Master's thesis

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Natural Ventilation Modeling in ZEB Lab

Master's thesis in Energy and Environmental Engineering
Supervisor: Hans Martin Mathisen
July 2020

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Acknowledgements

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A.Mital

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Abstract

Buildings account for 40% of the total energy consumption in Europe and create 36% of the CO_2 emissions. Achieving high energy efficiency in the Norwegian building stock will therefore play an integral part in creating a sustainable future and meeting our energy goals. Zero Emission Buildings are a large part of the solution, as over their lifetime they compensate for released emissions by their energy-efficient features and renewable energy production on-site.

ZEB Lab is one such project currently under construction in Trondheim, Norway. This NTNU and SINTEF collaboration will be a living lab, used for office space, education, research and, of course, as a laboratory. Spanning four floors and 1800m^2, the goal is to monitor energy use and have an area for full-scale research on Zero Energy Buildings. The object of this thesis has been to explore and model natural ventilation in ZEB Lab.

Theory has been studied to understand physical laws governing air flow processes in natural and hybrid ventilation. A detailed literature study has been performed, and flagship projects explored. A model has been created, and simulations performed in the whole building energy performance simulator DesignBuilder.

The focus of the model in DesignBuilder has been to evaluate natural ventilation and comfort conditions in ZEB Lab during summertime. Analyzed zones are the Canteen, Windbreaker 1, Meeting room 2.1 and 3.1, Twin cell 1, Open Workspace (WS) 3.2 and 3.3 and the Knowledge center. Logical results have been obtained but inexplicable anomalies have also been found.

Generally, ventilation air volumes have been found sufficient using only natural ventilation in the simulations. Predicted Mean Vote (PMV) has been found to be between -1.5 and -1 for occupied hours in all zones. Occupants will feel slightly cold, but the comfort requirements are fulfilled.

When comparing results from Open Workspace (WS) 3.2 and 3.2 different scenarios were modeled. Ventilation air volumes were highest when simulating without shading, possibly attributed to higher temperature difference driven flow.

Wind effects of natural ventilation have been cross-checked and verified to be logical using supplied weather data. Operative temperature has been proven to rise considerably in the scenario without shading. PMV has followed changes in operative temperature closely.

DesignBuilder has been proven as an interesting simulation tool with many features and functionality. Multi-zone, transient, thermal simulation with real weather data is possible for both natural and mechanical ventilation. The main drawback has been the lack of detailed zone-to-zone airflow analysis.

Sammendrag

Bygninger står for 40% av det totale energiforbruket i Europa, og 36% av CO_2-utslippene. Høy energieffektivitet i norsk bygningsmasse er derfor en viktig del av det å skape en bærekraftig fremtid og innfri energimål. Nullutslippsbygninger (ZEB) er en viktig del av løsningen. De er energieffektive, og gjennom levetiden kompenseres bygningsutslipp ved lokal, fornybar energiproduksjon.

ZEB Lab er ett slikt bygg som for tiden reises i Trondheim, Norge. Dette samarbeidsprosjektet mellom NTNU og SINTEF skal resultere i et såkalt 'living lab' brukt som kontor, undervisningsareal, og laboratoriet. Med fire etasjer og et bruksareal på 1800m^2 er tanken å monitorere energibruk og ha et sted for fullskala forskning på nullutslippsbygninger. Målet med denne masteroppgaven har vært å utforske og modellere naturlig ventilasjon og tilhørende komfort i ZEB Lab.

Teori har blitt studert for å forstå de fysiske lovene som danner grunnlaget for luftveksling i naturlig og hybrid ventilasjon. En detaljert litteraturstudie har blitt utført, og flaggskipprosjekter har blitt studert. En modell av bygget er implementert, og simuleringer er utført i programmet DesignBuilder.

Målet med modellen i DesignBuilder har vært å evaluere naturlig ventilasjon og komfort i ZEB Lab om sommeren. Blant sonene som har blitt analysert finner man kantina, vindfang, møterom, tvilling-rom, åpent arbeidslandskap, og kunnskapssenteret i fjerde etasje. Logiske resultater er funnet, samt noen uregelmessigheter.

Stort sett har naturlig ventilasjon gitt tilstrekkelige luftmengder. Predicted Mean Vote (PMV) har vært mellom -1,5 og -1 i løpet av arbeidsdagen. Beboere kommer til å føle seg litt kalde, men komfortkrav er innfridd.

Forskjellige scenarioer ble modellert, og Open Workspace (WS) 3.2 og 3.3 ble sammenlignet. Luftmengder var høyest når solskjerming ble fjernet, muligens grunnet større ventilasjon drevet av temperaturforskjeller.

Vind-effekten i naturlig ventilasjon har blitt analysert og verifisert til å oppføre seg logisk med importert værdata. Operativ temperatur har vist seg å øke betraktelig i scenarioet uten solskjerming. PMV har fulgt utviklingen i operativ temperatur tett.

DesignBuilder har vist seg å være et interessant simuleringsverktøy med mye tilgjengelig funksjonalitet. Multi-sone, transient, termisk simulering med ekte værdata er mulig for både naturlig, hybrid og mekanisk ventilasjon. En begrensning med verktøyet har vært mangelen på mulighet for detaljert luftstrømsanalyse fra en sone til en annen.

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1 Introduction

Our world has a constant and increasing demand for energy, in order for civilization to progress at the current rate. The energy needs of the built environment are a large part of this demand and pose a challenge.

Approximately 40 % of total energy consumption in Europe is due to buildings and the corresponding CO_2 emissions from the same are 36%. Some of the mitigating steps taken by the European Commission are establishing the Energy Performance of Buildings Directive in order to "boost energy performance of buildings". The ultimate goal is to «achieve a highly energy efficient and decarbonized building stock by 2050" (European Commission 2020).

This master thesis seeks to better understand and emphasize the role of hybrid ventilation in energy-efficient green buildings, specifically the ZEB Lab. This NTNU and SINTEF collaboration is currently under construction in Trondheim, and will be a living lab, used for office space, education, research and, of course, as a laboratory. The goal is to monitor energy use and have an area for full-scale research on Zero Energy Buildings. The ZEB Laboratory is designed with openable windows for natural and hybrid ventilation. Some are manually controlled by users while others have automated motor control systems.

The scope of this project includes understanding physical laws governing air flow processes in natural and hybrid ventilation. A detailed literature study will be performed, and flagship projects will be explored. A model will be created, and simulations performed in the whole building energy performance simulator DesignBuilder.

This thesis is a successor to project work done in Fall 2019 where CONTAM was used to explore airflows in simple models of the ZEB Lab. However, a limitation of CONTAM was that it does not model thermal effects in simulations. DesignBuilder was therefore chosen to use in this master's thesis, in order to explore new territory. A specific objective was also to evaluate DesignBuilder as suitable a tool for further work.

Problem Description

The title of this thesis is

Natural Ventilation Modeling in ZEB Lab

This thesis is a combination of literature study and simulations. Focus areas are the use of DesignBuilder as a tool for natural ventilation modeling in ZEB Lab and analysis of comfort and natural ventilation in the model. Comfort conditions and ventilation will be evaluated for the building model in summer week simulations.

Tasks that will be considered include theory on natural and hybrid ventilation, learning to operate the chosen simulation tool, DesignBuilder, literature survey (state of the art) on natural and hybrid ventilation. The model will be implemented, simulations will be run, and results analyzed.

2 Theory

The following chapter focuses on theory as the basis for understanding air flow and ventilation.

2.1 Indoor Environment

An extremely important objective for HVAC applications is providing conditions that are conducive to a good and healthy indoor environment. The following section focuses on some factors that are essential to a satisfactory indoor environment.

2.1.1 Thermal comfort

Human thermal comfort is defined in the ASHRAE Fundamentals Handbook of 2005 as “that condition of mind that expresses satisfaction with the thermal environment”. The term “condition of mind” is a relatively open term, but it is emphasized that the comfort judgement stems from a variety of inputs which are affected by physical, physiological, and psychological processes.

Building categories

NS-EN 16798-1:2019 categorizes buildings, and Table 1 shows the categories of indoor environmental quality (IEQ) based on occupant expectation.

Category	Level of expectation
IEQ_{I}	High
IEQ_{II}	Medium
IEQ_{III}	Moderate
IEQ_{IV}	Low

Table 1: Description of building categories from NS-EN 16798-1:2019

A normal expectation would be ‘Medium’, while a high level should be used for occupants with special needs (children, elderly, persons with disabilities, etc.). A lower level does not pose a health risk but can decrease comfort (Standard Norge 2019).

The ZEB Laboratory belongs in Category II.

Human Thermoregulation

As explained in ASHRAE 2005, heat is produced as a result of human metabolic activities. This heat must be continuously regulated and dissipated; this process mainly happens through heat transfer from human skin to the environment. For a resting, seated person this amount of heat is represented by the value of 1 met ($1\ met = 50\ kcal/h \cdot m^2$) (American Society of Heating and Air-Conditioning 2005). A higher activity level results in a higher value of met, as is illustrated in Table 2.

Activity	Met
Resting	
Sleeping	0.7
Standing, relaxed	1.2
Office	

Reading, seated/writing	1.0
Typing	1.1
Walking about	1.7
Misc.	
Cleaning	2.0 to 3.4
Basketball	5.0 to 7.6

Table 2: Typical Metabolic Heat Generation for Various Activities (ASHRAE 2005)

Clothing Insulation

Thermal insulation provided by clothing can be expressed in the unit clo ($1\ clo = 0.155\ m^2 \cdot K/W$). 1 clo in terms of clothing can be represented by a jacket, trousers, shirt, underpants, socks and shoes (Sintef and NTNU 2007).

Conditions for thermal comfort

The ASHRAE thermal sensation scale has been developed based on many studies on correlation between comfort level, temperature, humidity, sex and length of exposure ((American Society of Heating and Air-Conditioning 2005).

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

Prediction of Thermal Comfort

There are various ways to predict thermal comfort and thermal sensation. The PMV-PPD model is extensively used and accepted as a method of assessing design and field comfort conditions (American Society of Heating and Air-Conditioning 2005).

The Predicted Mean Vote (PMV) index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale. "Fanger (1970) related PMV to the imbalance between the actual heat flow from the body in a given environment and the heat flow required for optimum comfort at the specified activity" (ASHRAE 2005). The equation is described as follows

$$PMV = 3.155\ (0.303 \exp(-0.114M) + 0.028)L \tag{1}$$

where M is metabolic activity and L is the thermal load on the body. L is defined as the difference between internal heat production and heat loss to the actual environment – for a person hypothetically at comfort values at the actual activity level.

The Predicted Percentage Dissatisfied with a condition can be estimated after using Eq 1 as follows

$$PPD = 100 - 95 \exp[-(0.03353PMV^4 + 0.2179PMV^2)] \tag{2}$$

The dissatisfied includes everyone who does not vote -1,0 or +1.

Equation 2 is illustrated in Figure 2.

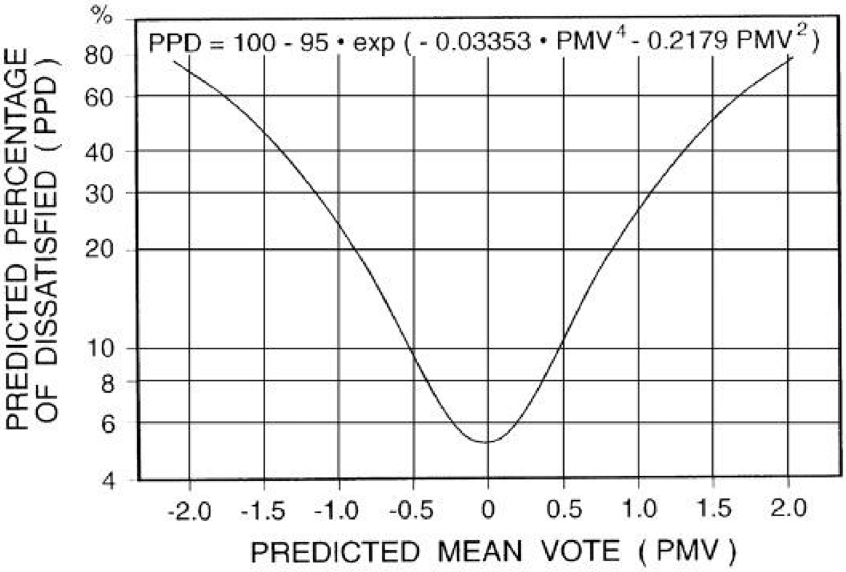

Figure 1: Relationship between PPD and PMV

(Source url: https://support.sefaira.com/hc/en-us/articles/115000576472-ASHRAE-55-interpretation-in-Sefaira)

Thermally Non-uniform Conditions and Local Discomfort

Thermal neutrality can be achieved for a body as a whole, while one or more parts of the body can experience unwanted heating and cooling, causing local thermal discomfort. Nonuniformities can be caused by cold windows, hot surfaces, drafts, or variations of these resulting in vertical air temperature difference, radiant asymmetry among other things.

Draught

Draught can be defined as "an undesired local cooling of the human body caused by air movement" (American Society of Heating and Air-Conditioning 2005). It is identified as one of the most annoying factors in office buildings, often eliciting demands for higher air temperatures or the stopping of ventilation systems.

Draught rate is defined as the percentage of people predicted to be bothered by draught and can be calculated as follows

$$\begin{gathered} DR = \left(34 - t_{a,l}\right)\left(\overline{v_{a,l}} - 0.05\right)^{0.62}\left(0.37 \cdot \overline{v_{a,l}} \cdot Tu + 3.14\right) \\ For\ \overline{v_{a,l}} < 0.05\frac{m}{s}, \qquad use\ \overline{v_{a,l}} = 0.05\frac{m}{s} \\ For\ DR > 100\%, \qquad use\ DR = 100\% \end{gathered} \tag{3}$$

where

$t_{a,l}$ is the local air temperature between $20 - 26℃$

$\overline{v_{a,l}}$ is the local mean air velocity, $< 0{,}5\frac{m}{s}$

Tu is the local turbulence intensity, between $10 - 60\%,$ use 40% if unknown (NS-EN ISO 7730 2005).

Recommended levels for different parameters

For a building in Category II as specified in Table 1, NS-EN 16798-1:2019 recommends a PPD lower than 10% and a PMV between -0.5 and +0.5. However, this is the recommendation for a building with mechanical heating and cooling. (It is important to note that the ZEB Laboratory does *not* have mechanical cooling). NS-EN 7730 limits the draught rate to lower than 20% for a building in Category B (same as Category II for NS-EN 16798-1).

Regarding temperature levels, NS-EN 16798-1:2019 provides a method to calculate acceptable indoor temperatures in buildings without mechanical cooling outside of winter months. The indoor temperature is calculated as a function of continuous mean outdoor temperature. Figure 2 is loaned from the standard (Figure B.1 page 48).

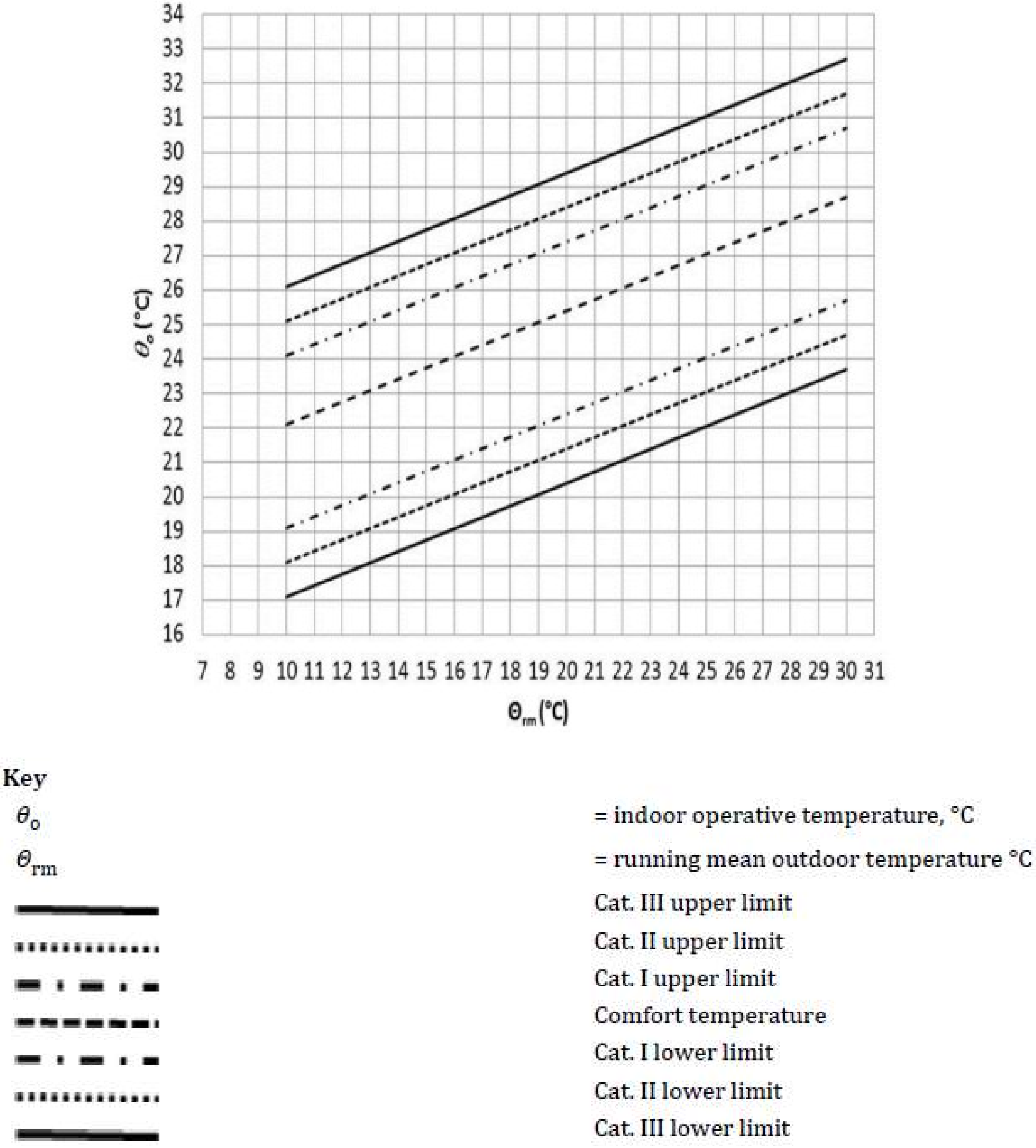

Figure 2: Acceptable indoor temperature limits from NS-EN 16798-1:2019

Atmospheric environment

Outdoor pollution and CO_2 levels (CO_2 is essentially "pollution" or air contaminants from humans) are parameters that affect the ventilation quality.

NS-EN 16798-1:2019 recommends a 500-ppm difference between indoor and outdoor CO_2 concentration for a Category II building. TEK17 mandates a ventilation rate of 26m^3/h per person in addition to 2.5m^3/h per m^2 floor space for an occupied room. The ventilation rate is meant to cover CO_2 generation from humans and emissions from materials and installations (DiBK 2017).

TEK17 also mandates that a ventilation system's air intake should be placed taking in to consideration the level of outdoor pollution. This ensures that poor air quality is not transferred inside. To prevent risk of respiratory diseases, PM_{10} should be less than 35 µg/m^3 7 days a year, and the winter median for NO_2 should be less than 40 µg/m^3.

2.1.2 Unwanted Consequences of a Poor Indoor Environment

Thermal Complaints

"Unsolicited thermal complaints can increase a building's operation and maintenance (O&M) cost by requiring unscheduled maintenance to correct the problem" (American Society of Heating and Air-Conditioning 2005). ASHRAE 2005 recommends avoiding this; the optimum temperature interval can be found for a building using complaint prediction models to determine the minimum discomfort temperature (MDT) and the minimum cost temperature (MCT).

Sick Building Syndrome (SBS) and Building-Related Illness (BRI)

As explained in (ASHRAE 2005), there is no clear, operative definition of SBS, but it is characterized by several adverse health effects that stem from occupying a so-called "sick" building. It spans a variety of complaints including fatigue, headaches, irritation in eyes/nose/throat/skin, nausea and building odors amongst others.

Building-related illnesses have known origins and are characterized by a different set of symptoms. Examples are typically hypersensitivity illnesses, like asthma, humidifier fever, allergic rhinitis caused by individual sensitization to bioaerosols (ASHRAE 2005).

These factors deter the wellbeing of occupants, increase costs and decrease productivity and therein profitability. Well-designed, well-implemented and well-managed ventilation is key in avoiding these problems.

2.2 Fluid Mechanics

Fundamental physical correlations are required to understand ventilation models and air flows.

Conservation of Mass

For a fixed control volume, the following equation applies,

$$\sum \rho_i q_i = 0 \tag{4}$$

where i represents an opening, and the summation applies to all openings in the envelope (Etheridge 2012). Essentially this correlation means that airflow into a building equals airflow exiting the building.

Buoyancy

The density of air varies with temperature; hot air has lower density than cool air and therefore, it rises above cool air. Eq. (5) expresses the simplified correlation after using the Boussinesq approximation,

$$\rho = \rho_{0\cdot}\frac{T_0}{T}. \tag{5}$$

$\rho_{0\cdot}$ and T_0 are reference density and temperature, respectively. This simplified expression is correct for very small temperature differences.

Reynolds number and types of flow

The Reynolds number has a general definition as follows,

$$Re \overset{\text{def}}{=} \frac{\rho \cdot \mathrm{U} \cdot \mathrm{L}}{\mu} \tag{6}$$

where U is the velocity. L represents the characteristic dimension, while ρ represents the density of the fluid and μ the viscosity (Etheridge 2012). The Reynolds number essentially represents the ratio of dynamic forces (numerator) and viscous forces (denominator).

The magnitude of the Reynolds number determines the type of flow that will occur.

Laminar flow has no random component in the velocity field. A good example of steady laminar flow is in a small envelope opening where pressure is generated only by buoyancy (Etheridge 2012). The flow is characterized by $Re < 2300$.

A turbulent flow is characterized by velocity and pressure at a point having random fluctuation about a non-random component. Turbulent flows are always unsteady. An example of turbulent flow is wind, since it has no constant speed or direction (Etheridge 2012). The flow is characterized by $Re > 2300$.

Transitional flow takes place between laminar and turbulent flow and is a sort of combination of the two, occurring when “one part of the flow field is neither laminar nor fully turbulent” (Etheridge 2012).

Bernoulli’s Equation

Bernoulli’s equation applies to inviscid flow and is as follows

$$\mathrm{P} + \rho \mathrm{g z} + 0.5\rho \mathrm{v}^2 = \text{constant, along a streamline} \qquad (7)$$

where P is the static pressure, $\rho \mathrm{gz}$ is hydrostatic pressure and $0.5\rho \mathrm{v}^2$ represents the dynamic pressure. Together these make up the total pressure (Etheridge 2012).

Essentially Bernoulli’s equation states that energy is conserved in a streamline; if velocity increases there will be a decrease in static pressure.

Orifice equation

The classical approach to calculating unidirectional air flow through a large opening is to use the orifice equation (Heiselberg and Sandberg 2006). The orifice equation is given by

$$q = C_d A \sqrt{\frac{2\Delta P}{\rho}}.$$

The discharge coefficient, C_d, is used to specify flow rates through the orifice and accounts for non-ideal effects. These could be caused by friction in the airflow path and the effect of contraction in the airflow path (Iqbal, Afshari et al. 2015).

Discharge coefficient

On a general basis, the discharge coefficient is treated as a constant since non-ideal effects are difficult to estimate. Typically, C_d is approximately 0.6 for a sharp-edged orifice, and slightly higher for other openings (Dols and Polidoro 2015).

However, it is important to note that the discharge coefficient for windows is not a constant, it is influenced by several factors. It can vary considerably with the window type, opening area and the pressure difference across the opening (Iqbal, Afshari et al. 2015).

The discharge coefficient is an important source of uncertainty in correctly predicting the ventilation rates through openings. Experimental values for the discharge coefficient have been obtained through studies over the years. A 1998 experimental study measuring the discharge coefficient found values in agreement with generally accepted values $C_d=0.6\pm0.1$ (Flourentzou, Van Der Maas et al. 1998).

On site experimental measurements were carried out in a study from 2016. It was shown that the discharge coefficient ranged between 0.41 to 0.81 for a side-hung casement window. For a bottom hung casement window, the discharge coefficient was found to be 0.84 (Cruz and Viegas 2016).

The following equation can be used to calculate the discharge coefficient for internal openings when conditions are steady-state and flow is buoyancy-driven (Allard, Alvarez et al. 1998),

$$C_d = 0.4 + 0.0075\Delta T.$$

The Design Builder manual suggests using a value between 0.6 and 0.65 for sufficient accuracy (Design Builder).

Airflow around buildings/Effects of wind

Wind is turbulent and creates flows that are difficult to track around building structures. Wind force on the surface of a building creates positive pressure on the windward side, and suction on the leeward side(s) (Allard, Alvarez et al. 1998).

