	South open	East closed	East open	North closed	North open	West closed	West open
Living room	206	18	217	19	236	24	245	21
Home office	116	9	130	17	152	26	141	13
Kitchen	97	10	97	12	108	16	112	12
Small bedroom	150	15	134	14	175	33	156	20
Master bedroom	108	13	126	13	142	15	113	5
Total	677	65	704	75	813	114	767	71

Old windows	TEK 10 closed	TEK 10 open	Low-energy closed	Low-energy open	Passive house closed	Passive house open
Living room	75	12	96	13	151	14
Home office	34	5	48	7	71	7
Kitchen	31	6	44	6	65	6
Small bedroom	31	7	56	10	95	12
Master bedroom	22	3	36	5	70	5
Total	193	33	280	41	452	44

New windows	No openings	Living room	Living room and office	All rooms, central control	All rooms zonal control	Living room and small bedr.
Living room	129	11	14	15	14	14
Home office	62	12	7	2	2	11
Kitchen	53	5	6	8	6	6
Small bedroom	75	14	12	6	6	11
Master bedroom	53	8	5	3	3	7
Total	372	50	44	34	31	49

E.2 Full year simulations

Table (E.2): Hours of thermal discomfort in each zone for the full-year simulations

Old windows	Trondheim closed	Oslo closed	Copenhagen closed	Paris closed	Rome closed	Trondheim open	Oslo open	Copenhagen open	Paris open	Rome open
Living room	230	271	273	488	986	36	40	22	151	310
Home office	101	137	133	252	577	22	8	12	76	134
Kitchen	111	130	115	225	500	18	21	11	65	138
Small bedroom	126	130	60	291	692	36	8	6	95	77
Master bedroom	96	103	51	277	699	22	5	4	74	44
Total	664	771	632	1533	3454	134	82	55	461	703

New windows	Closed	All windows, central control	AHU on	AHU off if T>14	AHU off if T>16	AHU off if T>18
Living room	275	42	31	36	35	37
Home office	126	17	12	13	12	13
Kitchen	129	24	16	17	19	18
Small bedroom	149	33	14	25	25	24
Master bedroom	123	21	8	13	13	13
Total	802	137	81	104	104	105

Appendix F Risk Assessment

The following pages are the risk assessment done prior to the work on the thesis.

Unit: Department of Energy and Process Engineering **Date: 24.01.2017**

Line manager: Olav Bolland

Participants in the identification process: Solveig Blandkjenn (student), Hans Martin Mathisen (supervisor)

Short description of the main activity/main process: Master project for student Solveig Blandkjenn. Ventilative cooling of Zero Emission Buildings (ZEB).

Is the project work purely theoretical? NO *Answer "YES" implies that supervisor is assured that no activities requiring risk assessment are involved in the work. If YES, briefly describe the activities below. The risk assessment form need not be filled out.*

Signatures: *Responsible supervisor:* [signature] *Student:* [signature]

ID nr.	Activity/process	Responsible person	Existing documentation	Existing safety measures	Laws, regulations etc.	Comment
01	Working in heights, on latters or chairs	Solveig Blandkjenn	None	None	Forskrift om utførelse av arbeid kap 17	
02	Working with air velocity transducers	Solveig Blandkjenn	None	Keeping the transducers in the protective tubes	None	

Unit: Department of Energy and Process Engineering **Date: 24.01.2017**

Line manager: Olav Bolland

Participants in the identification process: Solveig Blandkjenn (student), Hans Martin Mathisen (supervisor)

Short description of the main activity/main process: Master project for student Solveig Blandkjenn. Ventilative cooling of Zero Emission Buildings (ZEB).

Signatures: *Responsible supervisor:* *Student:*

Activity from the identification process form	Potential undesirable incident/strain	Likelihood:	Consequence:			Risk Value (human)	Comments/status Suggested measures
		Likelihood (1-5)	Human (A-E)	Environment (A-E)	Economy/ material (A-E)		
Working in heights, on latters or chairs	Fall down and injure person or equipment	3	A	A	A	A3	Show caution
Working with air velocity transducers	Damage air velocity trancducers	3	A	A	B	A3	Show caution, only handle the transducers when they are in the protective tubes.

Likelihood, e.g.:
1. *Minimal*
2. *Low*
3. *Medium*
4. *High*
5. *Very high*

Consequence, e.g.:
A. *Safe*
B. *Relatively safe*
C. *Dangerous*
D. *Critical*
E. *Very critical*

Risk value (each one to be estimated separately):
Human = Likelihood x Human Consequence
Environmental = Likelihood x Environmental consequence
Financial/material = Likelihood x Consequence for Economy/materiel

Potential undesirable incident/strain
Identify possible incidents and conditions that may lead to situations that pose a hazard to people, the environment and any materiel/equipment involved.

Criteria for the assessment of likelihood and consequence in relation to fieldwork
Each activity is assessed according to a worst-case scenario. Likelihood and consequence are to be assessed separately for each potential undesirable incident. Before starting on the quantification, the participants should agree what they understand by the assessment criteria:

Likelihood

Minimal 1	Low 2	Medium 3	High 4	Very high 5
Once every 50 years or less	Once every 10 years or less	Once a year or less	Once a month or less	Once a week

Consequence

Grading	Human	Environment	Financial/material
E Very critical	May produce fatality/ies	Very prolonged, non-reversible damage	Shutdown of work >1 year.
D Critical	Permanent injury, may produce serious serious health damage/sickness	Prolonged damage. Long recovery time.	Shutdown of work 0.5-1 year.
C Dangerous	Serious personal injury	Minor damage. Long recovery time	Shutdown of work < 1 month
B Relatively safe	Injury that requires medical treatment	Minor damage. Short recovery time	Shutdown of work < 1week
A Safe	Injury that requires first aid	Insignificant damage. Short recovery time	Shutdown of work < 1day

The unit makes its own decision as to whether opting to fill in or not consequences for economy/materiel, for example if the unit is going to use particularly valuable equipment. It is up to the individual unit to choose the assessment criteria for this column.

Risk = Likelihood x Consequence
Please calculate the risk value for “Human”, “Environment” and, if chosen, “Economy/materiel”, separately.

About the column ”Comments/status, suggested preventative and corrective measures”:
Measures can impact on both likelihood and consequences. Prioritise measures that can prevent the incident from occurring; in other words, likelihood-reducing measures are to be prioritised above greater emergency preparedness, i.e. consequence-reducing measures.

MATRIX FOR RISK ASSESSMENTS at NTNU

CONSEQUENCE	Extremely serious	E1	E2	E3	E4	E5
	Serious	D1	D2	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Not significant	A1	A2	A3	A4	A5
		Very low	Low	Medium	High	Very high
		LIKELIHOOD				

Principle for acceptance criteria. Explanation of the colours used in the risk matrix.

Colour	Description
Red	Unacceptable risk. Measures must be taken to reduce the risk.
Yellow	Assessment range. Measures must be considered.
Green	Acceptable risk Measures can be considered based on other considerations.