Wind pressure coefficient

This is a dimensionless number that shows the relation between static and dynamic (wind velocity) pressure at a given point on a surface, illustrated as follows,

$$C_p = \frac{p_s}{p_d} \tag{8}$$

p_s is the pressure on the building surface, while p_d is the "local outdoor atmospheric pressure at the same level in an undisturbed wind approaching the building." (American Society of Heating and Air-Conditioning 2005). p_d is derived from Bernoulli's equation as follows,

$$p_d = \frac{\rho {U_H}^2}{2} \tag{9}$$

where

U_H is the approach wind speed at upwind wall height (m/s) and

ρ is the ambient air density (kg/m^3) (Gullbrekken, Uvsløkk et al. 2018).

According to Etheridge and Sandberg in 'Building Ventilation-Theory and Measurement', for a given building and environment, the pressure coefficient can be set to a function of only the wind direction φ, rendering

$$\Delta C_p = f\{\varphi\} \tag{10}$$

where

$$\Delta C_p = C_{p1} - C_{p2} \tag{11}$$

and C_{p1} is the windward pressure coefficient and C_{p2} is the leeward coefficient.

Wind pressure coefficient values depend on both building shape and wind direction. They are also influenced by nearby buildings, vegetation, and terrain features. According to Gullbrekken, Uvsløkk et al. 2018, there are three methods to estimate C_p: full-scale tests, model tests in wind tunnel experimental facility and the derivation of parametric equations using experimental data. Experimental data can be used to validate Computational Fluid Dynamics (CFD) models, and CFD simulations can also provide a database for parametric studies. However, the only way to obtain accurate wind pressure coefficients for a specific building is to perform a full-scale test for the building in question. This is a difficult and expensive process that requires expertise. Therefore, it is done rarely and parametrically obtained values are widely used (Gullbrekken, Uvsløkk et al. 2018).

Figure 3 shows an example of a wind pressure profile generated in CONTAM.

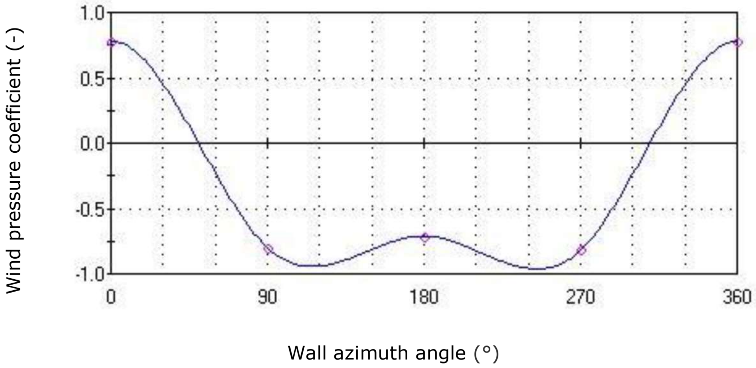

Figure 3: Example wind pressure profile

2.3 Ventilation

Ventilation is the process of moving outdoor (fresh) air into a building or a room and then distributing the air. The main purpose of ventilation is to provide a healthy indoor environment for the occupants.

2.3.1 Ventilation Strategies

Ventilation strategies encompass the methods used to ventilate a building and can either be natural, mechanical or hybrid ventilation.

2.3.1.1 Natural ventilation

Natural ventilation is the process of ventilation using the natural forces of buoyancy and wind and external air as supply air.

Ventilation due to temperature difference

"Ventilation arising from temperature difference is generally referred to as *stack effect*[1] ventilation" (Etheridge and Sandberg 1996). The flow arises due to density differences.

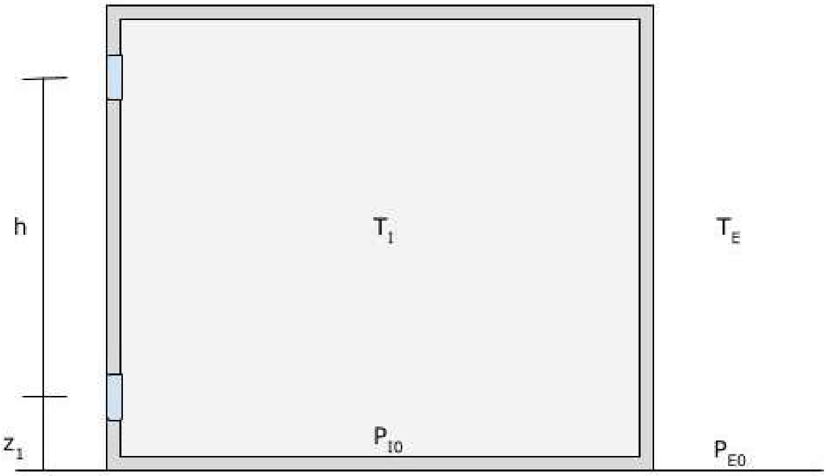

Figure 4: Illustration to support eq.(13) and (14). Inspired by Etheridge and Sandberg (1996)

As explained in Etheridge and Sandberg 1996, a uniform internal temperature gives rise to a pressure difference at height z,

$$\Delta p = P_{E0} - P_{I0} - gz(\rho_E - \rho_I). \tag{12}$$

Assuming identical openings, the pressure differences across the lower and upper openings can be found to be

$$\Delta p_{lower} = P_{E0} - P_{I0} - (\rho_E - \rho_I)gz_1 \tag{13}$$

$$\Delta p_{upper} = P_{E0} - P_{I0} - (\rho_E - \rho_I)g(z_1 + h) \tag{14}$$

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[1] The analogy comes from chimney stacks, since both flows are connected to density differences. However, air flow in chimneys is in a significantly higher degree of motion and technically cannot be considered applicable to this simple situation.

The equilibrium condition for conservation of mass flow makes the conditions such that Δp_{lower} is equal to $-\Delta p_{upper}$ and we get (in absolute value),

$$\Delta p_{lower} = \Delta p_{upper} = (\rho_E - \rho_I)gh/2. \tag{15}$$

As illustrated in Etheridge and Sandberg (1996), the ventilation rate equals

$$q = C_d A\sqrt{\Delta\rho gh/\rho}. \tag{16}$$

Using eq.(5), we can write eq.(16) in terms of temperature,

$$q = C_d A\sqrt{\Delta T gh/T_I}. \tag{17}$$

Neutral plane

Buoyancy dictates that hot air rises, since it is heavier than cool air. "In the absence of wind, warm, light air flows through the upper part of an opening, while cool air flows through the lower part in the opposite direction"(Allard, Alvarez et al. 1998).

According to Etheridge and Sandberg 1996, there will be some point z_n where the pressure difference, Δp, will be equal to zero. This height is referred to as the *neutral point*; in 2D this is the neutral plane. At this height there will be no air flow, neither into the building nor out from the building. Above this height Δp creates outflow, and below there will be inflow.

Pressure profiles

A general pressure profile describing the situation in the previous section is illustrated in Figure 5.

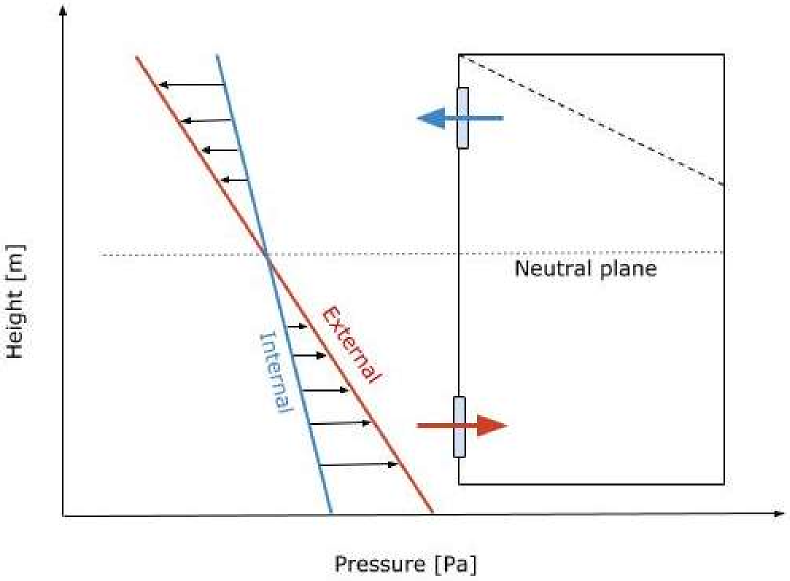

Figure 5: General pressure profile. Black arrows show the air flow direction.

Ventilation due to wind

Wind-driven ventilation is illustrated by Figure 6, which is a simple case of a building with two openings.

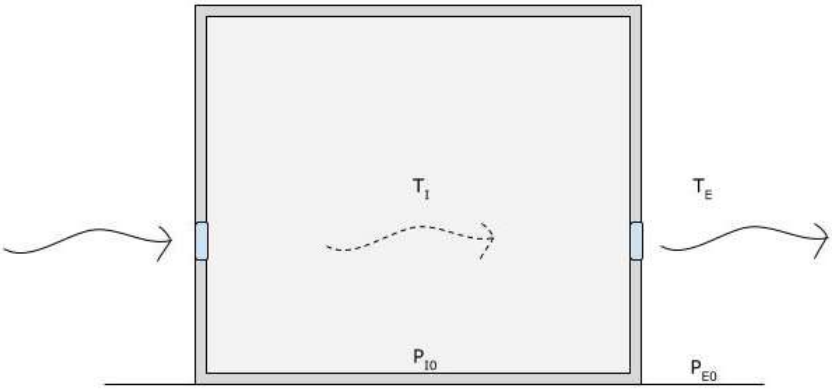

Figure 6: Cross ventilation. Inspired by Etheridge and Sandberg (1996)

The pressure difference over the building due to wind is proportional to the dynamic pressure term $\frac{1}{2}\rho U^2$, where U is the wind speed (Etheridge and Sandberg 1996). The pressure difference can be illustrated using the following correlation, correcting for wind direction using C_p,

$$\Delta p = \rho_E\, U^2 \Delta C_p/2 \tag{18}$$

where ρ_E is the exterior air density and U is the wind speed.

When the two openings are identical, the pressure differences across the openings are simply equal to half the pressure difference across the building. Using eq.(18) the pressure difference over a single opening becomes

$$\Delta p = \rho_E\, U^2 \Delta C_p/4. \tag{19}$$

The ventilation rate through the building can be found using

$$q = C_d A U \sqrt{\Delta C_p/2} \tag{20}$$

where C_d is the discharge coefficient and A is the area of the opening (Etheridge and Sandberg 1996).

Advantages and disadvantages of Natural Ventilation

Definitive statements regarding pros and cons of natural ventilation depend on a variety of factors such as external climate and the purpose of the building and are therefore difficult to ascertain.

However, on a general basis it has been claimed the natural ventilation provides the advantage of "contributing to a sustainable building environment". Natural ventilation also provides increased occupant control and satisfies their desire to not be completely isolated from the outside environment. (Etheridge 2012)

One disadvantage is that in hot and humid climates the cooling provided can be limited. Filtration and/or quality of outside air, and dependency on outdoor weather are also general issues for natural ventilation processes.

2.3.1.2 Mechanical Ventilation

"Mechanical ventilation refers to the use of fans for supplying and/or extracting air" (Etheridge and Sandberg 1996). The fans are often connected to a duct system and together with other components like valves they form a mechanical ventilation system.

"A supply fan will cause an increase of pressure and an outflow through openings. When a supply fan and an extract fan with equal flow rates are fitted, there will be no pressure difference generated at equilibrium. Such a combination is generally referred to as a *balanced* system."(Etheridge and Sandberg 1996).

Advantages and disadvantages of Mechanical Ventilation

A mechanical ventilation is perceived to be reliable since it does not depend on external weather conditions and can be coupled with a heat recovery unit to increase energy efficiency.

Disadvantages include the added need for space for equipment, noise from fans and especially energy use for fans and monitoring systems.

2.3.1.3 Hybrid ventilation

Hybrid ventilation combines the use of natural and mechanical ventilation in order to utilize freely available resources and decrease energy use for ventilation. When natural forces are strong enough to independently cover the ventilation demand, the mechanical system is shut down (Lie 2015).

Hybrid ventilation mainly uses three working principles: mixed-mode, fan-assisted natural ventilation and mechanical ventilation assisted by natural forces (Lie 2015). Mixed-mode ventilation is discussed further.

Mixed-mode ventilation

Mixed-mode ventilation is assisted by different control strategies in order to get to independent systems to co-operate. The source for this section is Lie's master thesis (Lie 2015). The different strategies are described below.

Concurrent system

This is the most common strategy wherein the natural and mechanical system operate at the same place at the same time. The mechanical system supplements the natural forces, and users can control the openings as they wish.

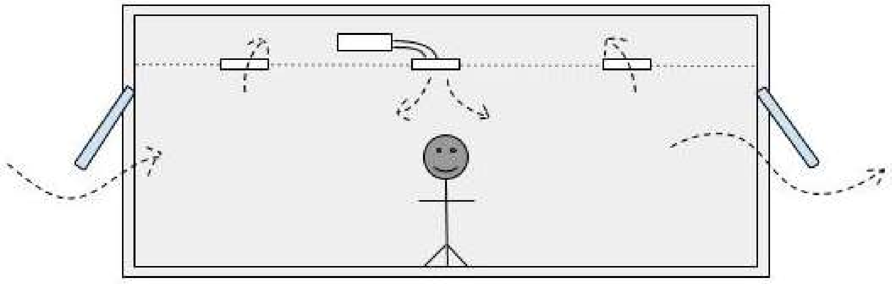

Figure 7: Concurrent mixed-mode ventilation. Replicated from (CBE).

Change-over system

This strategy switches between using either natural or mechanical ventilation based on algorithms from the building’s automation system.

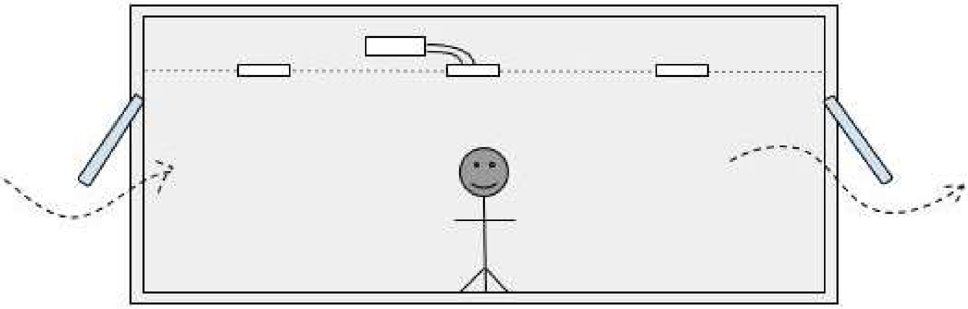

Figure 8: Change-over mixed-mode ventilation, natural. Replicated from (CBE).

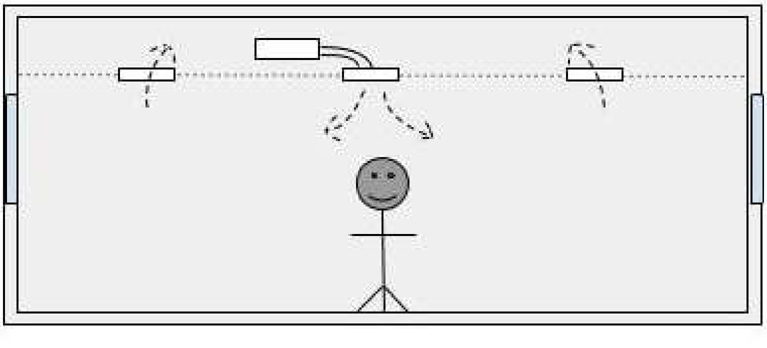

Figure 9: Change-over mixed-mode ventilation, mechanical. Replicated from (CBE).

Zonal system

The building is divided into different zones which have different ventilation strategies. Natural and mechanical ventilation can then be utilized at the same time in different places.

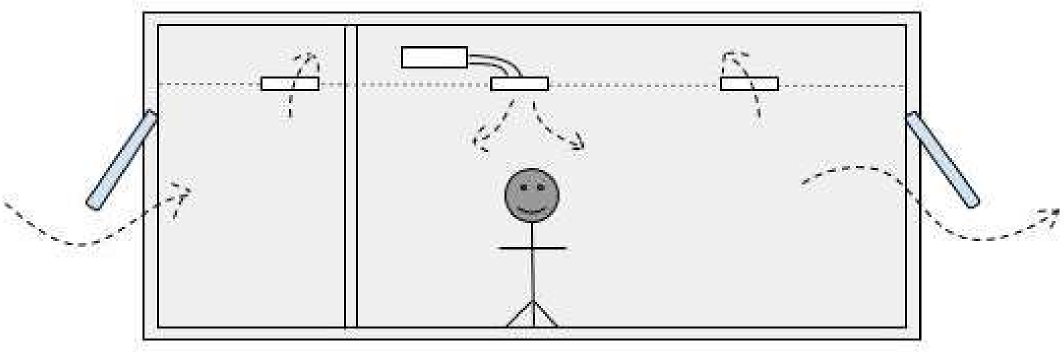

Figure 10: Zonal mixed-mode ventilation. Replicated from (CBE).

Advantages and disadvantages of Hybrid Ventilation (Lie 2015)

Among the advantages of using hybrid ventilation we find reduced energy use for fans, higher user satisfaction, increased flexibility and reliability, and the potential for reducing the design dimensions for mechanical systems.

Disadvantages encompass the increased risk of outdoor pollution entering the building, higher time demand for accurate design, increased complexity and we also risk the systems coming in conflict with each other and decreasing efficiency.

2.3.2 Air Distribution

Once the supply air has come into the building, there are different ways to facilitate internal air motion. Displacement and mixing ventilation are described further.

2.3.2.1 Displacement ventilation

According to Etheridge and Sandberg (1996), traditional displacement ventilation air supply happens at a temperature lower than the room temperature, at the floor level. The cool air is heated up by objects and occupants in the room and rises, while warm air is extracted at the ceiling level. The process is illustrated in Figure 11.

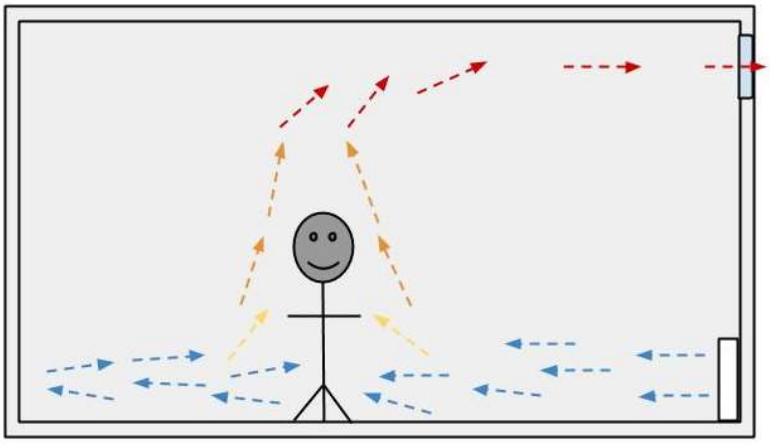

Figure 11: Displacement ventilation, inspired by Nilsson (2003)

Since displacement ventilation utilizes the natural thermal buoyancy forces, it is only satisfactorily effective when there is excess heat to be removed in a room. However, this is not seen as a restriction since even in cold climates like that of Scandinavia cooling is required to remove excess heat from people, computers and other office machinery.

Displacement ventilation has several potential advantages such as better air quality and efficient cooling. One potential risk is temperature stratification and local discomfort (cold feet, hot head).

2.3.2.2 Mixing ventilation

In mixing ventilation, the air is supplied to the room in the form of jets. The principle is illustrated in Figure 12 (Nilsson and Commtech Group 2003). Air is supplied at a speed high enough to move the total air volume of the room.

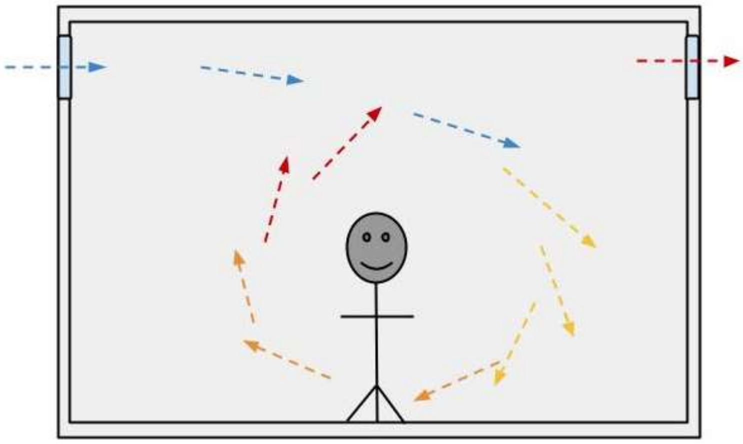

Figure 12: Mixing ventilation, inspired by Nilsson (2003)

Air can be supplied from an inlet at the ceiling, at the walls or even from the middle of the room. However, as Nilsson states in Achieving the Desired Indoor Climate, it is advantageous to place the air inlet outside the occupied zone so that the air velocity is reduced, minimizing the risk of draught.

The contamination concentration is uniform due to the uniform mixing of air. The supply air velocity is also limited due to the accompanying noise generation.

2.3.3 Air Jets

Supplying air to a room at a relatively high-speed results in an air jet. Jets can be classified based on the shape of the opening they originate from, and a jet's proximity to a wall. Openings can be circular, radial or linear. If a jet enters close to a wall which is parallel to the flow, the free flow is hindered on one side, creating a wall jet (Nilsson and Commtech Group 2003).

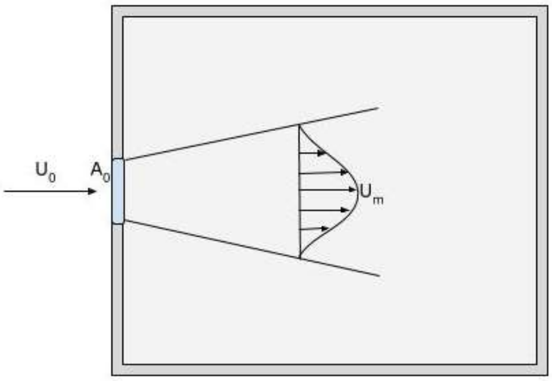

Figure 13: Free jet, inspired by Stensaas and Hovland (2001)

If an inlet is placed close enough to a wall, for example 0.2-0.3 m away from the ceiling, low pressure is created close to the ceiling. This causes the cool, supply air to "stick" to the surface. This is characterized as the Coanda effect and can be used as a tool to ensure that the cold air gets warmed up before entering the occupied zone hence minimizing risk of draught (Stensaas and Hovland 2001).

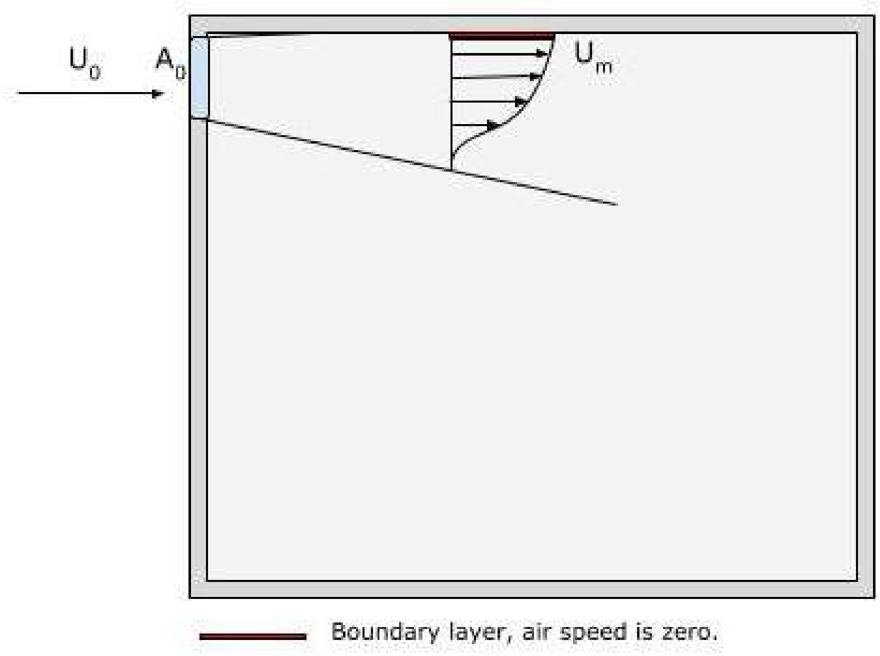

Figure 14: Wall jet, inspired by Stensaas and Hovland (2001)

A linear jet is characterized by the width of the opening being much larger than its height, as illustrated in Figure 15.

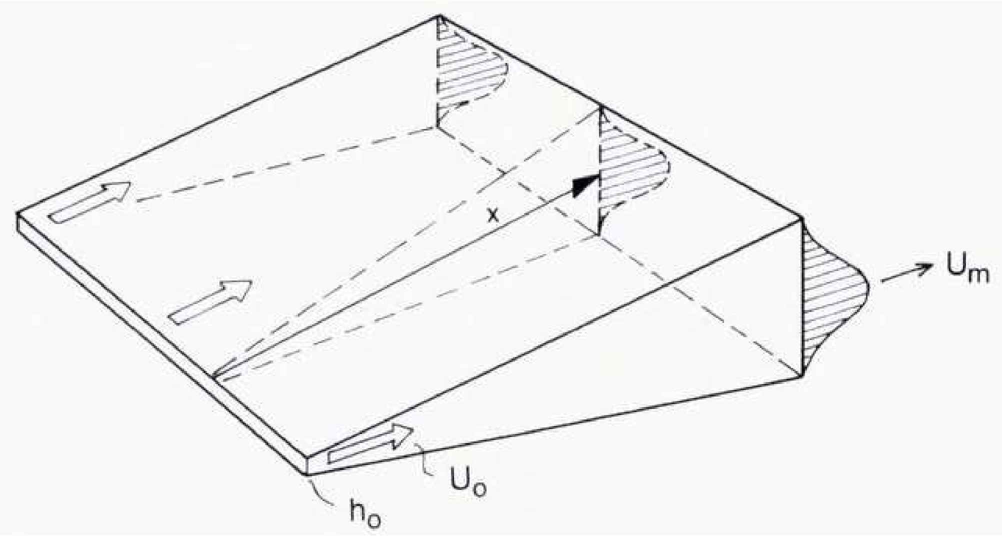

Figure 15: Plane, free jet from Ventilasjonsteknikk (Skåret 2000)

Equations have been developed to calculate the velocity and temperature of the jet once it is in the room. Eq.(21) and (22) illustrate the correlation (Skåret 2000).

$$U_m = U_0 \sqrt{K_2 \cdot \frac{\rho_E}{\rho_I} \cdot \frac{h_0}{\varepsilon x}} \tag{21}$$

$$\Delta T_m = \Delta T_0 \sqrt{\frac{0.75K_2}{i^2} \cdot \frac{\rho_E}{\rho_I} \cdot \frac{\varepsilon h_0}{x}} \tag{22}$$

K_2 is a constant relating to the shape of the inlet, in this case a linear form. In practice its value lies between 3.0 and 6.0.

ε is the contraction coefficient, 0.63 for sharp edges

i is the impulse loss factor. This varies with the grating factor, and is 1.0 for no grating.

2.3.4 Ventilation Management

In order to properly manage the ventilation in a building a specific strategy should be adopted and implemented. Three common management strategies are described below.

CAV, Constant Air Volume

CAV systems are run on a constant air flow at all times, dimensioned for the maximum load. To save energy the system is shut down outside of working hours weekends i.e. this is an on-off system. This process can also be automized (Stensaas and Hovland 2001).

CAV systems can either be used only for introducing cool fresh air, or they can be used in combination with temperature control to cover thermal demands. The air volume will still be constant, but the temperature then varies (Stensaas and Hovland 2001).

VAV, Variable Air Volume

Instead of the method of capacity regulation being adjusting the supply air temperature while holding the air volume constant, VAV regulates the air volume at a constant temperature according to cooling demand.

This strategy has the advantage of lower air volumes, hence reducing operation costs for fans (Stensaas and Hovland 2001).

DCV, Demand-Controlled Ventilation

A DCV system can be defined as "a ventilation system with feed-back and/or feed-forward control of the airflow rate according to a measured demand indicator" (Maripuu 2011). Both temperature and air flow can be regulated.

The demand can be determined by values and parameters that affect different factors, for example, thermal comfort or air quality. Room temperature is often the main indicator for thermal comfort, while carbon dioxide (often occupancy) is the most common indicator for air quality.

DCV systems are complex in nature but result in energy savings.

3 Literature review

The following section presents the literature study for this thesis.

3.1 Ventilative Cooling

Ventilative cooling is being increasingly utilized and can be employed as a tool to counteract the downside of highly insulated buildings, namely that they tend to get overheated and require cooling.

"Ventilative cooling is an air system that cools a building using ventilation air from outside at its actual temperature and humidity in which the air transfer may be by natural, mechanical or hybrid means. Generally, ventilative cooling reduces the energy consumption of cooling systems while maintaining thermal comfort."(Venticool 2019)

In the research paper 'Ventilative cooling as a solution for highly insulated buildings in cold climate', a hybrid window ventilation system is analyzed in IDA ICE for a Norwegian kindergarten. The main results showed significant energy saving while using ventilation cooling that follows low outdoor temperatures. It was also observed that for very warm days, acceptable indoor temperatures were difficult to attain without night setback or mechanical cooling (Alonso, Mathisen et al. 2015).

In a study titled 'Optimizing Hybrid Ventilation Control Strategies Toward Zero-Cooling Energy Building' (Hassan Mohamed and Mauro 2019), an open plan office building situated in Glasgow employing stack assisted cross ventilation was modeled in the whole-building simulation tool IDA ICE. Findings showed that the different hybrid ventilation strategies were able to reduce the cooling demand to zero. Fan energy is also saved. The only drawback discovered was a potential increase in the space heating demand. The optimal trade off was found by reducing fan energy by 68% and allowing an increase in heating demand of 1.3 kWh/m^2.

There are ongoing standardization processes regarding integrating ventilative cooling in existing European technical documents. These will focus on setting criteria and providing guidance on designing and dimensioning ventilative cooling systems (Venticool 2019).

3.2 Research findings

A 2012 case study of the Wisconsin Institutes for Discovery (Menassa, Taylor et al. 2013) focused on an experimental approach to test and analyze various hybrid ventilation strategies. The performance criterion tracked were energy savings, occupant comfort and indoor-air quality. The building can be looked at as a maximized variant of the ZEB Laboratory as it consists of laboratories, offices and study and eating areas over 4 stories and a footprint of 33,000m^2 (Menassa, Taylor et al. 2013).

The main findings showed that the ideal hybrid ventilation strategy gave 56 percent average savings in ventilation and cooling loads. A potential for 28% of the 111-day cooling season was established to be possible to cover by hybrid ventilation.

This was the case for a complex building with high process loads and stringent ventilation requirements in the various laboratories. Therefore, hybrid ventilation was only employed in public spaces. It also differs from the ZEB Lab in that it has mechanical cooling installed. However, the positive effects of hybrid ventilation are still valid and transferrable.

Night cooling and predictive control

A 2018 study (Yuan, Vallianos et al. 2018) developed a predictive thermal mass model for thermal mass cooling in a 17-story high institutional building employing hybrid ventilation (fan-assisted). Openings for night ventilation cooling were based on outdoor temperature and relative humidity. The building treats the corridors as "generic transition zones/buffer spaces with flexible thermal comfort limits". The motorized façade openings follow inputs from a weather station on the roof of the building. The main findings showed that lowering the minimum outdoor temperature allowed into the building had a great effect in reducing energy consumption for cooling. Also, changing the criterion from relative humidity to humidity ratio resulted in more operation hours and hence higher energy savings.

Adaptive comfort in naturally ventilated offices

An interesting study from 2019 titled 'Use of adaptive control and its effects on human comfort in a naturally ventilated office in Alameda, California' (Zhai, Honnekeri et al. 2019) explored the mechanisms underlying the finding that naturally ventilated building are experienced to be comfortable over a wider range of temperatures. The different adaptive control opportunities employed by the occupants to meet comfort needs were observed. These included window state, ceiling fan usage, heater usage, and of course, indoor and outdoor conditions. It was found that conditions were acceptable for 98% of the survey period, where the indoor temperature ranged from 16-28°C. Windows were opened by occupants when outdoor temp was higher than 15°C. Naturally, window opening happened at arrival and with regard to outdoor temperature. During winter, heaters were turned on over an hour after arrival and starting to work (sedentary activity). Fans were used when indoor temperature rose above 25°C. Using these adaptive control measures, occupants experienced thermal neutrality and satisfaction from 18-25°C. These findings empirically strengthen the basis for adopting adaptive comfort models in office buildings.

State-of-the-art developments

An exciting ongoing project in Switzerland is NEST; Next Evolution in Sustainable building Technologies. It is planned as a future living and working laboratory, consisting of a "central backbone building" (completed in 2016) and exchangeable living and office buildings or units (Block, Schlueter et al. 2017). The goal is to test innovative systems under real-world conditions, much like the ZEB Lab intends. One of the NEST modules, HiLo, is planned as a research and innovation building in the area of lightweight construction and adaptive building systems. Construction on HiLo (High performance, Low energy) began in 2019, and operation is planned to commence in 2020. The unit is planned as a two-bedroom apartment for visiting faculty.

Occupant-centered control in HiLo (Block, Schlueter et al. 2017)

Occupant-Centered Control (OCC) can be defined as a

> "learning-based building control that detects occupant-building interaction, learns the occupant's comfort needs, and automatically adapts building services to these requirements. This control strategy reduces the need for occupant's actions, achieves a level of comfort specifically tailored to the occupant, and further improves energy savings compared to conventional building control strategies."

The programmable logic controller (PLC) implemented in HiLo's home automation system will monitor sensors for temperature, humidity, CO_2, PIR and lux, the HVAC system and the electrochromic glass shading system. The home automation system is designed to monitor the mentioned parameters and occupant-building interaction, execute control algorithms on a central computer and finally, send set point values to the building services.

OCC represents an exciting new phase in BAS. HiLo's strategy is illustrated in a lighting control study wherein occupant specific illuminance levels in each office were learned by the control system using only detection of the use of standard light switches. Energy savings during the study amounted to 37.9% compared to a standard setting control baseline .

Data Predictive Control (DPC)

An experimental study in another unit at NEST has demonstrated data predictive control for energy optimization and thermal comfort in buildings (Bünning, Huber et al. 2020). The approach is supposed to reduce modelling effort required for model predictive comfort by learning the building's behavior using historical data. The experiment proved successful for a six-day experiment resulting in a 25% cooling energy reduction.

3.3 Case examples

Table 3 shows an overview of a few buildings using different ventilation types.

Name	Building type	Building year	Location	Area (m^2)	Ventilation principle	Comment
Harvard HouseZero[2]	Living lab, office	2018	Cambridge, MA, USA	427	Natural ventilation	Retrofitted pre-1940's building
2226[3]	Office	2012	Lustenau, Austria	2421	Natural ventilation	No mechanical HVAC
Powerhouse Drøbak	School	2018	Drøbak, Norway	886[4]	Hybrid ventilation	All-air HVAC, heating using displacement vent. (Myrup, Dokka et al. 2018)
Mesterfjellet skole[5]	School	2014	Larvik, Norway	6000	Hybrid vent., mixed-mode	
Powerhouse Kjørbo [6]	Office	1980, Rehab. in 2017	Sandvika, Norway	5200	Simplified mechanic ventilation	Night passive cooling. Thermal mass exploited.
B&O Headquarters[7]	Office	1998	Struer, Denmark	5000	Fan-assisted natural vent.	
Liberty Tower Meiji University[7]	Office/ university	1998	Tokyo, Japan	53000	Hybrid ventilation	High-rise with central core for stack ventilation. CO2 and temp. control

Table 3: Case examples

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[2] https://snohetta.com/project/413-harvard-housezero ELLER https://harvardcgbc.org/research/housezero/

[3] https://www.baumschlager-eberle.com/en/work/projects/projekte-details/2226-lustenau/

[4] https://www.powerhouse.no/prosjekter/drobak-montesorri/

[5] Lie, M. (2015). Hybrid ventilasjon i moderne bygninger, NTNU.

[6] Halderaker, I. D. (2016). Design and Energy Analysis of Natural and Hybrid Ventilation Strategies for Norwegian Office Buildings, NTNU.

[7] Heiselberg, P. (2006). "Design of natural and hybrid ventilation." DCE lecture notes(005).

Nydalen Vy

Nydalen Vy is an 18-storey high, 10,000m^2 office and apartment building in Oslo, planned to be Norway's first "combination"[8] building using exclusively natural ventilation. It is one of the pilot projects in Naturligvis; a research project concentrating on passive heating and cooling in energy-efficient buildings of the future. The project is led by Skanska, partnering with several prominent entities, Snøhetta, SINTEF Byggforsk, FutureBuilt and WindowMaster being a few of them (Stoknes et al. 2018).

The report on Naturligvis (Stoknes et al. 2018) explains that the research project itself, and therefore Nydalen Vy, is inspired by the pioneer building 2226 in Lustenau, Austria. "2226" represents the comfort interval of the building; the indoor temperature should normally be within this interval of 22-26°C. The building arguably redefines the normative passive house. There is no artificial insultation - the 78 cm wide walls are made only of air, clay and bricks. The floor height is between 3.3-4.5 meters, and there are no artificial, suspended ceilings. Nor is there any mechanical ventilation.

Comfort is achieved by letting the occupants, the lights and the computers act as radiators while the thermal mass of the building provides necessary cooling. Air changes take place through the deep set triple-glazed windows which avoid overheating and are controlled either manually or by using CO_2 sensors (Stoknes et al. 2018).

Naturligvis' flagship Nydalen Vy aspires to a so-called "TripleZero" goal – to buy less than 0 kWh energy for the purpose of ventilation, heating and cool for the office area. Energy balance is achieved on a yearly basis using local photovoltaic production.

The natural ventilation concept is implemented using automatic motorized openings high up, supplemented by lower manual openings. The automatic openings are controlled by CO_2 level and internal temperature in addition to an outdoor weather station measuring wind speed, direction, temperature and precipitation. The control systems are provided by the proprietary algorithms of WindowMaster.

The adopted strategy is to supply each floor separately primarily using single-sided ventilation during the winter and cross ventilation during the summer. A somewhat higher CO_2 level is permitted during wintertime to avoid extreme heat loss. During the summer, the automated openings are controlled by the internal temperature setpoint.

Other pilot projects for Naturligvis are Drøbak Montessori school and House Zero at Harvard. Nydalen Vy represents an exciting new phase in the Norwegian built environment and is expected to be completed in 2020.

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[8] Both office and residential area

Drøbak Montessori School (Myrup, Dokka et al. 2018)

Drøbak Montessori School is Norway's first plus-energy school and the first Norwegian Powerhouse school. The Powerhouse concept is to have the building produce more renewable energy throughout its lifetime than consumed in materials, production, operation, and demolition. The school is designed for 60 students over a heated area of 900m^2.

The ambitious energy goals have been fulfilled in part by implementing an efficient and low-pressure ventilation system. Displacement ventilation in relatively tall rooms was chosen. Depending on the season, the system varies between operating as fully mechanical or hybrid. In addition, the HVAC system is all-air, with both ventilative heating and cooling.

During occupied hours, fresh air is supplied with a supply temperature varying between 16-18°C to ensure an efficient displacement ventilation strategy. Air flow rate is regulated according to air temperature and CO_2. During unoccupied hours, the system switches to heating or cooling mode dependent on the season. The air flow rate in heating mode is set to the maximum calculated air flow rate for the room. When the heating setpoint is reached, the air flow rate is reduced to the minimum calculated air flow rate for the room.

Extract air is removed from zones to adjacent areas by overflow. There is a centrally placed atrium through which exhaust air is let out directly during the summer. During the heating period, the air is driven through the AHU for heat recovery purposes.

Myrup, Dokka et al. performed a one-day field test in one of the classrooms in February 2018 to validate the ventilation system. The focus was on CO_2 and temperature measurements. Night heating with displacement ventilation was found to function satisfactorily with a "relatively high supply temperature" (average 27,5°C). During the occupied hours in normal mode, the average supply air temperature was 17.3°C. It took 1,5 hours for the room temperature to stabilize at 19-20,5°C after the occupants arrived. Measurements also showed that CO_2 levels were stable during the night and then rose when people entered the room.

4 Presentation of ZEB Lab

The objective of this thesis is to explore natural ventilation modeling in ZEB Lab. This section provides general information about the project and building.

4.1 Ambition level

According to the Research Centre on Zero Emission Buildings (ZEB) a zero emission building compensates for its greenhouse gas equivalent emissions during its lifetime (Fufa, Schlanbusch et al. 2016). There are six ZEB ambition levels; and ZEB Lab aims to achieve the third highest – the ZEB-COM level. COM represents emissions related to Construction and installation, Operation and Materials.

The project is a joint venture between NTNU, SINTEF and The Research Council of Norway. The following research questions are central to the project (Jacobsen and Andresen 2018)

- What technical and architectural solutions are needed to achieve good office and education conditions in a Zero Emission Building?
- How do users influence the energy consumption in the building and how do they adapt ZEB technologies?

4.2 ZEB Lab

ZEB Lab is meant to be an experimental facility combining research spaces, offices and educationally purposed rooms. The facility will be a living lab and serve as a playground for full scale research on zero-emission buildings and occupant-building interaction. The scope includes innovative solutions for ventilation and energy technologies (Time, Nocente et al. 2019).

4.2.1 Building structure

The ZEB Lab is currently under construction at the Gløshaugen campus of the Norwegian University of Science and technology (NTNU) and is expected to start test operation in August of 2020. The building will have four floors and span 1800m^2 (Time, Nocente et al. 2019). A live construction update can be found on zeblab.no.

The first floor will primarily house ancillary functions such as a wardrobe area, toilets, storage, the energy central and the canteen. The second floor shall have twin cells for research, workspaces and meeting rooms. The twin cells will be dedicated to research on energy use and user-building interaction. The third floor will consist of both open and closed-off workspaces, as well as meeting rooms. Flexible touch down areas are planned both on the second and third floor. The fourth floor will primarily house classrooms and a large technical room. The technical room will double as a "showroom" to present the technical implementations in the building (Leinum 2019). Toilets are naturally to be found on every floor.

On-site renewable energy production will be provided by PV-panels on the roof and facades (south, east and west) covering an area of about 1200 m^2 (Jacobsen and Andresen 2018).

Windows

Windows span approximately 28% of the BRA covering a total area of 488m^2 (Jacobsen and Andresen 2018). While most of the windows will be unopenable, the openable ones are differentiated by the control method; some are manually controlled (by users) while others have automated motorized control systems. The opening area is restricted to 20 and 60% of the geometric area respectively for the manual and motorized windows (Leinum 2019). The openable windows' placement is designed to facilitate natural ventilation. The ZEB Lab facades are illustrated in Figure 16.

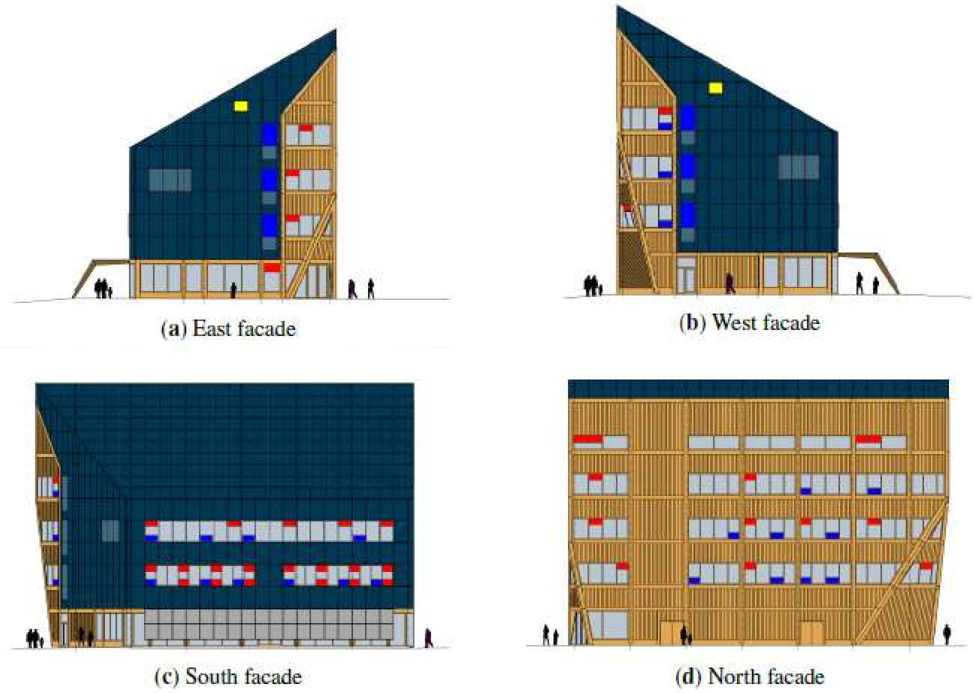

(a) East facade
(b) West facade
(c) South facade
(d) North facade

Figure 16: Facades of the ZEB Laboratory. Blue windows are manually controlled, red windows are motorized. (Illustration: Link Arkitektur acquired from Nemitek presentation by Hans Martin Mathisen 20.9.2019)

In Figure 16, manually controlled windows are illustrated by the blue squares, while motorized ones are red. Most of the windows are grey and unopenable. The east and west facades have one motorized fire hatch each, illustrated by the yellow square.

4.2.2 Using ZEB Lab

ZEB Lab has an estimated lifetime of 60 years during which the ZEB-COM level will be achieved (Time, Nocente et al. 2019).

As an operational office and educational building, ZEB Lab will be occupied during normal working hours. Main usage is assumed to be from 08:00 to 16:00, with some degree of activity extending from 07:00 to 20:00 (Leinum 2019).

The building is designed for about 70-100 occupants (including students), the number varying according to lecture times etc. (Leinum 2019).

4.3 Ventilation in ZEB Lab

ZEB Lab is designed to explore different ventilation strategies while monitoring energy use and user behavior and satisfaction. The building is designed for operation and research on both natural and mechanical ventilation, as well as a combination of the two in hybrid mode (Time, Nocente et al. 2019). The main staircase acts as an extract for air both for mechanical and natural ventilation.

4.3.1 Mechanical Ventilation

ZEB Lab has a central mechanical ventilation system. Displacement ventilation is the chosen ventilation strategy, but the different floors each employ a different air distribution system (Time, Nocente et al. 2019). This is done presumably to maximize research possibilities. According to the SINTEF document 'ZEB Laboratory-Research Possibilities', the first floor will have inlet devices at floor level. The second floor will have porous ceiling boards in the suspending ceiling board, the third is designed to supply air through slots and the fourth through wall air terminals at floor level.

Exhaust air is removed through ducts in the wardrobes, toilets and the main duct connected to the main stairwell (Leinum 2019).

Mechanical cooling is not installed apart from in the twin cells. The twin cells are designed with an independent HVAC system and technical room to support research.

4.3.2 Natural Ventilation

The windows in ZEB Lab are design to assure cross ventilation on opening. The fire hatches close to the roof act as an outlet for buoyancy driven air flow (Time, Nocente et al. 2019).

Other principles that are planned for the ZEB Lab are morning fresh air, pulse ventilation and slot ventilation (Leinum 2019). Morning fresh air entails opening motorized windows before occupant arrival to ensure a fresh sensation. Pulse ventilation is the opening of windows for a very short period of time, suitable for periods of low ambient temperature. Slot ventilation is opening a small portion a window (10-20mm) during occupied hours to ensure continuous inflow of fresh air.

Implementation of the above strategies naturally depends on the season and ambient temperature (Leinum 2019).

4.3.3 Ventilation Mode

ZEB Lab can be operated in mechanical, natural or hybrid mode. Hybrid mode differs based on prevailing season.

The mechanical mode entails supply air restricted to the HVAC system and manually controlled windows (The motorized windows are not in play). Natural ventilation mode abandons mechanical air supply and relies solely on windows (both manual and motorized) (Leinum 2019).

Hybrid ventilation summer mode has natural ventilation as the chosen priority, and mechanical ventilation is used as a supplement when needed. Hybrid ventilation winter mode has a converse strategy (Leinum 2019).

4.4 Control Strategies

Different control strategies for ZEB Lab are described in this section.

Ventilation Control

Each floor is divided into four regulatory zones, except for the fourth floor which will have only two zones. Two AHUs are planned, and dampers will be used to regulate the pressure level for each zone when the balanced mechanical system is working. There will be temperature sensors for the fans as well as pressure sensors for control and monitoring purposes. Temperature, motion and CO_2 sensors will be used for DCV in each zone. (ZEB Lab team 2019)

The motorized windows can be controlled locally to the desired position. They will be closed if motion sensors detect an empty room for over five minutes (ZEB Lab team 2019). This avoids overheating/cooling.

Shading Control

ZIP screens, mounted on the outside, are planned for shading windows. Automatic functions are based on setpoints for glare and solar radiation. Mobile, manual control for shading in each room will also be possible. The manual functions are reverted automatically if motion sensors detect an empty room. As a safety measure the screens are set to roll up at high winds or low temperatures (ZEB Lab team 2019).

5 Model Structure and Implementation in DesignBuilder

This section describes the simulation tool, the implemented model, and registered input.

5.1 Simulation tool

The simulation tool chosen for the purpose of this master thesis is DesignBuilder. DesignBuilder is described in its help manual as a "user-friendly modelling environment where you can work with virtual building models. It provides a range of environmental performance data such as: energy consumption, carbon emissions, comfort conditions (…) and HVAC component sizes".

The underlying dynamic simulation engine that generates performance data belongs to EnergyPlus. EnergyPlus is the US Department of Energy's (DOE) building energy simulation program for modeling building heating, cooling, lighting, ventilation, and other energy flows. DesignBuilder has integrated the EnergyPlus engine to provide a user-friendly graphical interface, which is something EnergyPlus lacks.

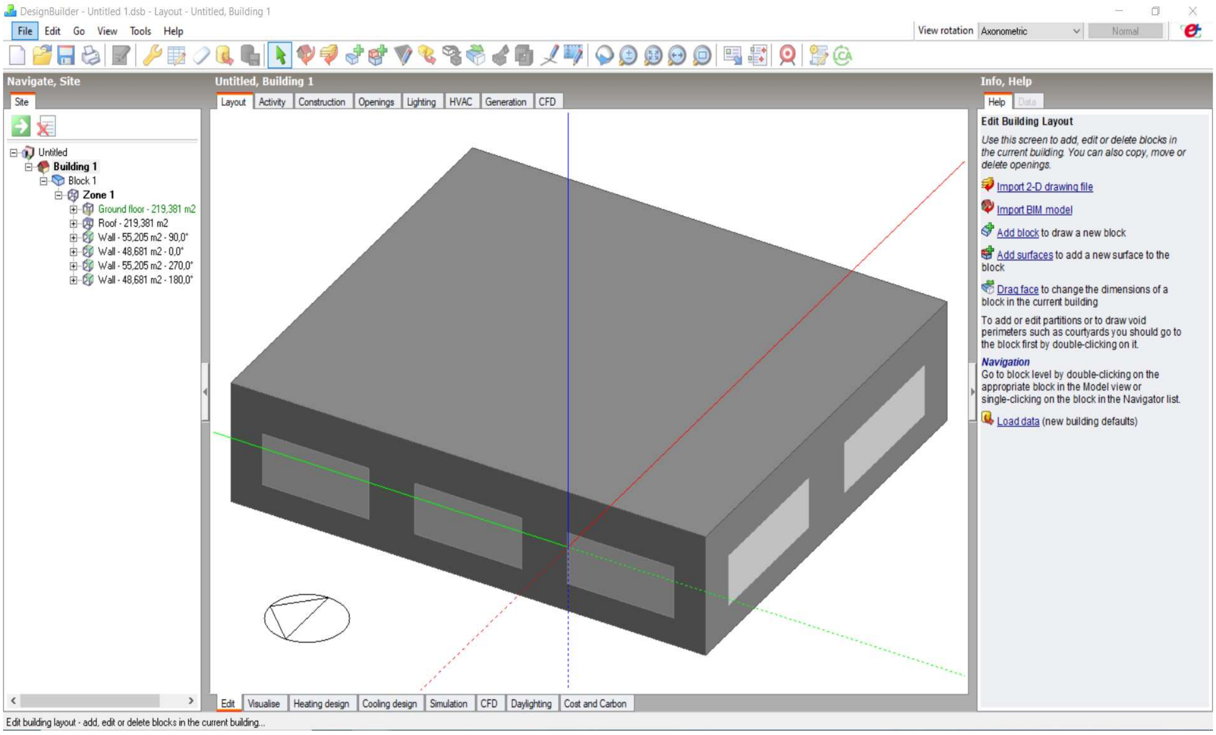
For the purposes of this thesis, the functions that have been utilized are mainly comfort conditions during natural ventilation. Version 6.1.5.4 was used with an evaluation license.

User Interface

Figure 17 shows a screenshot of the intuitive graphical user interface in DesignBuilder.

The window to the right is the Navigation panel and to the right we see the Info panel. In the middle is the Edit screen, where building geometry can be graphically implemented. Screen tabs for different functions such as editing and simulation can be seen towards the bottom of the window, while towards the top are the Model tabs for Activity, HVAC etc.

Figure 17 shows a simple one-zone building. Façade areas can be easily seen in the drop-down menu of the Navigation panel.



Untitled
Building 1
Block 1
Zone 1
Ground floor - 219,381 m2
Roof - 219,381 m2
Wall - 55,205 m2 - 90,0°
Wall - 48,681 m2 - 0,0°
Wall - 55,205 m2 - 270,0°
Wall - 48,681 m2 - 180,0°

Edit Building Layout

Use this screen to add, edit or delete blocks in the current building. You can also copy, move or delete openings.

Import 2-D drawing file

Import BIM model

Add block to draw a new block

Add surfaces to add a new surface to the block

Drag face to change the dimensions of a block in the current building

To add or edit partitions or to draw void perimeters such as courtyards you should go to the block first by double-clicking on it.

Navigation
Go to block level by double-clicking on the appropriate block in the Model view or single-clicking on the block in the Navigator list.

Load data (new building defaults)

Edit building layout - add, edit or delete blocks in the current building...

Figure 17: DesignBuilder interface

5.2 Model structure

The following section describes the implementation of the model in DesignBuilder.

5.2.1 Building structure

DesignBuilder has the ability to model multi-zone complex geometry and the ZEB Lab model structure has been implemented as best as possible. Dimensions for the model were taken from floor plans and an IFC-file obtained from the project group for ZEB Lab.

The first-floor height is set to 4.45 m, the next two are 3.85 m high while the fourth floor has a height of 11.85 m at the highest point. The building spans a total height of 24 m. Floor area is set at 440m^2 per floor, giving a total floor area of 1760m^2 for the whole building.

A rendered view of the building structure generated in DesignBuilder is presented in Figure 18.

Figure 18: Rendered views of southwest (to the left) and northeast (to the right) facades of ZEB Lab model in DesignBuilder

5.2.2 Zoning

Internal zoning was implemented to achieve realistic modeling of airflow and temperature. Simplified zones were made based on floor plans and zonal division obtained from the project database. These are illustrated for each floor in Figure 19.

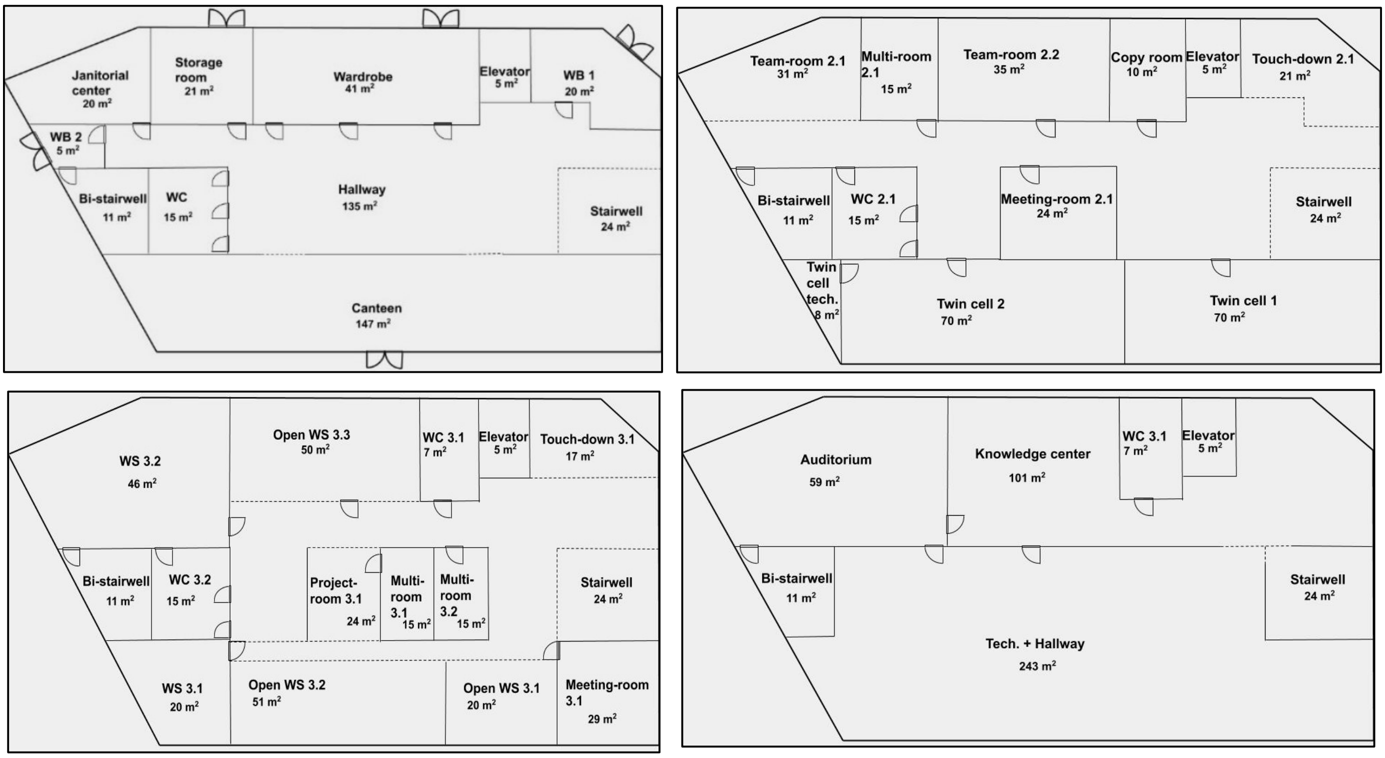


Figure 19: Zonal division for ZEB Lab model for first floor (top left), second floor (top right), third floor (bottom left) and fourth floor (bottom right).

Dashed lines represent holes or virtual partitions between zones. The acronym WS stands for Workspace.

5.2.3 Ventilation in Design Builder

Design Builder provides two options when modeling natural ventilation in a building; either Scheduled or Calculated.

The Scheduled option entails explicitly defining a natural ventilation air change rate for each zone and is used if one can make a reasonable estimate of natural ventilation rates. When using the Calculated option, natural ventilation is based on window openings, cracks, buoyancy, and wind-driven pressure differences. This thesis uses the Calculated Natural Ventilation option.

DesignBuilder uses the Airflow Network method of EnergyPlus to calculate air flows. This is a validated approach (Gu 2007).

When modeling Calculated natural ventilation, wind effects can be reduced or excluded by varying the Wind factor under the Options of the Natural Ventilation tab. Default wind pressure coefficients have been used.

Infiltration

When using Calculated natural ventilation, DesignBuilder includes a single crack in each surface of the simulation to model infiltration. Airtightness is set using a crack template. The template slider option is chosen and set to ‘Good’. Each setting corresponds to a predefined default setting for infiltration in openings, walls, floors/ceilings, and roofs.

5.2.4 External Openings

External Doors

Entrance doors on the western and northeastern facades have a height of 3 m and width of 2 m. Opening area is set to 50% of the geometric area, and opening time is set to 15% between 08:00-16:00 during weekdays. This entails the assumption that the doors will be half-open for 1.2 hours on an average between 08:00-16:00.

Northern doors have a height and width of 2.1 m. The opening schedule is the same as for entrance doors, however opening time is decreased to 5% as it is assumed these doors will not be as frequently used since they connect to the Storage and Wardrobe.

The canteen door has a height of 3.5 m and a width of 2 m. The canteen door is set to open 10% of its geometrical area between lunch hours 11:00-13:00. This was assumed to be an acceptable area for ventilation purposes as the door is quite large.

Windows

ZEB Lab has both openable and unopenable windows. The openable windows are divided into windows with motorized or manual control. Figure 20 illustrates the different windows in ZEB Lab.

a. Eastern façade

b. Western façade

c. Southern façade

d. Northern façade

Figure 20: Illustration of window types

Window properties and dimensions implemented in the model follow the set up in Table 4. The main types are divided into 'Manual control', 'Motorized control' and 'Unopenable' windows. It is assumed that the opening area is the cross-sectional, measurable geometrically openable area of the window (for rectangular windows, the rectangular area in addition to the two triangular areas on either side).

	Category	Height [m]	Width [m]	Area [m^2]	Opening [%]	Openable area [m^2]
Manual control	Small	0,46	0,93	0,43	0,20	0,09
	Large	0,46	1,17	0,54		0,11
	Side	1,80	1,11	2,00		0,40
Motorized control	Small	0,46	0,93	0,43	0,60	0,26
	Large	0,46	1,17	0,54		0,32
	First floor	0,56	1,46	0,82		0,49
	Fire hatch	1,00	1,00	1,00	1	1,00
Unopenable	First floor, east	2,50	1,47	3,68	-	-
	First floor, west	2,50	1,57	3,93	-	-
	First floor, south	3,00	1,44	4,32	-	-
	First floor, north	2,50	1,10	2,75	-	-
	Large, middle	0,79	1,20	0,95	-	-
	Large, lower/upper	1,35	1,20	1,62	-	-
	Large, whole	1,91	1,20	2,29	-	-
	Small, whole	1,79	0,93	1,66	-	-
	Small, middle	0,87	0,93	0,80	-	-
	Small, lower/upper	1,33	0,93	1,23	-	-
	Fourth floor, north	1,31	2,23	2,92	-	-
	Side	0,90	1,11	1,00	-	-

Table 4: Window properties and dimensions implemented in the DesignBuilder model

The 'Small' openings pertain to the southern façade on the second floor.

'Side' openings are the narrow windows found on the East and West facades with manually controlled windows placed over an unopenable window.

The opening position for windows is assumed, and set to the top for motorized windows (to minimize risk of draught), and bottom for the manually controlled ones (for better occupant reach).

Relative elevation in terms of distance from the floor in question to the bottom of the window is presented in Table 5.

	Window/Orientation	Bottom elevation [m]
First floor	N,S,E,W	0,5
Second floor	N,E,W	0,8
	S	0,85
Third floor	N,S,E,W	0,8
Fourth floor	N_upper	4,61
	N_lower,E,W	0,8
All floors	Side	0

Table 5: Relative elevation of windows implemented in the DesignBuilder model

Some unopenable windows have been merged in the DesignBuilder model to reduce simulation time.

The discharge coefficient is set to 0.65 for all the windows as per the suggestion of the DesignBuilder help manual.

Window glazing

The chosen window glazing for ZEB Lab in the model is a default template 'Triple glazing, clear, LoE, argon-filled'. This is assumed to be sufficient.

Shading

Shading is implemented in DesignBuilder as a 'Shade roll- medium opaque' mounted on the outside to imitate ZIP screens. The control method set for shading operation is chosen to be 'Solar'. Shading is initiated over the setpoint of 120 W/m^2 and implemented for manual and unopenable windows in the model. It is important to note that shading does not affect Calculated natural ventilation flows through windows during the simulation. However, it is unclear how the algorithm works when radiation is over the setpoint and the windows are set to be opened.

5.2.5 Internal openings

Internal doors have a dimension of 2 m x 1 m, 100% opening area for 5% of the time between 08:00-16:00. This entails the assumption that doors are fully open for 0.4 hours in an 8-hour workday.

Holes are modeled in the place of floor dividers in the stairwells to correctly model airflow in these zones.

5.2.6 Occupancy

ZEB Lab is designed to be used as an office, laboratory, and an educational space. Therefore, occupants will comprise of regular office workers, researchers, and students. Occupancy in the various zones will naturally vary with parameters such as lectures hours, meetings etc.

Assumptions are made to approximate the average occupancy in each zone, shown in Table 6 in Appendix A. The main occupancy of the building is assumed to take place between 07:00 and 17:00.

Implementation of occupancy in Design Builder is done by creating personalized schedules for similar zone types. An example is shown in Figure 21, and detailed information for all zones can be found in Appendix A.

The maximum number of occupants for Open Workspace 3.2 is set to 10 people and Figure 21 shows the fractional occupancy implemented for the zone. The schedule shows occupancy from 07:00 to 17:00 with a break for lunch during 11:00 to 13:00.

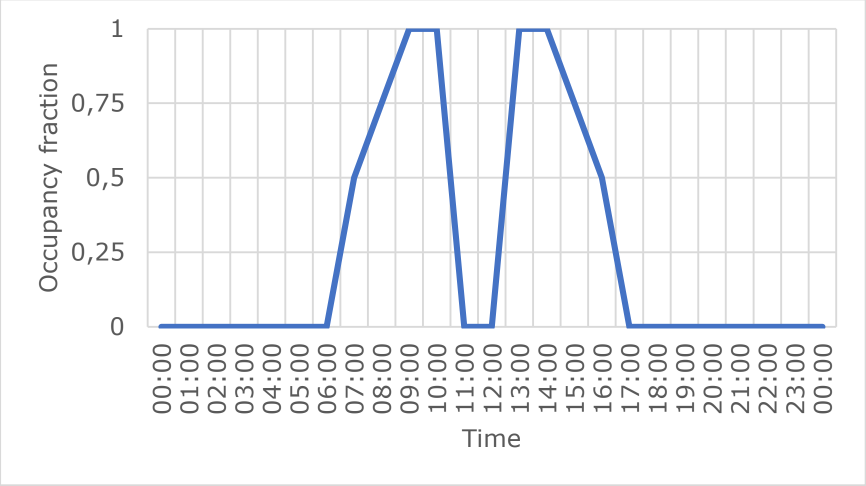


Figure 21: Occupancy schedule for workspaces

Internal gains

Under the Timing option of Model Options, internal gains are set to operate with occupancy. These include the Lighting, Computers, Office Equipment and Miscellaneous tabs under Activity. It is assumed that this is a sensible simplification. Internal gains have been modeled to include simulation of the risk of overheating.

5.2.7 Control method

The chosen control mode for natural ventilation in the model is '2-Temperature'. This entails that the zone's openable windows are opened if $T_{zone} > T_{out}$ and $T_{zone} > T_{set}$ and the operation schedule allows venting. T_{zone} is the temperature in the zone in question, T_{out} is outdoor temperature and T_{set} is the ventilation setpoint temperature.

T_{set} is set to an indoor minimum temperature of 22°C to avoid overcooling the zones. The operation schedule for the openable windows is set to 'On 24/7'. One exception is the only openable window on the first floor, which can be opened only between 07:00-18:00 on weekdays for security reasons. It is assumed that there will be automized control methods in place in the ZEB Lab that regulate the closing of windows when there is precipitation, high winds, risk of overcooling etc. based on weather station monitoring.

In DesignBuilder, doors are controlled exclusively by schedules, and not natural ventilation controls.

5.2.8 Weather

Design builder uses EnergyPlus epw format hourly weather data for simulations. Epw weather files are available from EnergyPlus for two locations in Norway; Oslo and Bergen. In this thesis, the weather file for Bergen has been used. It is assumed to be similar enough to the weather in Trondheim.

Under site details, the building’s exposure to wind has been set to ‘2-Normal’.

5.3 Results in Design Builder

Design Builder has an array of possible output parameters. In this thesis a few specific ones have been chosen to analyze.

Outside dry-bulb temperature and internal operative temperatures are looked at. For Comfort Analysis Fanger’s PMV has also been chosen. The program calculates PMV according to ISO 7730.

Regarding ventilation, Design Builder provides the sum of outside air (in ac/h) flowing into the zone through the HVAC system, infiltration, and natural ventilation. It is not possible to separate the three factors. However, since no mechanical ventilation is installed the numbers are limited to outside fresh air from natural ventilation and infiltration.

Heat balance in each zone is analyzed including factors such as external air, internal air, occupancy, and solar gains through exterior windows. It is important to note that in DesignBuilder internal and external air is presented in heat flow (kW), and not air volume. It is also not possible to know where the internal air is coming *from*; just that it is entering the zone and how it affects the heat balance i.e. if the air is warm or cold relative to the zone temperature.

Hourly and sub-hourly values per zone have been analyzed on a zone level in the results. Daily and monthly values are averaged and can provide a misleading interpretation of the results.

6 Results and Discussion

The following section presents results from simulations, and associated discussion. The summer simulation week is set to 22nd-28th July.

6.1 Site Data

Site weather data is presented here to better understand weather phenomenon that affects the simulations. This is site weather reported by EnergyPlus, as seen in site data at zone level. The data is naturally the same for every zone.

Outdoor Dry-Bulb Temperature

Figure 22 shows the outdoor dry-bulb temperature in Celsius for the chosen summer week. It is obvious that temperatures rise during the day and decrease at night. However, temperatures do not sink below 8,5° even during the night. The peak temperature is 25,5° occurring on 27th July at 13:00.

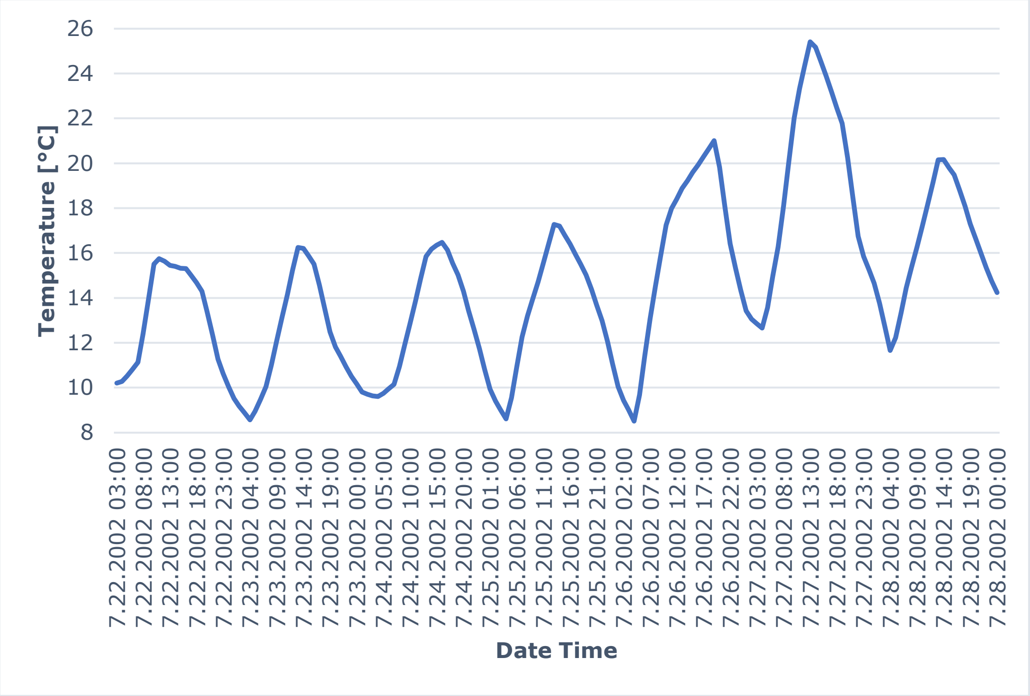


Figure 22: Outdoor dry-bulb temperature

Solar Data

Figure 23 presents direct normal and diffuse horizontal solar radiation on ZEB Lab in kW/m² for the chosen summer week. Both values peak during the daytime from 11:00-16:00 and decrease to zero during the night.

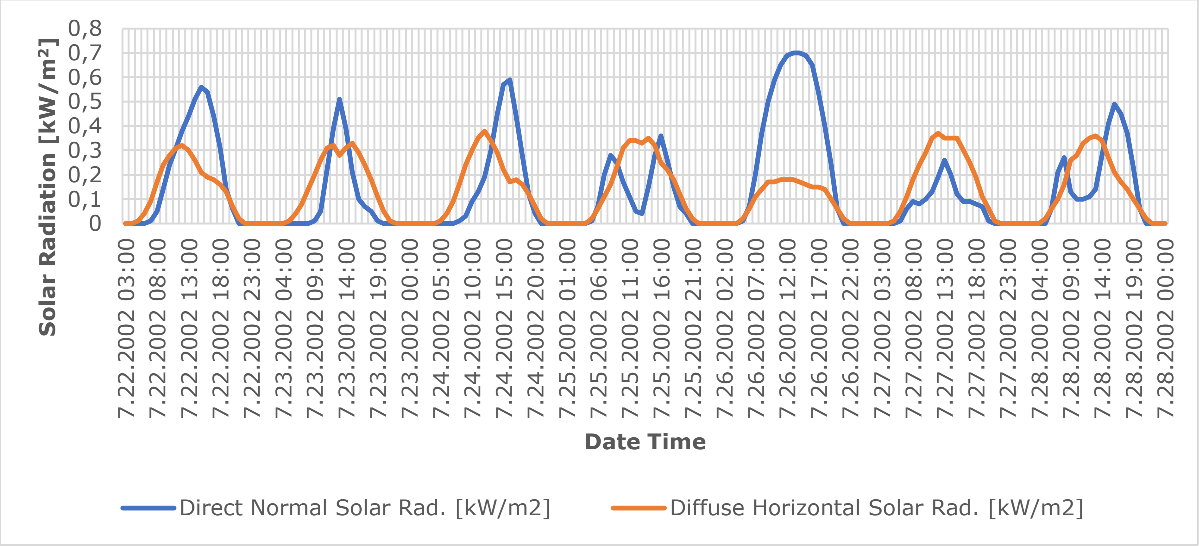


Figure 23: Solar radiation

Figure 24 shows the solar azimuth and altitude. The solar altitude peaks at 13:00 every day at about 50°. Sunrise is at approximately 04:00 while sunset is at approximately 22:00.

The solar azimuth follows the convention of North=0°. The Sun is in the East at 90° solar azimuth at 08:00 in the morning. At 13:00 it is in the South and arrives at the West at 18:00. Sunset at 22:00 is at a solar azimuth of ca. 320°.

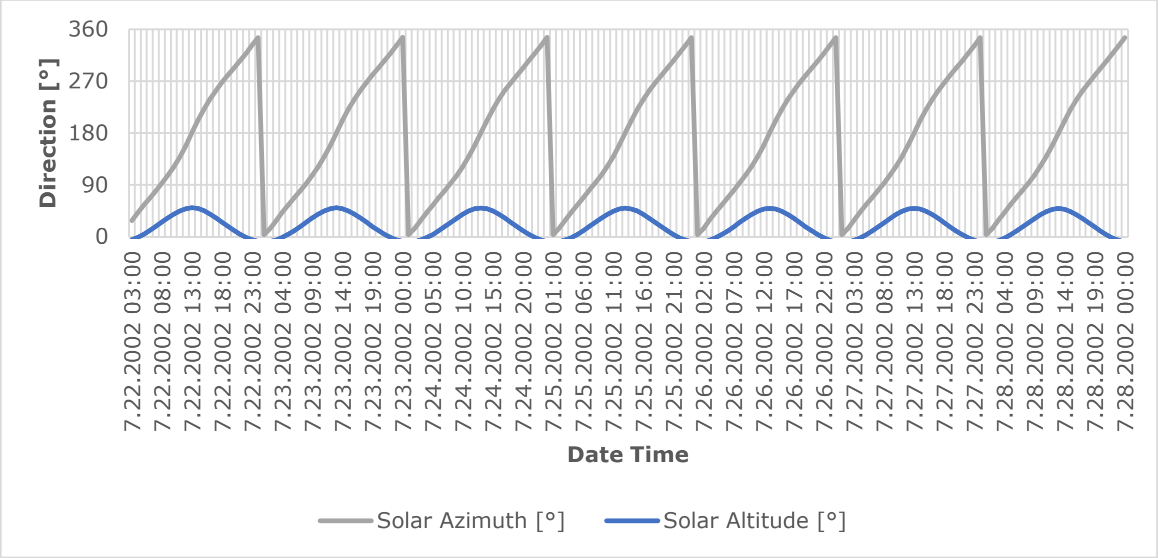


Figure 24: Solar azimuth and altitude

Wind Data Figure 25 shows wind data comprising of wind speed and wind direction for the chosen simulation week. The general trend is decreasing wind speeds during nighttime, and higher wind speeds around 15:00. Wind direction varies throughout the day.

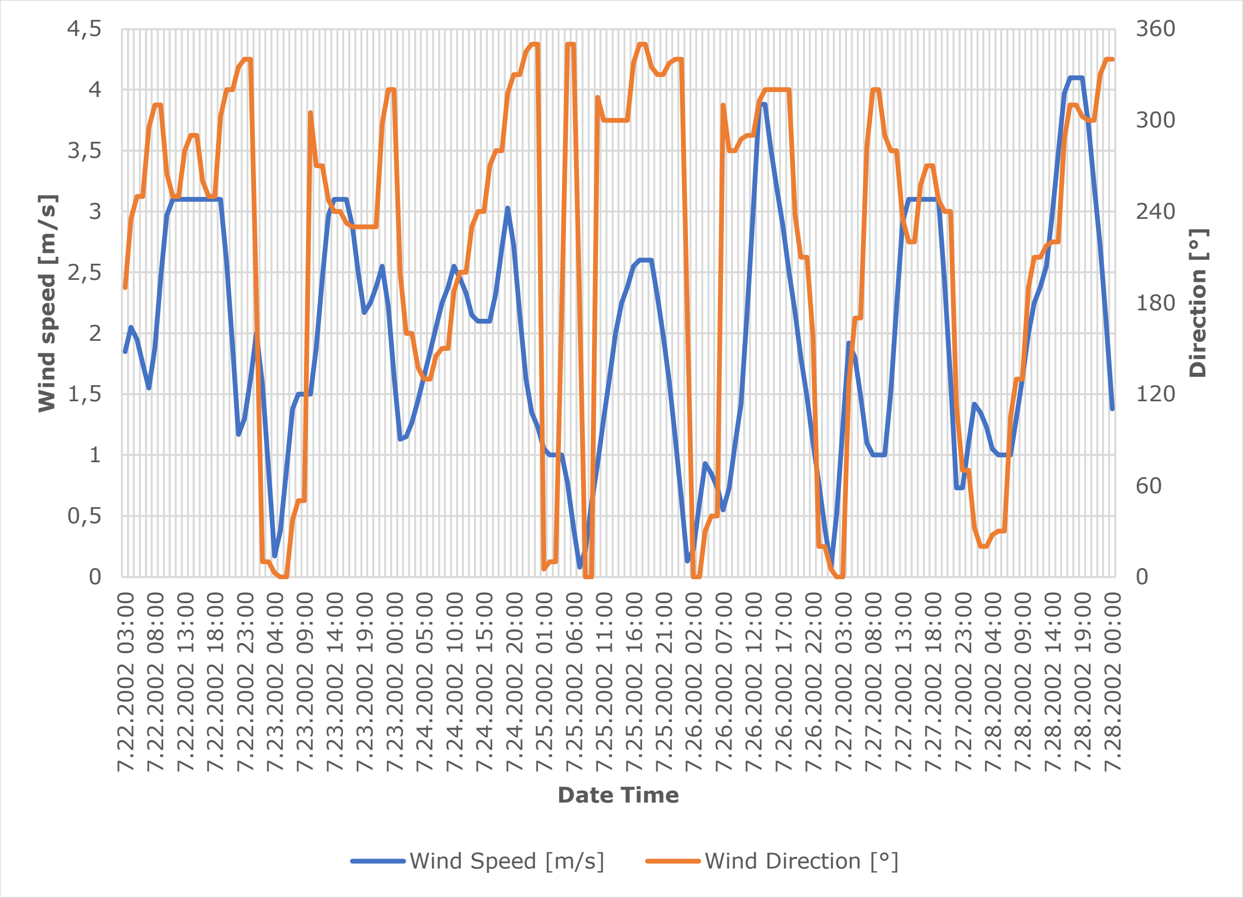


Figure 25: Wind data

6.2 Zone Results

This section presents results per zone. A few chosen zones from each floor are presented.

On the first floor, the Canteen and Windbreaker 1 were chosen. The canteen was chosen since it is an integral part of the first floor with a very specific, concentrated occupancy schedule. The windbreaker was chosen due to its exposure being the main entrance and the point of a large pressure difference.

On the second floor, Twin cell 1 and Meeting room 2.1 were chosen to analyze. Meeting room 2.1 was noteworthy as it has no exterior contact. Twin cell 1 is one of the main work and research spaces on the second floor, and therefore interesting to analyze.

On the third floor, two open workspaces were chosen, Open WS 3.2 and 3.3 because of their orientation. 3.2 has south-facing windows, while 3.3 has north facing windows. Meeting room 3.1 was chosen in addition, as it is a corner space, making it a high-risk zone.

On the fourth floor the knowledge center was chosen. This is a large zone, which is especially interesting due to its many north facing windows and its opening to the stairwell.

6.2.1 General Observations

The first five days depicted in the results graphs are workdays, and the last two comprise the weekend, as can be seen by the Occupancy plot on the heat balance graphs.

External air heat balance coincides with fresh air, in that fresh air entry into a zone coincides with a negative contribution to the heat balance in the room.

PMV naturally closely follows operative temperature in all zones.

6.2.2 Canteen

Occupancy schedule: Canteen	Maximum ventilation air requirements according to TEK17, assuming 30 occupants: 1150m^3/h

Figure 26 shows the heat balance and ventilation for the canteen.

Occupancy heat flows show that the canteen is occupied during lunch hours from 11:00-13:00 and a couple of hours before and after. This is correct according to the implemented occupancy schedule for the zone. Occupants lead to internal gains of approximately 2.5 kW at maximum occupancy.

The internal air graph shows that although the general trend is that internal air flow entering the canteen is cold (negative heat balance), during occupancy, internal air flow provides a warm heat flow. Occupancy and warm internal air flow coincide.

Solar gains on exterior windows have two peaks, one in the morning one in the evening, and follow the same daily trend.

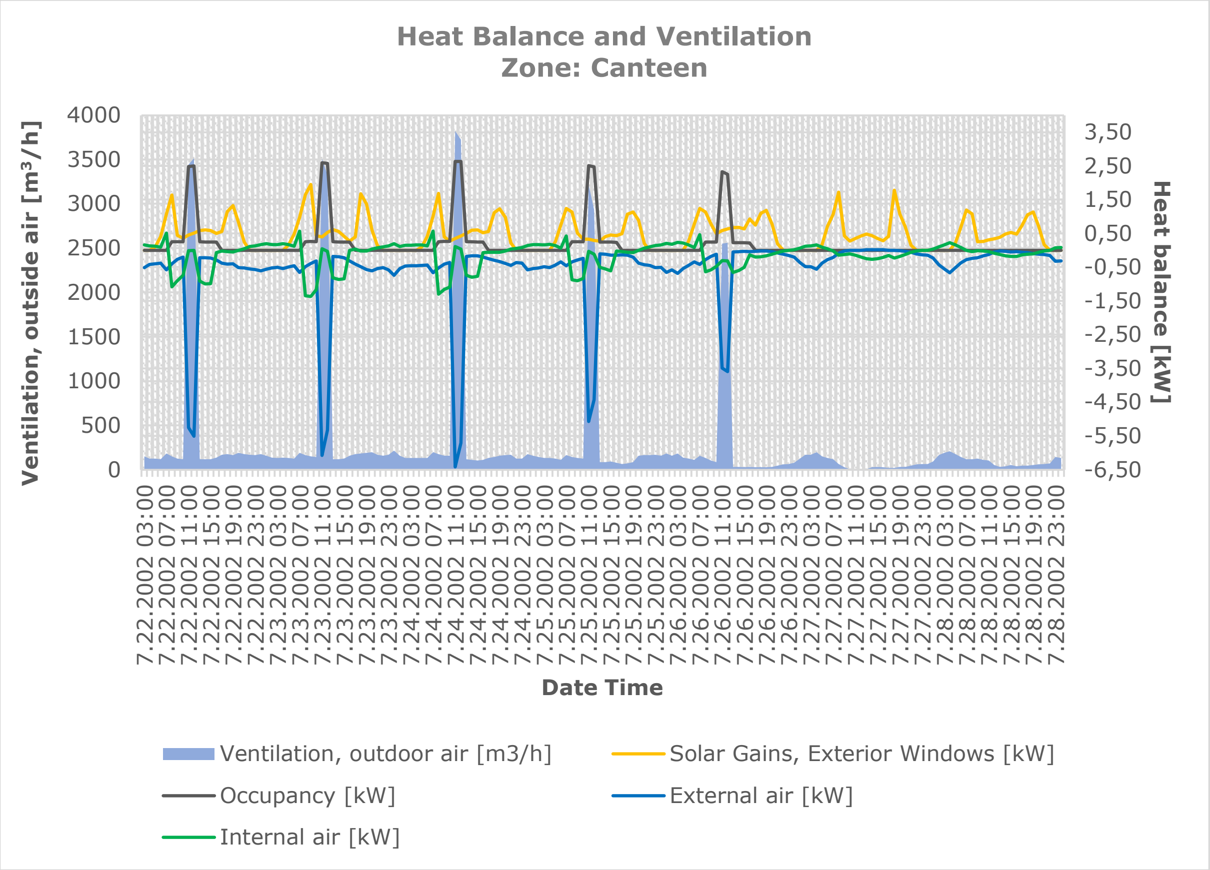


Figure 26: Heat balance and ventilation graph for the Canteen

Outdoor air flows into the canteen during lunch, when the southern canteen door is set to open. The amount of air is more than sufficient, over doubling the requirements on Monday to Thursday. The high air amount raises the risk of draught but can be combatted by lowering the opening percentage of the door area (currently set to 10%).

Friday shows a decrease of almost 1000 m^3/h in ventilation. This can be attributed to the smaller difference in outdoor and indoor temperature difference, as illustrated in Figure 27.

The external air heat balance shows a logical development, coinciding with fresh air entering the zone.

Figure 27 presents the comfort conditions in the canteen. Operative temperatures are around 21°C during occupied hours and the temperature reaches a peak on Friday at almost 23°C at 13:00. The peak is presumably caused due to the high outdoor temperature. PMV is close to -1.5 during occupied hours, this means that lunch eaters will feel cold. Shading can be reduced to increase internal temperatures, and the door can be further closed to avoid entry of cold air.

It can be observed that the operative temperature has a "delay" after occupancy, probably due to the great influx of cold air during lunch. Operative temperature naturally follows outdoor temperature too, and both temperatures are higher from Friday to Sunday as compared to Monday to Thursday.

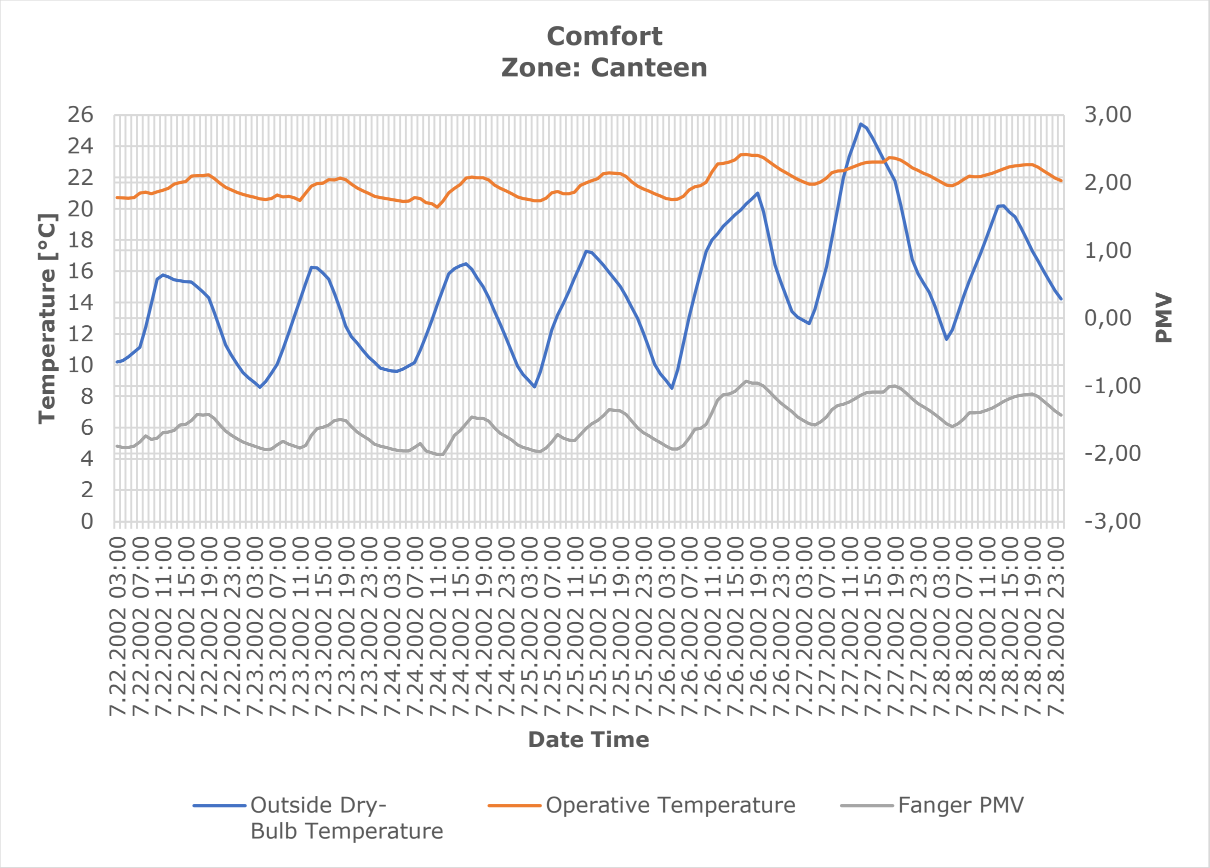


Figure 27: Comfort graph for the Canteen

6.2.3 Windbreaker 1

Occupancy schedule: Start_end	Maximum ventilation air requirements according to TEK17, assuming 2 occupants: 102m^3/h

Figure 28 shows the heat balance and ventilation results for this zone.

Windbreaker 1 is the zone housing the main entrance to the ZEB Lab on the northeast façade. The occupancy heat gains show that this is a room for transient traffic. The door opening is set to 50% of the geometric area, and the door is set to open for 1.2 hours on an average between 08:00-16:00.

Ventilation coincides with door opening, which happens between 8:00-16:00. There is one motorized window in this zone, but it is doubtful whether it has any effect on fresh air inflow, since temperatures are rarely over 22°C (the minimum temperature for natural ventilation control) as can be seen in Figure 29.

Ventilation air flows in this zone are extremely high compared to requirements, almost 14 times on Tuesday for example. The is logical as this zone is exposed to a large pressure driving force, being at the bottom of the building. Again, this can be combatted by lesser door opening time and opening area percentage.

The plot for internal air regarding heat balance shows that there is no internal air flowing into the zone. This is logical considering the position of the windbreaker.

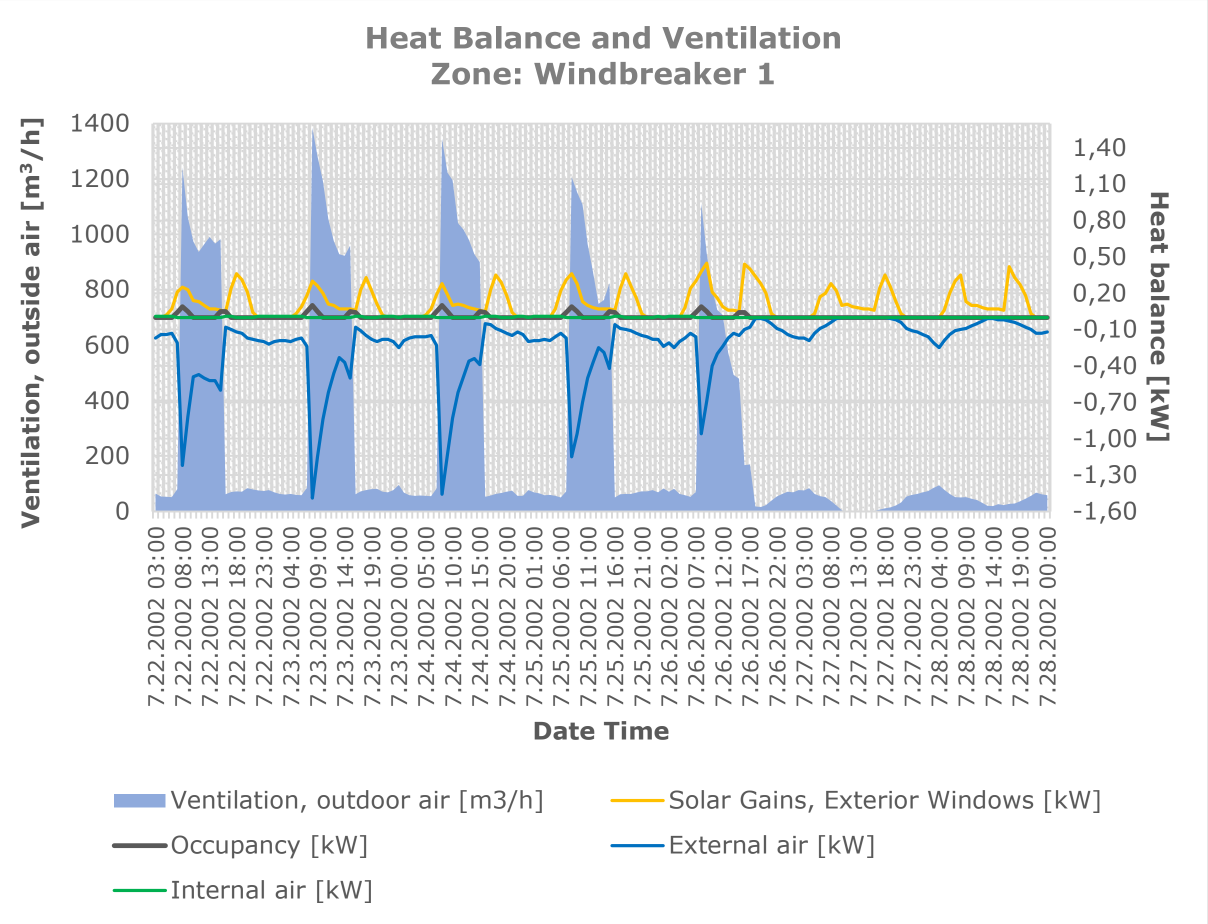


Figure 28: Heat balance and ventilation graph for Windbreaker 1

Figure 29 presents comfort conditions in Windbreaker 1. The operative temperature graph shows a dip every morning at 08:00 when the door operation begins. Temperature rises gradually inside during the workday and rises further after 16:00 once the door operation has ended.

PMV during occupied hours is very low, never rising above ca. -2,5. This means that the first entry into the building will be experienced as very cold on first entry. However, since this is just a zone for thoroughfare this should not be a serious problem. Anyhow, the amount of air can be reduced by closing the door more often.

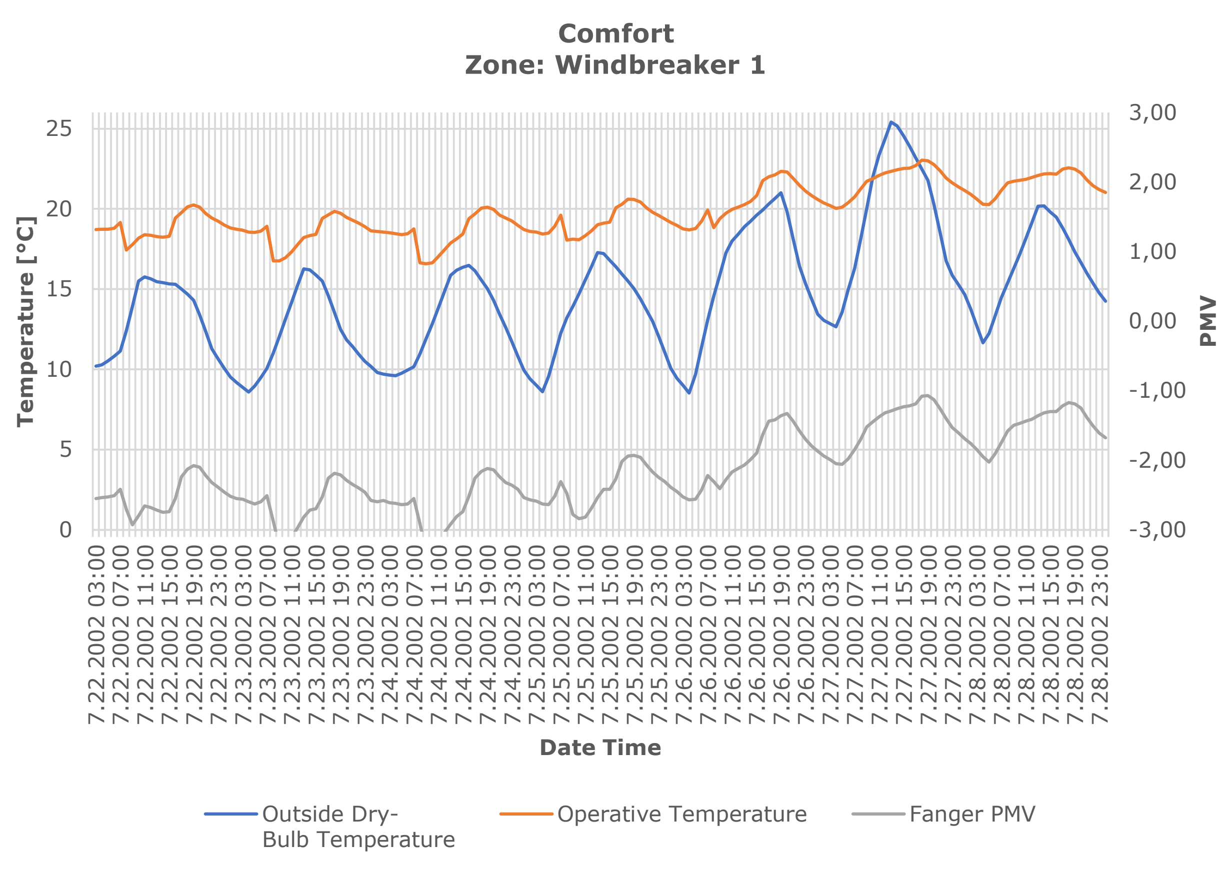


Figure 29: Comfort graph for Windbreaker 1

6.2.4 Meeting room 2.1

Occupancy schedule: Meeting_room	Maximum ventilation air requirements according to TEK17, assuming 5 occupants: 190 m³/h

Figure 30 shows the heat balance and ventilation results for this zone.

We can see that because this room has no connection to the exterior through windows, there is no ventilation from outdoor air or solar gains through exterior windows. Heat balance for external air is also moot. Occupancy can be observed according to the implemented schedule. Cold air inflow to the zone can be observed during the workday, inversely coinciding with occupancy.

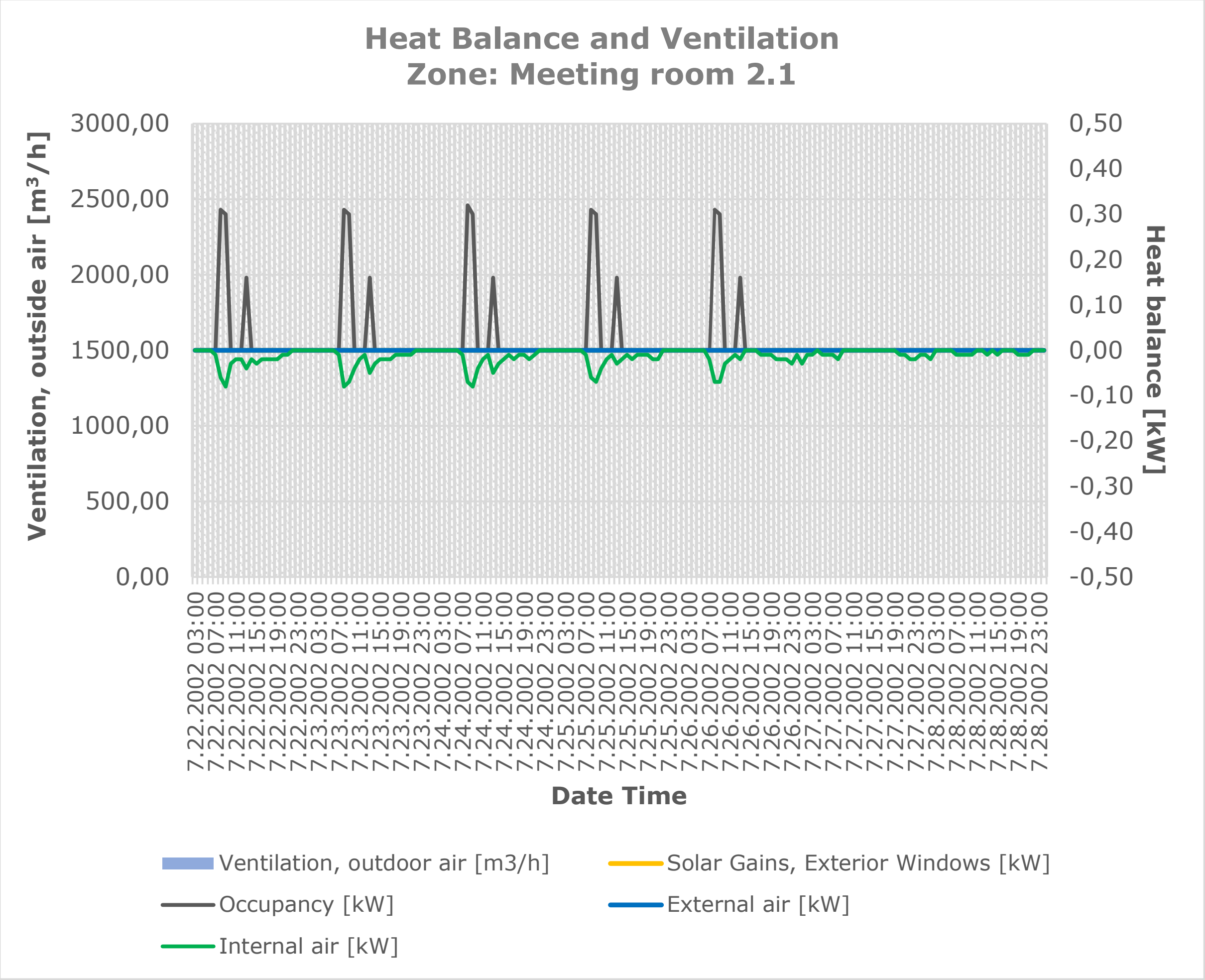


Figure 30: Heat balance and ventilation graph for Meeting room 2.1

Figure 31 presents comfort conditions in this zone.

Relative to other zones, occupancy has a very visible effect on operative temperature. Internal gains due to occupancy can clearly be seen raising the temperature in the zone. Operative temperature is stable over 22°C all week.

PMV is close to -1.25 during occupied hours, which is slightly cold but temperature comfort requirements are fulfilled.

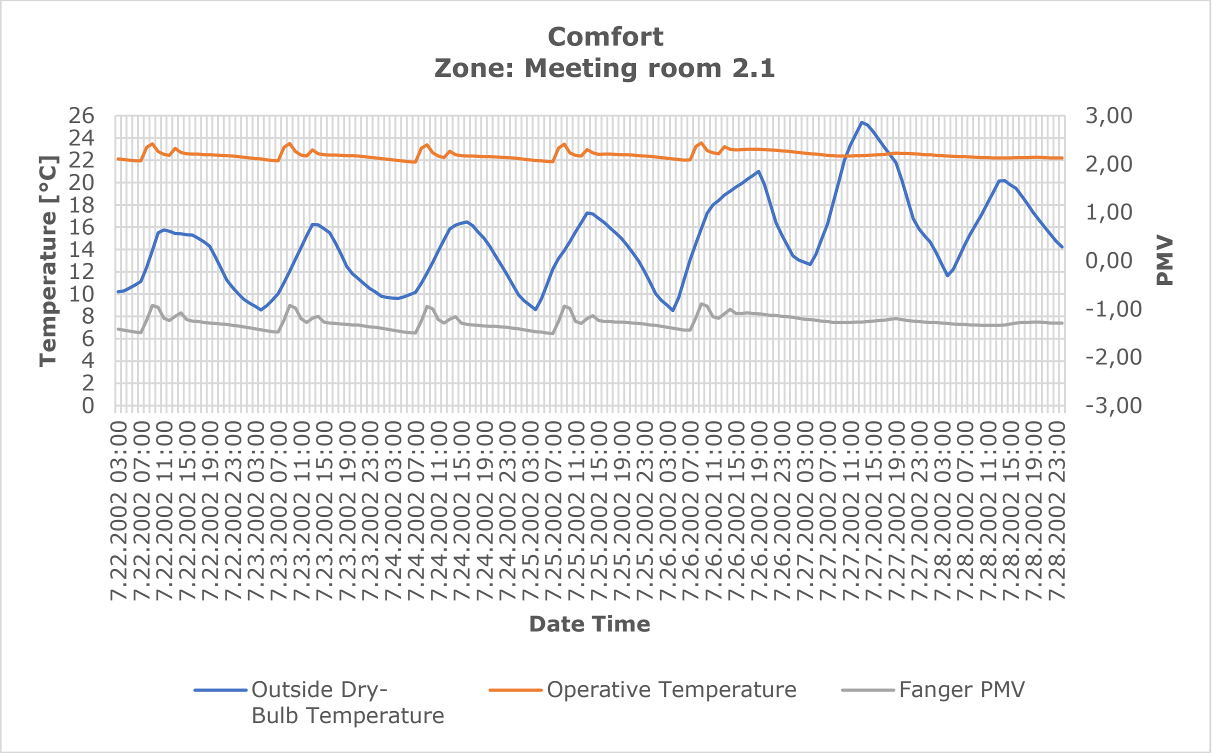


Figure 31: Comfort graph for Meeting room 2.1

Further analysis on air flow

The inflow of internal air is approximated using Eq. 23

$$P_{air} = \frac{1}{3600}\dot{V}\rho C_p \Delta T\ [kW] \tag{23}$$

where

P_{air} is the heat balance due to air inflow

$\dot{V}$ is volume flow in m^3/h

ρ is ambient air density

C_p is the specific heat capacity of air in $kJ/kg \cdot K$

T is the temperature difference between the two zones.

Naturally, it is assumed that the internal air flow stems from the hallway, since this is the zone the meeting room door is connected to. Air temperature is found from the simulations results.

Heat balance due to internal air at 9:00 on Monday is -0.08 kW as seen in Figure 30. The hallway air temperature at the same time is 21.8°C. The air temperature in the meeting room is 24.4°C. C_p and ρ are assumed to be constants at 1.0 kJ/kg·K and 1.2 kg/m^{3,} respectively.

The volume flow is then found to be 92 m^3/h using Equation 23. This is an insufficient amount of air compared to TEK requirements. Airflow can be increased by opening the door over a longer period, as it is currently set to 5% of the time between 08:00-16:00, i.e. 24 minutes. It is also probable that, in reality, the meeting room door will be open all the time *except* for during occupancy, causing more air inflow.

6.2.5 Twin cell 1

Occupancy schedule: Workspace	Maximum ventilation air requirements according to TEK17, assuming 10 occupants: 435 m^3/h

Figure 32 shows the heat balance and ventilation results for this zone. The space is well ventilated and fulfills requirements during occupied hours. Occupancy can be observed throughout the day, with a break for lunch.

On Friday there is a peak in ventilation from 13:00-15:00. This can be explained by the fact that the operative temperature is stable above 22°C for a longer period than usual. This means that the windows will be open for a longer period, hence allowing more ventilation. This argument is supported by the fact that even though there is a peak in ventilation, there is no effect on the heat balance due to external air; meaning that the air coming in from outside is probably warmer. Eq. 23 shows that when the power is the same, air flow and temperature difference are inversely proportional. Another example of the same phenomenon can be seen on Saturday, where there is a peak in ventilation air at ca. 19:00. However, this is not expressed by external air heat balance, presumably since outdoor temperature is at an all-week high on Saturday.

Internal air heat balance is stable at zero, indicating that there is no heat flow from other zones into Twin cell 1.

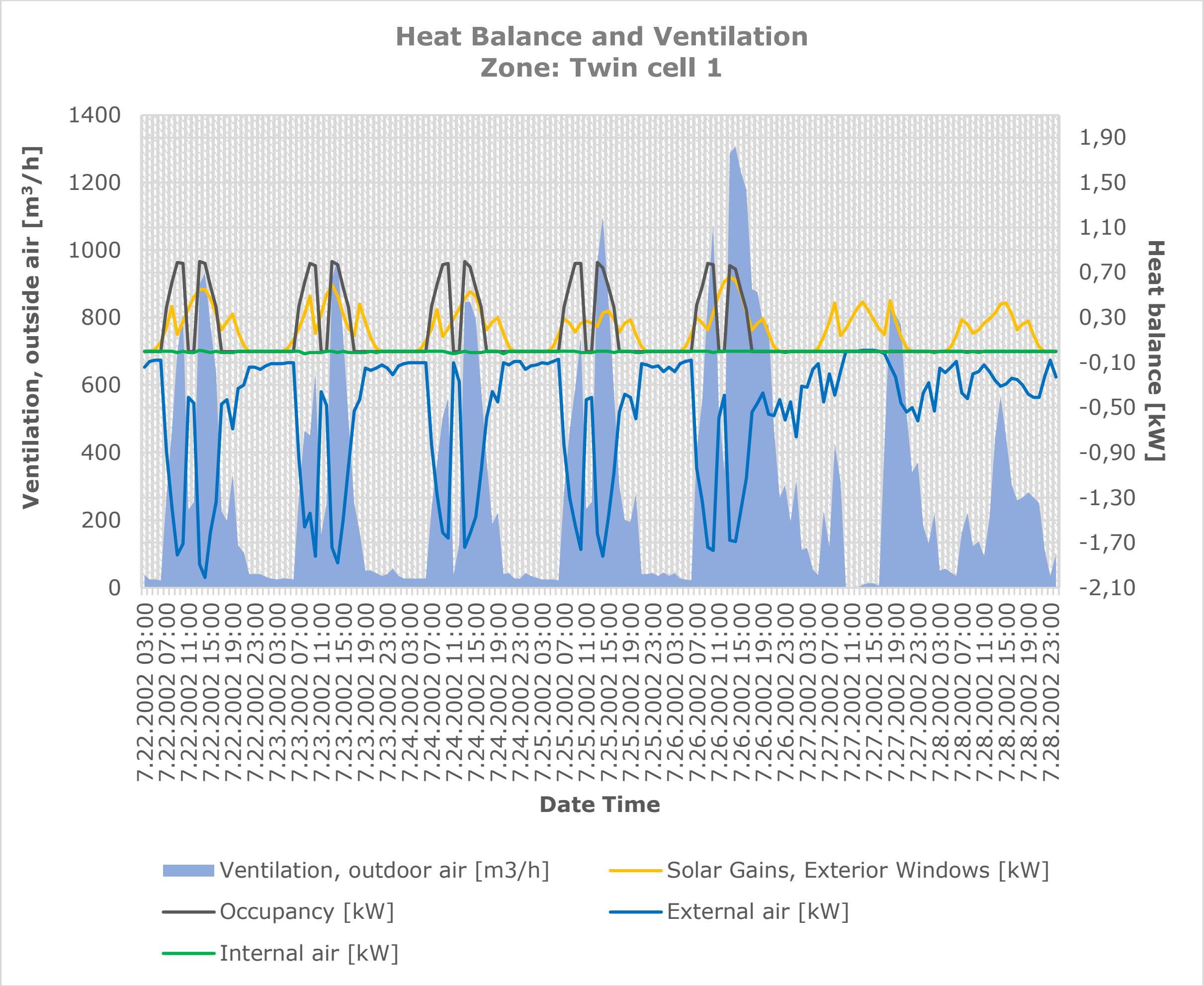


Figure 32: Heat balance and ventilation graph for Twin cell 1

Figure 33 presents comfort conditions in this zone. The operative temperature hovers around the minimum natural ventilations temperature setpoint, 22°C, the whole week. PMV has its highest value during occupied hours at -1 on Friday at 15:00, which is also the time that has the highest operative temperature during the work week.

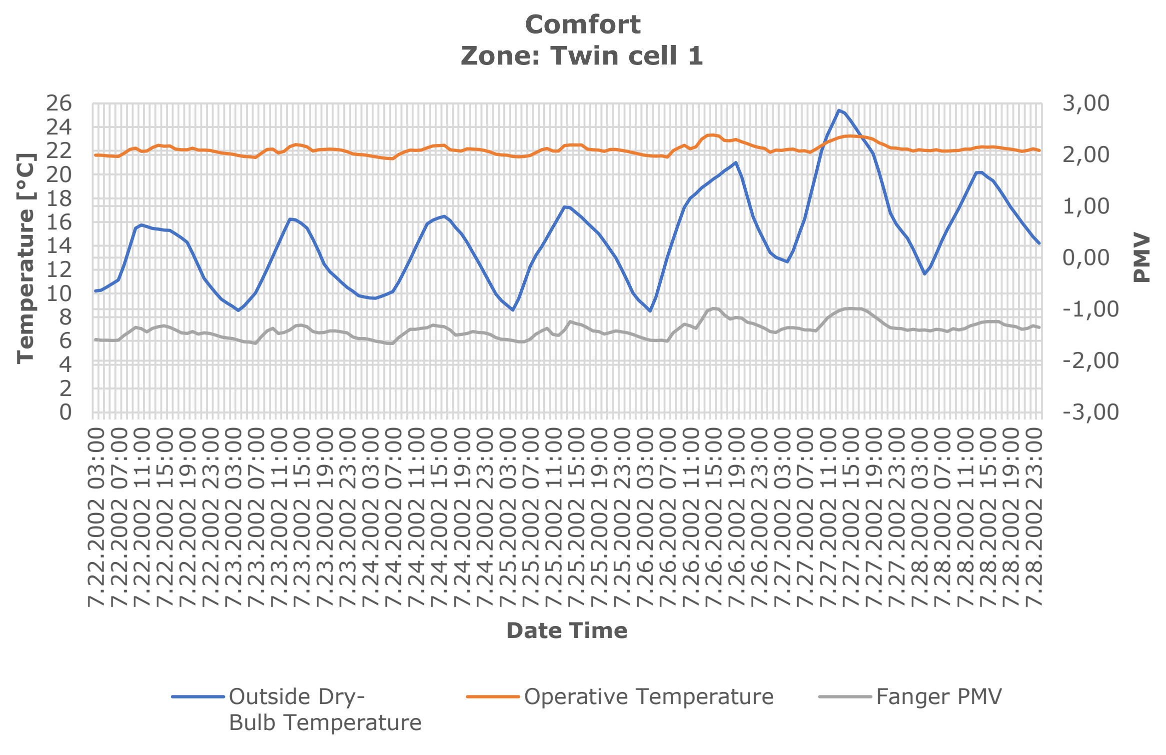


Figure 33: Comfort graph for Twin cell 1

6.2.6 Meeting room 3.1

Occupancy schedule: Meeting room	Maximum ventilation air requirements according to TEK17, assuming 5 occupants: 203 m^3/h

Meeting room 3.1 is situated in the southeast corner of the third floor. Figure 34 shows the heat balance and ventilation results for this zone.

Results from this zone are quite similar to those from Twin cell 1. Temperatures hover at 22°C almost all week. Friday shows a peak in ventilation, as operative temperature in the zone is over 22°C for a relatively long time. An additional likeness is the absence of internal air inflow.

Ventilation is sufficient most days during occupied hours in the first half of the day. Occupancy from 13:00 to 14:00 rarely fulfills ventilation air requirements for 5 people, reaching only about 150 m^3/h. A possible explanation can be wind effects.

On Wednesday at 08:00, wind speed is 2.25 m/s, coming from the southeast direction (150°). At 13;00, however, wind is coming from the southwest direction (230°) at a speed of 2.15 m/s. This information can be found in Figure 25. Southeast wind at a higher speed is naturally cause for higher ventilation in a zone oriented in the same direction.

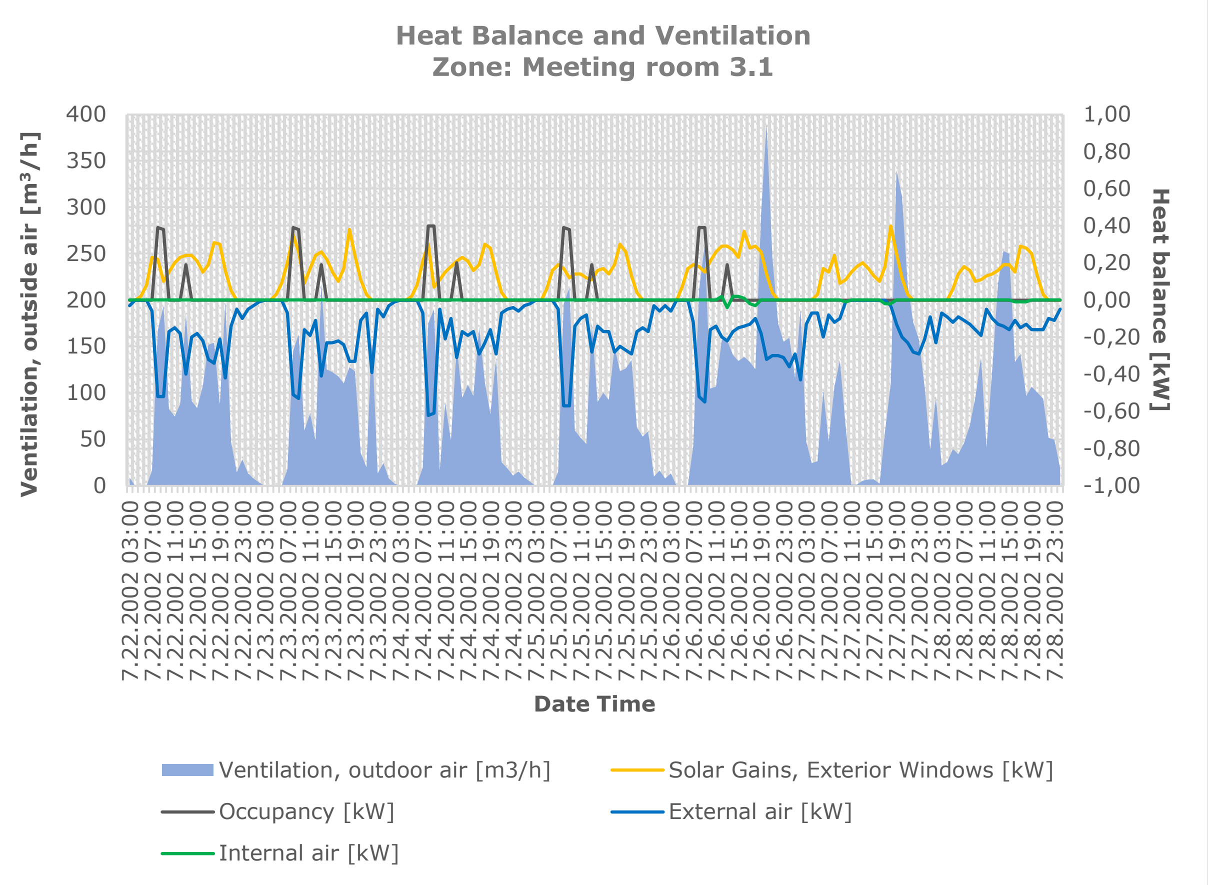


Figure 34: Heat balance and ventilation graph for Meeting room 3.1

Figure 35 presents comfort conditions in this zone.

PMV during occupied hours is approximately -1,5; this is quite cold. Removing shading could be explored to increase solar gains to the room. A higher minimum temperature for natural ventilation could be considered, however this would negatively affect the amount of fresh air coming into the zone.

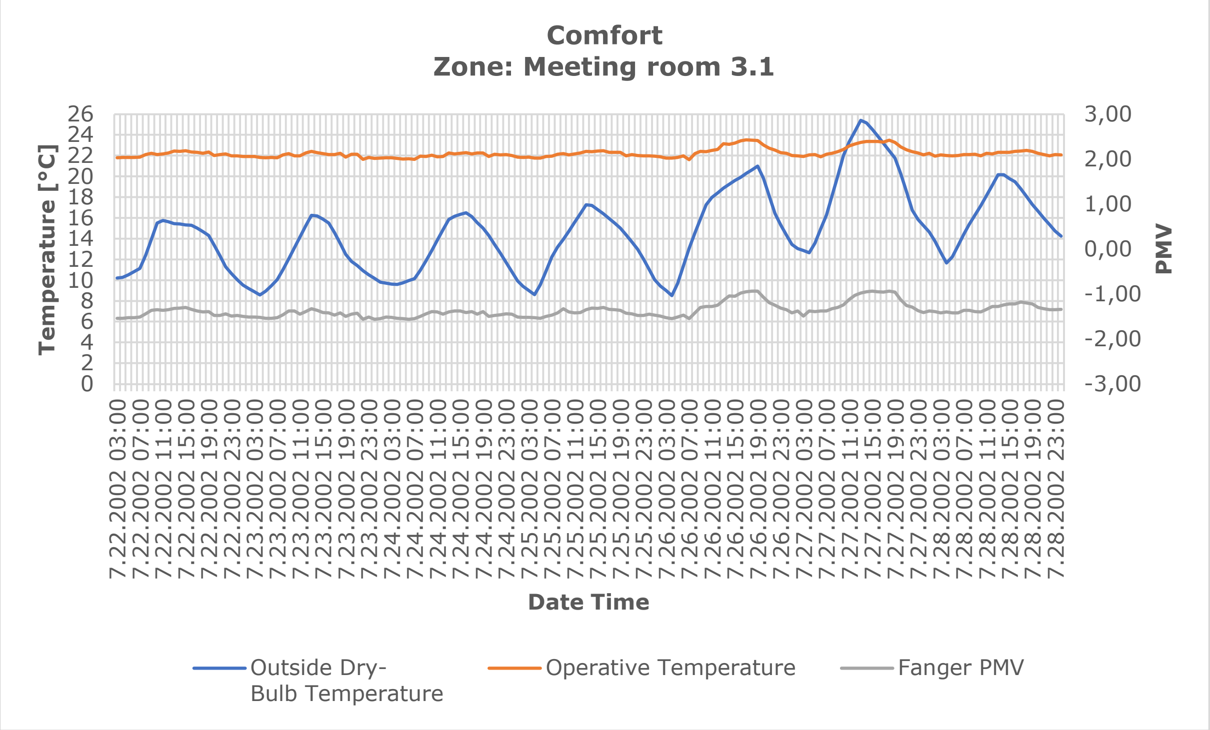


Figure 35: Comfort graph for Meeting room 3.1

6.2.7 Knowledge center

Occupancy schedule: 12-14.	Maximum ventilation air requirements according to TEK17, assuming 30 occupants: 1033 m^3/h

Figure 36 shows the heat balance and ventilation results for this zone. It can be observed that the amount of ventilation air is not sufficient during occupied hours. It is noteworthy that at other times during the day, it is not problematic to fulfill ventilation air requirements.

Ventilation excluding the effects of wind is also plotted in Figure 36. On Friday at 13:00 there is a large difference between ventilation based on whether wind effects are included and not. This is supported by the wind data in Figure 25 which shows that wind speed is high (3,88m/s) and is coming from the northwest (312°) on Friday at 13:00. This probably causes the spike in wind-driven ventilation. It is also interesting to note that during the rest of the week, wind-induced ventilation is quite low, i.e. ventilation in this zone is mainly driven by temperature differences.

The general trend in this zone is that internal air has a positive direction on heat balance i.e. that incoming air is warm. However, during occupied hours this shifts, and internal air is cold relative to the room. A concrete reason for this has not been found. The Knowledge center has a complex floor plan, with several doors in addition to an opening to the stairwell, which makes it difficult to pinpoint a reason for this development.

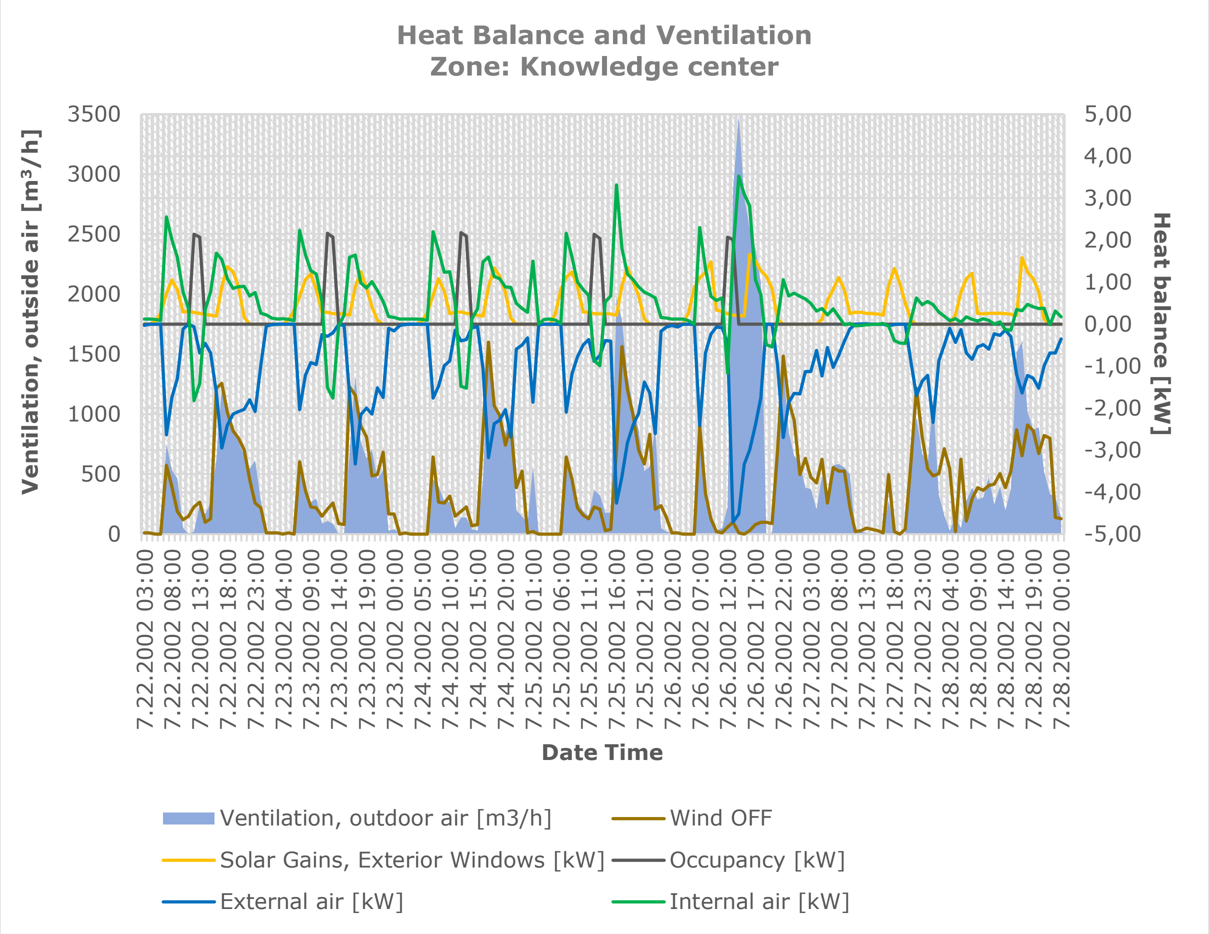


Figure 36: Heat balance and ventilation graph for the Knowledge center

Figure 37 presents comfort conditions in the knowledge center, and Figure 38 provides a zoomed version, focusing only on Monday.

Figure 38 shows that the operative temperature rises only slightly, from 23.26°C to 23.33°C between 12:00-14:00, presumably due to internal gains.

During occupied hours PMV is approximately -1, meaning occupants are likely to find the room slightly cool. Shading can be removed to increase solar gains, although this might increase risk of glare.

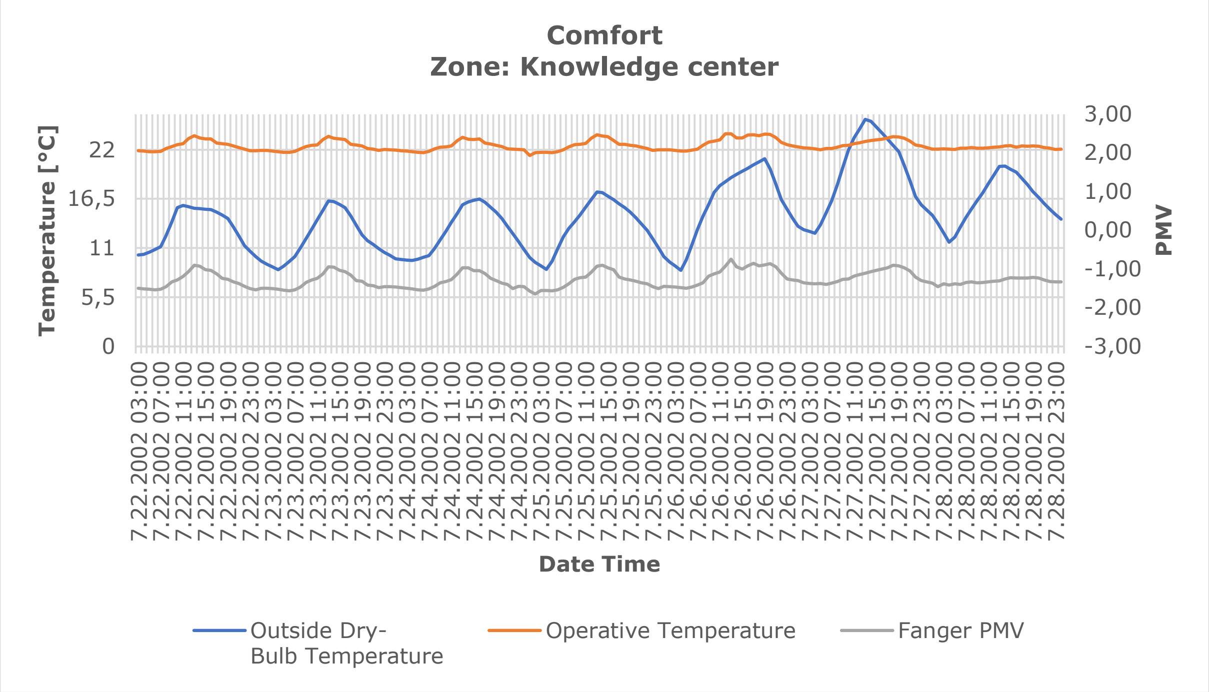


Figure 37: Comfort graph for Knowledge center

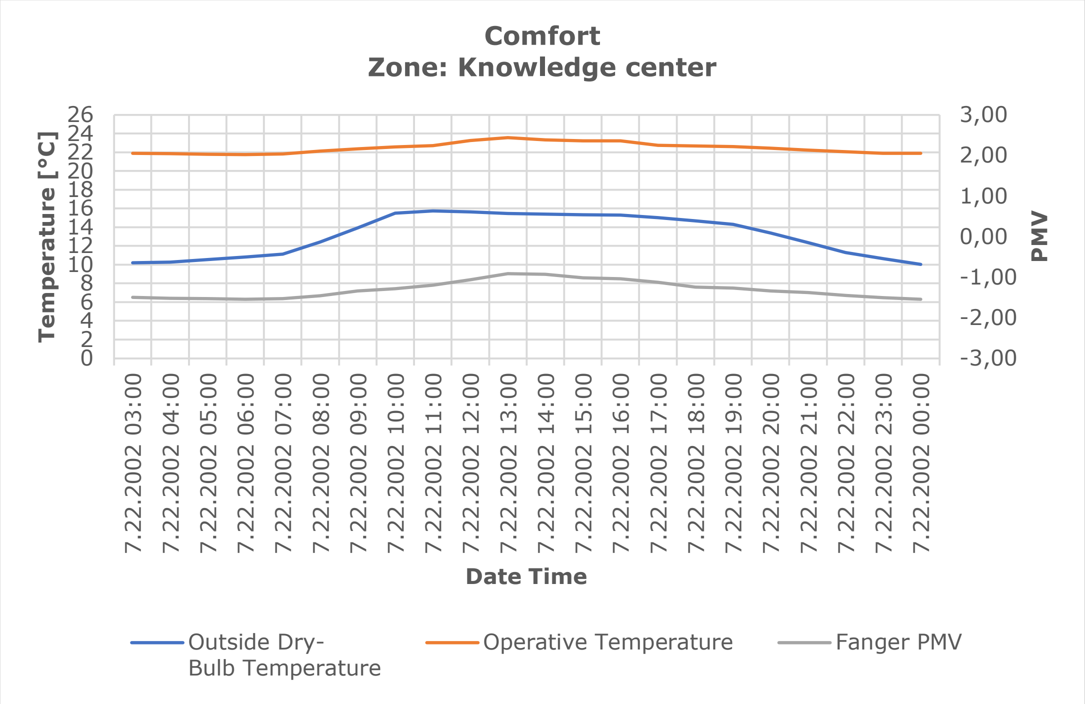


Figure 38: Comfort graph for Knowledge center on Monday 22nd July

6.3 In-depth zone results for Open WS 3.2 and 3.3

6.3.1 Open WS 3.2

Occupancy schedule: Workspace	Maximum ventilation air requirements according to TEK17, assuming 10 occupants: 390 m^3/h

Figure 39 shows the heat balance and ventilation results for this zone.

Ventilation air is sufficient during occupied hours and fulfills the TEK requirement of 390 m^3/h. One exception to this trend is on Friday after lunch. There is no fresh air entering the zone, however, there is a spike in incoming internal air. We can also see that there is mostly warm internal air coming into the zone, except for a spike in cold air after lunch on Friday. An explanation for this is not found. Logically, since the temperature is over 22°C in the zone at this time (see Figure 43), windows should be open to let in fresh air.

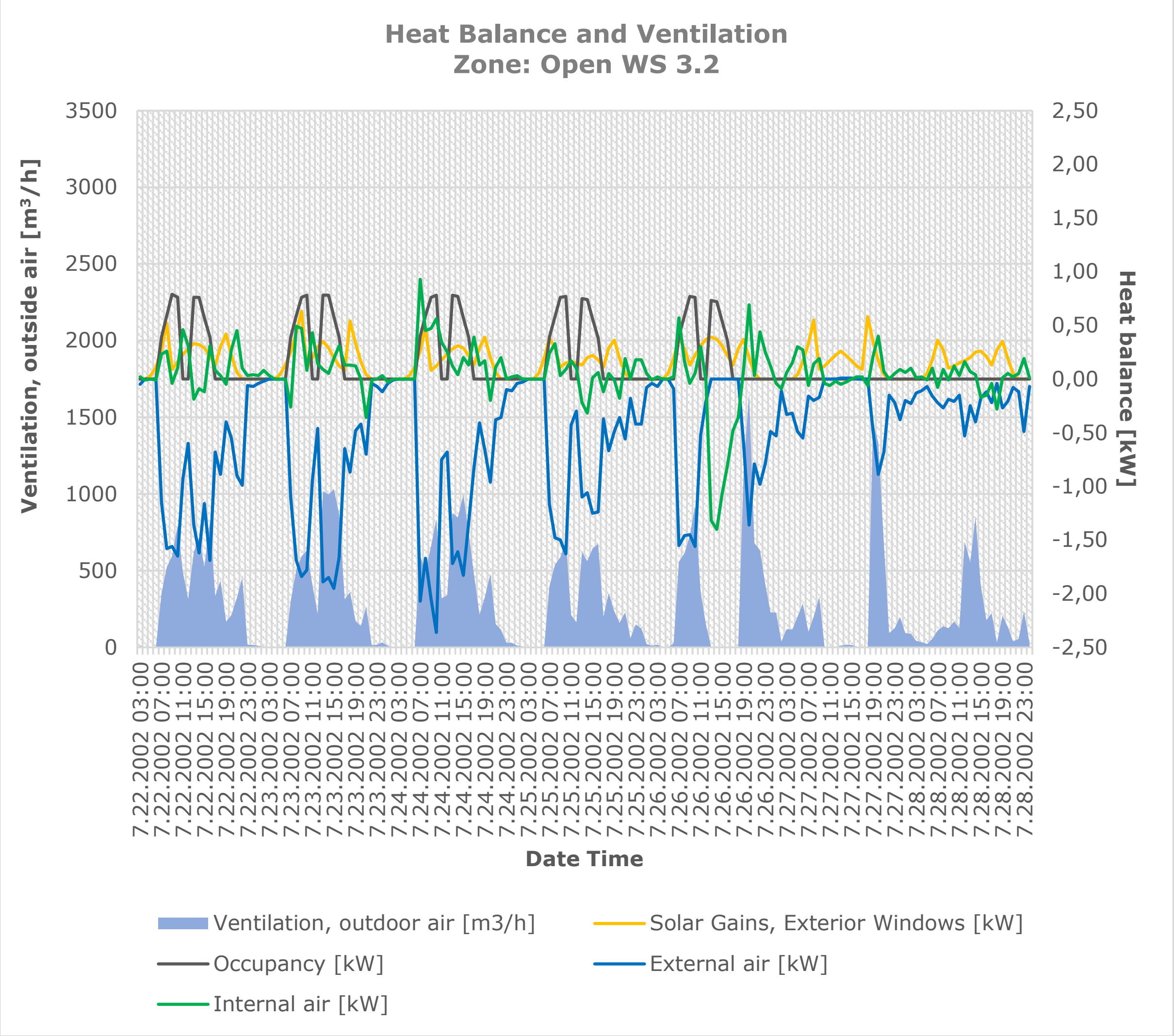


Figure 39: Heat balance and ventilation graph for Open WS 3.2

6.3.2 Open WS 3.3

Occupancy schedule: Workspace	Maximum ventilation air requirements according to TEK17, assuming 10 occupants: 390 m^3/h

Figure 40 shows the heat balance and ventilation results for this zone.

Ventilation air is sufficient during occupied hours and fulfills the TEK requirement of 390 m^3/h. Friday has a large increase in ventilation at 13:00, just as in the Knowledge center. Open WS 3.3 is oriented towards the North so this is a logical development. Internal air inflow is exclusively a positive contribution in the heat balance.

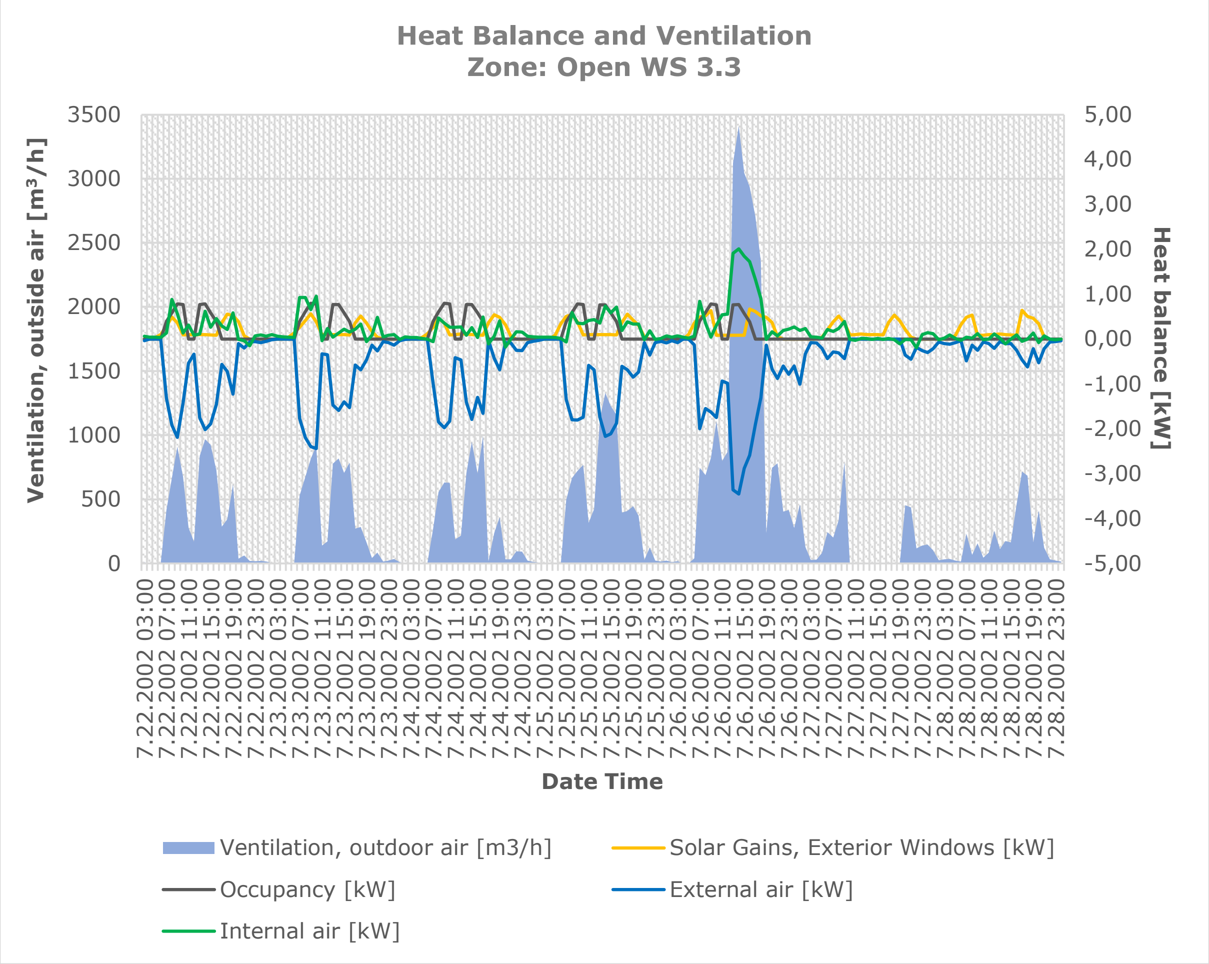


Figure 40: Heat balance and ventilation graph for Open WS 3.3

6.3.3 Comparison between Open WS 3.2 and 3.3

Different scenarios have been simulated for further analysis of Open WS 3.2 and 3.3.

The 'No wind' simulation excludes wind effects in natural ventilation. In another scenario, all shading is removed, and in the third, the opening area of motorized windows is reduced from 60% to 30%. The baseline simulation is the one used in all previous results.

Ventilation, operative temperature and PMV comparisons are shown in Figure 41-48 for the different scenarios in Open WS 3.2 and 3.3.

Window areas per square meter for the two zones are similar.

Ventilation

Figure 41 and 42 show ventilation comparison for different scenarios in Open WS 3.2 and 3.3, respectively.

Figure 41 and 42 show that on a general basis, ventilation air has the highest flow in the 'No shading' scenario. This is logical since wind effects are not excluded in addition to a higher indoor temperature (see Figures 43 and 44). This causes a larger temperature difference between indoor and outdoor temperature, leading to higher temperature difference-driven ventilation.

An anomaly can be observed in Figure 41 on 26th July at 15:00. The only scenario giving rise to ventilation is the one excluding wind effects. This is illogical as all other scenarios account for buoyancy-driven ventilation too.

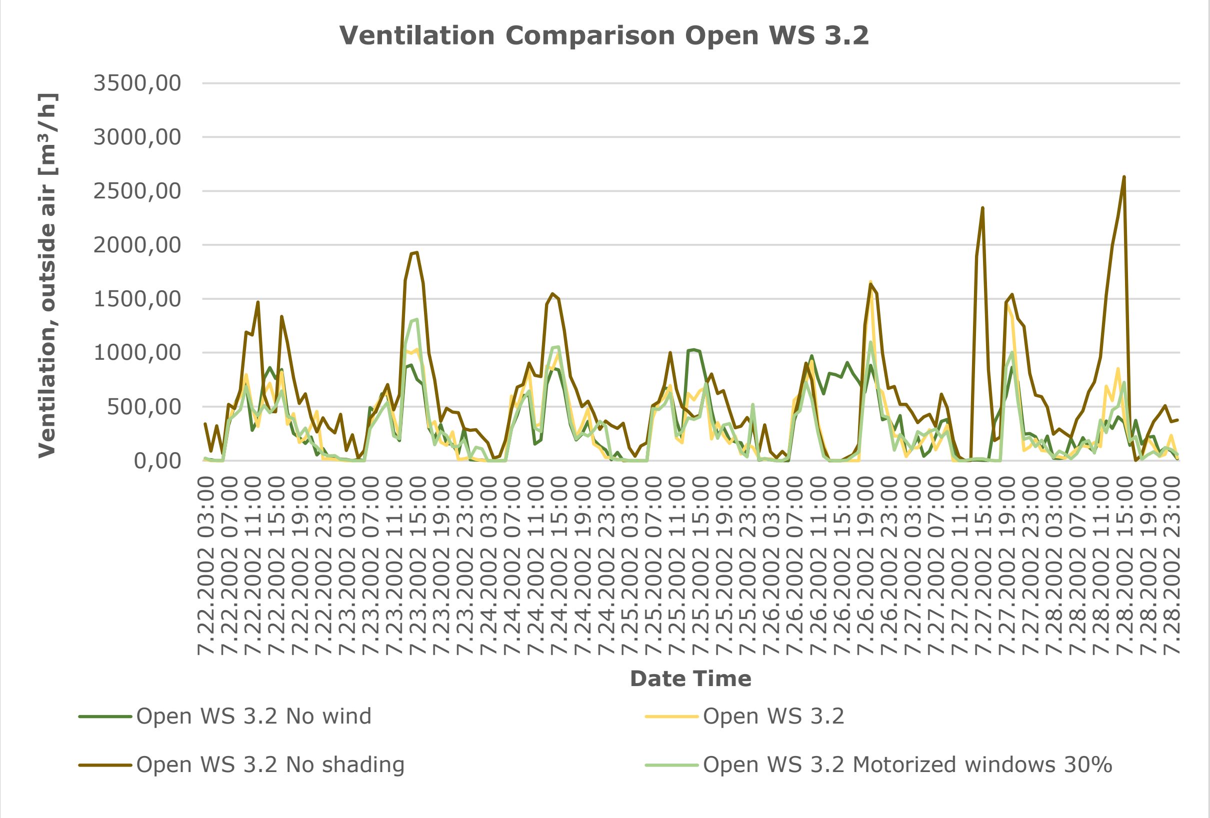


Figure 41: Ventilation comparison for different scenarios in Open WS 3.2

The effect of closing the motorized windows can be clearly seen in Figure 42 on 26th July at 15:00. It is clearly illustrated that the ventilation spike on Friday is wind induced. The baseline and 'No shading' lines peak at 3300m^3/h while closing the motorized windows creates a decrease of approximately 1000 m^3/h. The lowest ventilation rate is shown by the 'No wind' graph at 1000 m^3/h.

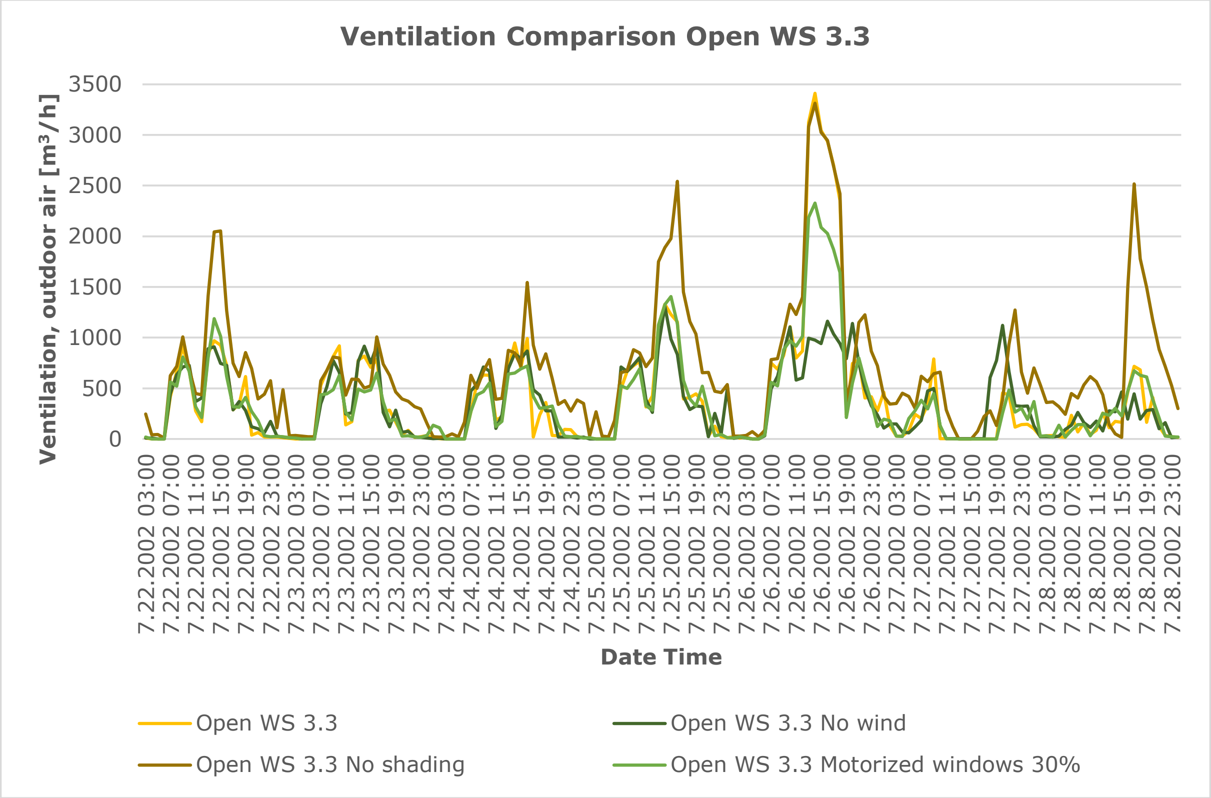


Figure 42: Ventilation comparison for different scenarios in Open WS 3.3

It can be observed that ventilation volume flows are approximately the same in both zones for the 'No wind' scenario, peaking at about 1000 m^3/h. This means that when natural ventilation is driven by temperature difference, ventilation in both zones is similar. This is logical since indoor temperatures in the two zones are quite alike. Differences are caused by other phenomena, such as wind and orientation, and solar radiation.

Operative Temperature

Figure 43 and 44 show the operative temperature for different scenarios in Open WS 3.2 and 3.3 respectively.

Both figures show that the indoor operative temperature is highest for the 'No shading' scenario. This is natural since solar gains are highest in this case. There is not much difference in operative temperature in the other three scenarios for both zones.

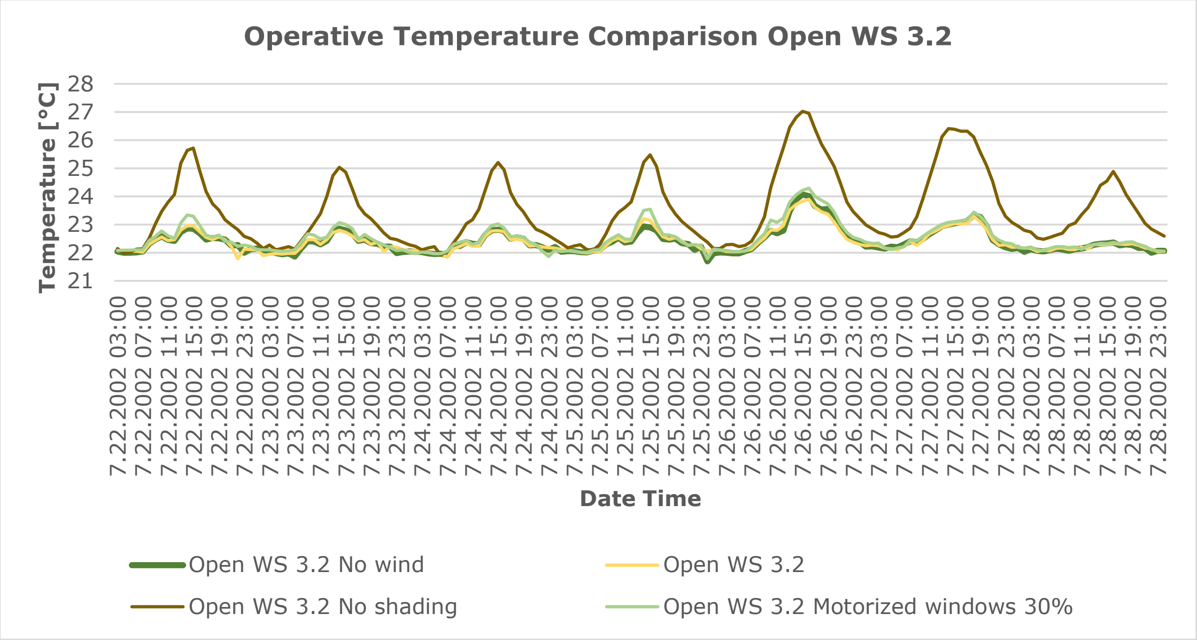


Figure 43: Operative temperature comparison for different scenarios in Open WS 3.2

It is interesting to note that the second highest peak from Monday to Thursday in Open WS 3.3 stems from motorized windows being closed to 30%. A more intuitive development would be if it were the 'No wind' scenario that had the second highest peak since wind presumably has a cooling effect.

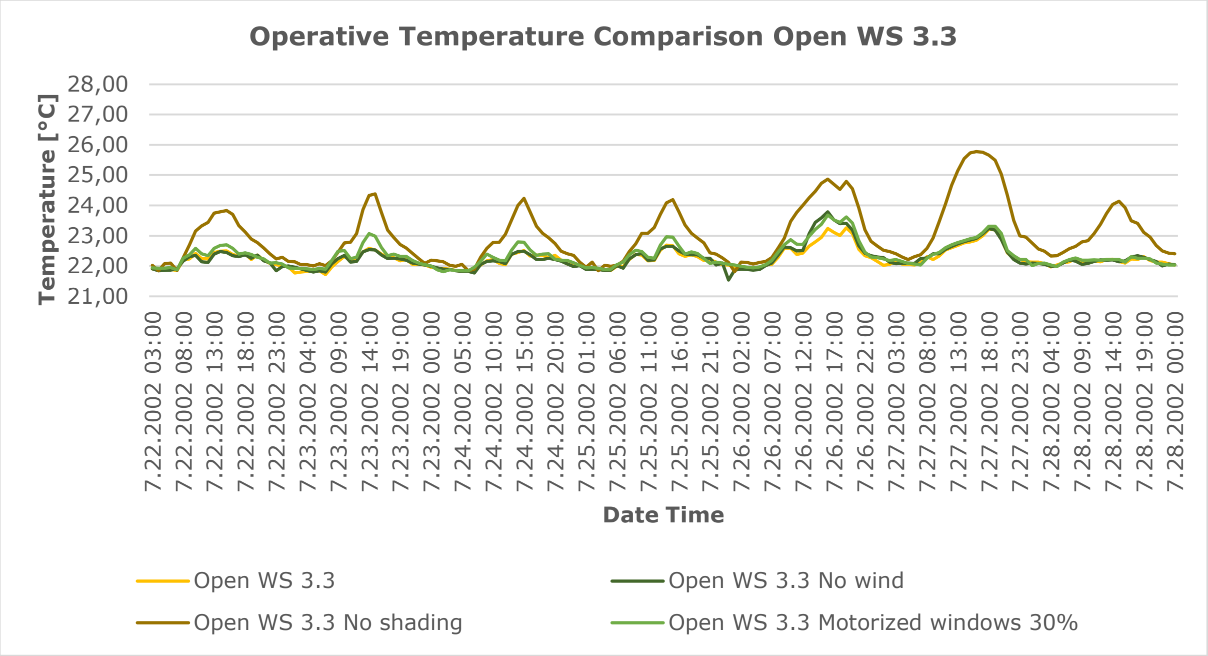


Figure 44: Operative temperature comparison for different scenarios in Open WS 3.3

It can be observed that operative temperatures in Open WS 3.2 are consistently higher than those in Open WS 3.3 by approximately a degree. This can be attributed to the fact that 3.2 is south facing while 3.3 is north facing. Solar gains for exterior windows in the baseline scenario can be seen in Figure 45.

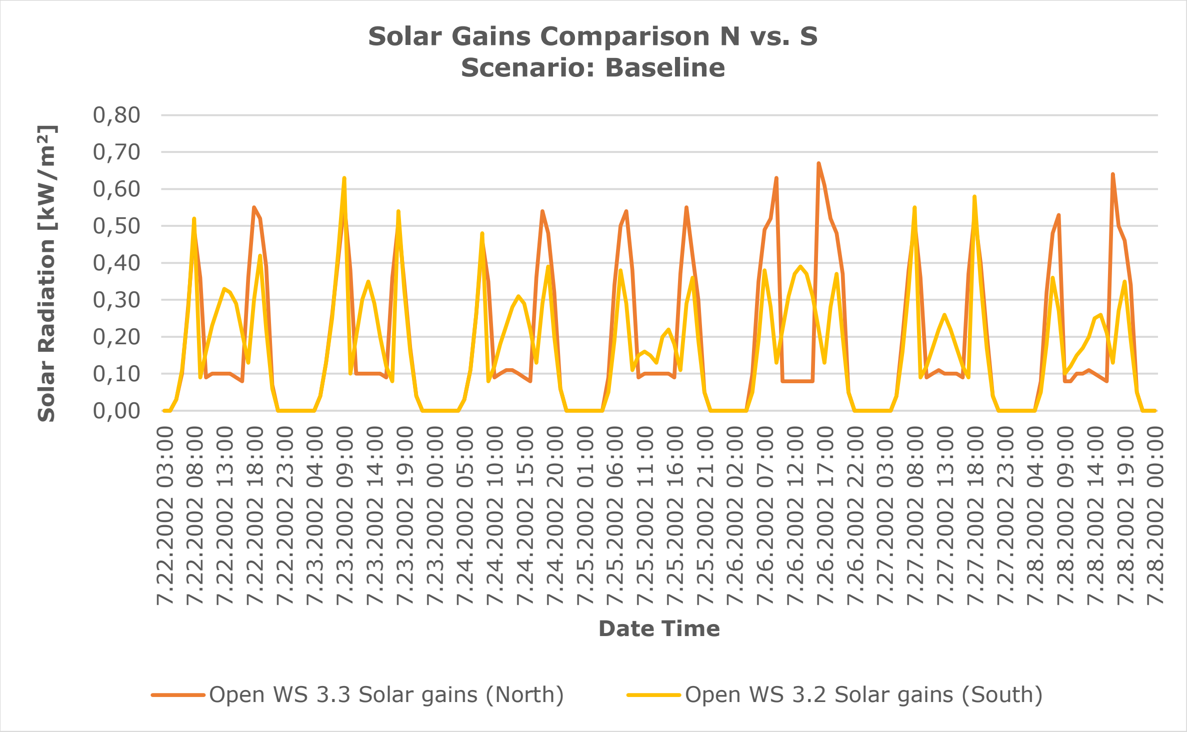


Figure 45: Solar gains through exterior windows, North and South. Baseline scenario.

It can be observed that south facing windows experience solar gains with peak values thrice a day. For north facing windows the middle peak that occurs at midday, during occupied hours, is missing. This could be the reason for the higher temperature in south-facing Open WS 3.2

The same pattern can be observed in baseline results for solar gains through exterior windows in other zones with the same orientation too.

Solar gains for exterior windows in the ‘No shading’ scenario can be seen in Figure 46. The difference in solar gains between north and south facing windows is obvious and clearly illustrated. Solar gains through southern exterior windows are between two- and four-times larger than their northern counterparts.

An explanation for the dip in solar radiation at 13:00 on 25th July can lie in Figure 23, where Direct normal solar radiation has a similar dip at the same time. This affects only the graph for the southern solar gains as the solar azimuth at this time is 179°.

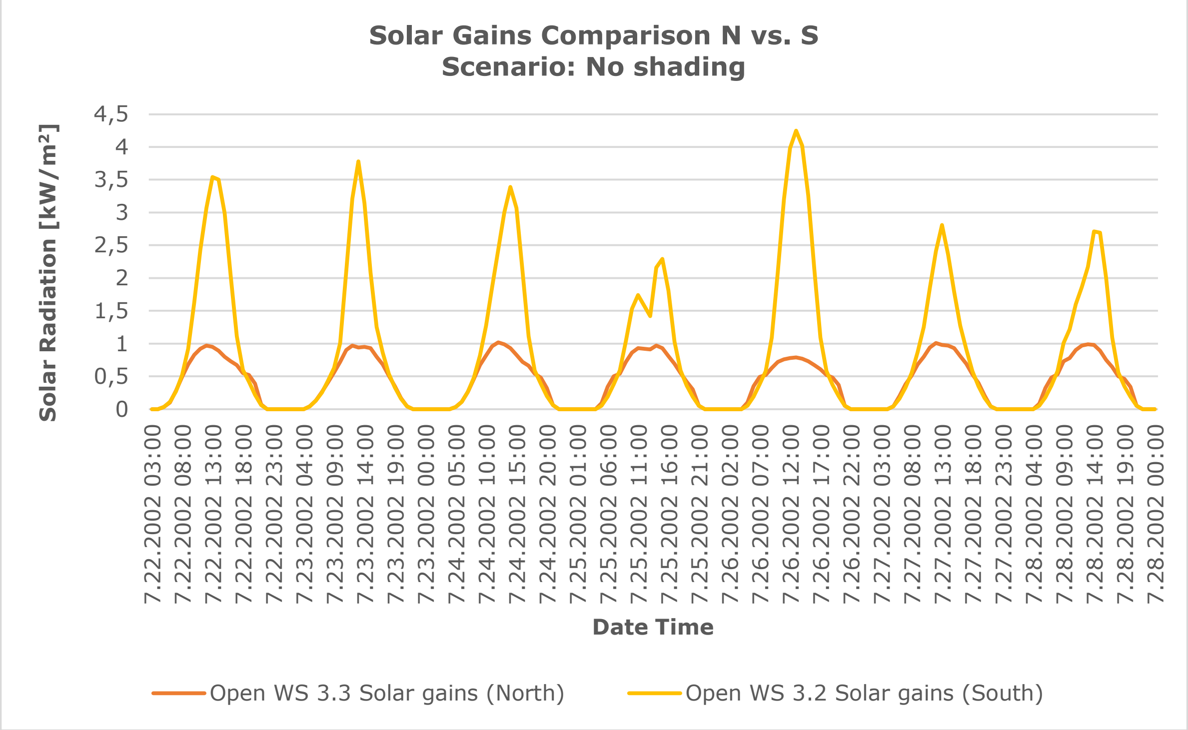


Figure 46: Solar gains through exterior windows, North and South. No shading.

Comparing Figure 45 and 46, it is easy to see the effect of shading on solar gains through exterior windows. The dips and variations that can be observed in solar gains in the baseline scenario are most likely caused by the shading algorithm, steered by the selected Solar setpoint of 120 W/m².

PMV

Figure 47 and 48 show the PMV for the different simulated scenarios in Open WS 3.2 and 3.3 respectively.

PMV for the 'No shading' scenario can be observed to be the closest to neutral zero for both zones. There is not much differentiating the other three scenarios with regards to PMV. As usual, PMV closely follow the development in operative temperature and therefore occupants in Open WS 3.2 are slightly closer to neutral than those in 3.3

It is interesting to note that even though the operative temperature in WS 3.2 on Friday is 27 °C, PMV is 0.22 i.e. almost neutral. It would seem that DesignBuilder is quite stringent in its calculation of PMV.

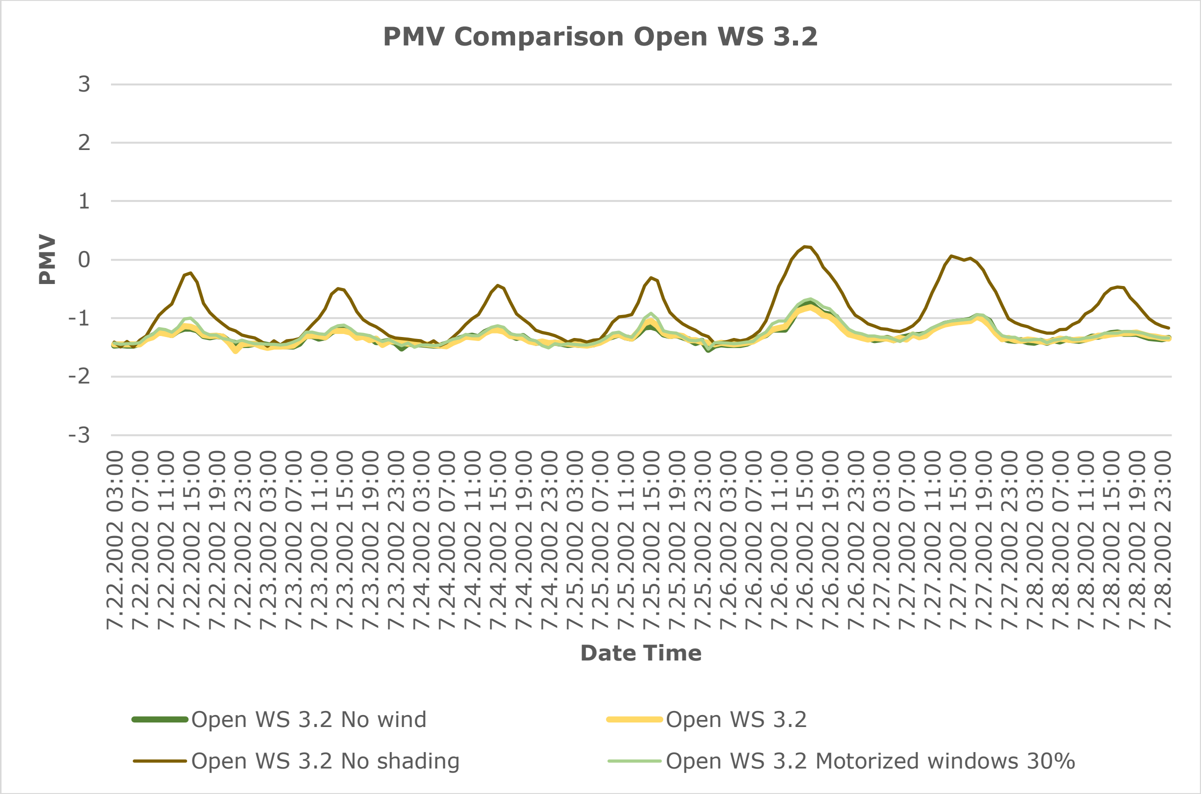


Figure 47: PMV comparison for different scenarios in Open WS 3.2

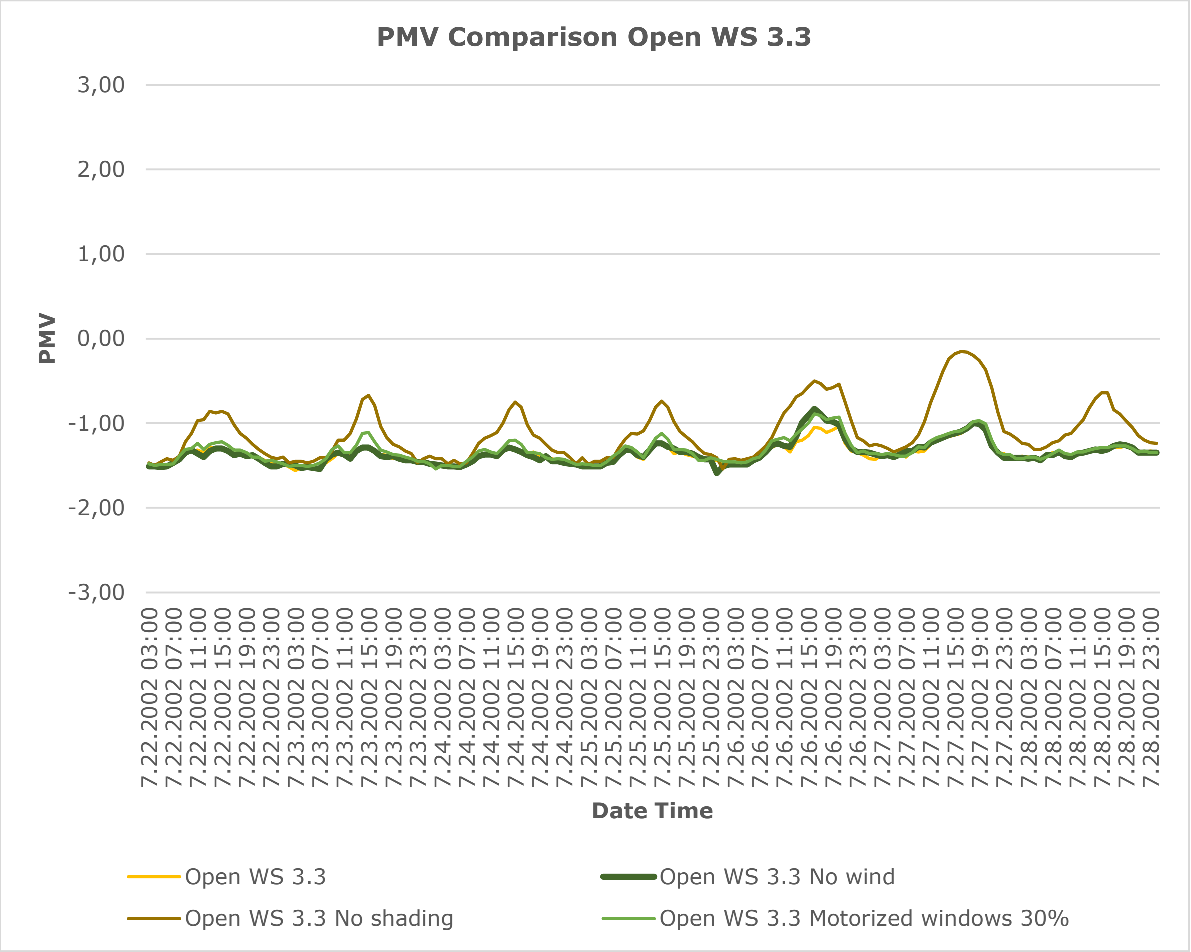


Figure 48: PMV comparison for different scenarios in Open WS 3.3

7 Discussion

This section aims to provide an overall discussion for the thesis, including literature study, simulations, and results.

The approach for this thesis has included learning the basis of theory on natural and hybrid ventilation. A detailed literature study has been performed using resources at NTNU such as Oria and Scopus databases. Comparable case studies for Zero Energy Buildings have been challenging to find for a Nordic climate. A model for simulation has been created for the ZEB Lab in DesignBuilder. Simulations provide a simplification of reality, but naturally an experimental approach was not possible since the ZEB Lab is currently under construction.

In order to create a realistic model of ZEB Lab available information on the project has been studied. Know-how regarding the use of DesignBuilder was also necessary to obtain and proved to be quite a time-consuming task. The help manual for the program has been extensively used.

DesignBuilder has a lot of available functionality and proved to be good for modeling realistic building structures. It was also straightforward, albeit time-consuming, to customize parameters for each opening. However, the main drawback was the limitation regarding airflow analysis. Airflow could not be tracked from zone to zone, the available output was heat balance effect in kW of external and internal air coming into the zone in question.

There is some uncertainty with regard to the weather file since it uses Bergen weather data. Trondheim weather data should be used in future endeavors to ensure further result reliability. Occupant load in the simulated ZEB Lab was based on assumptions and is another source of uncertainty. Weekdays were modeled with identical occupancy schedules, when in reality, this will not be the case.

Time permitting, there were many other parameters that could have been varied. This thesis has focused on natural ventilation during summertime. It would be interesting to further develop the models using hybrid and mechanical ventilation strategies in other seasons. The shading control method and/or setpoint could have been varied to further analyze solar gains. Opening area of windows could have been further varied to check effects on ventilation and comfort.

The control method for natural ventilation was based on a minimum indoor temperature for natural ventilation. When the temperature in the zone was higher than this setpoint, *and* higher than outdoor temperature, windows were opened. The setpoint was chosen to be 22°C. During the chosen simulation summer week, indoor temperatures were higher than the outdoor temperature on all but one day. Therefore, the brunt of the control system was left to the minimum indoor temperature setpoint. It could be interesting to use the setpoint as a variable parameter for further analysis.

Results have been exported from DesignBuilder and processed manually using Excel, hence human error is a source of uncertainty in the results.

The general trends found from the results have been that natural ventilation has been sufficient in providing fresh air to most of the zones in ZEB Lab. PMV has been stable for most analyzed zones at about -1. This means that occupants will feel slightly cold in the

ZEB Lab, but the building model does fulfill comfort requirements through indoor temperature. It can also be assumed that if occupants in fact are cold in the real ZEB Lab, the possibility of closing windows manually will be useful. It is also interesting to note that some results indicate that PMV calculation is very strict in DesignBuilder. At an operative temperature of 27°C, PMV was said to be +0.22.

These simulations show that it can be possible to provide sufficient ventilation in office buildings using natural forces during summertime while fulfilling comfort requirements, even in a Nordic climate. These results could be used to strengthen the argument basis for choosing hybrid ventilation in harsher climates, even for buildings with a high ambition level. It can also be noted that the results did not show any demand for mechanical cooling.

8 Conclusion

The focus of the model in DesignBuilder has been to evaluate natural ventilation and comfort conditions in ZEB Lab during summertime.

Analyzed zones are the Canteen, Windbreaker 1, Meeting room 2.1 and 3.1, Twin cell 1, Open WS 3.2 and 3.3 and the Knowledge center. Logical results have been obtained but inexplicable anomalies have also been found.

Generally, ventilation air volumes have been sufficient using only natural ventilation in the simulation. PMV has been found to be between -1.5 and -1 for occupied hours in all zones. Occupants will feel slightly cold, but the comfort requirements are fulfilled.

When comparing results from Open Workspaces 3.2 and 3.2 different scenarios were modeled. Ventilation air volumes were highest when simulating without shading, possibly attributed to higher temperature difference driven flow.

Wind effects of natural ventilation have been cross-checked and verified to be logical using implemented wind data. Operative temperature has been proven to rise considerably in the scenario without shading. PMV has followed changes in operative temperature closely.

DesignBuilder has been proven to be an interesting simulation tool with a many features and functionality. Multi-zone, transient, thermal simulation with real weather data is possible for both natural and mechanical ventilation. This thesis has focused on natural ventilation, and wind effects have also been analyzed. The main drawback has been the lack of detailed zone-to-zone airflow analysis.

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Appendix A

Table 6: Occupancy information per zone

	Zone	Occupants (max)	Schedule
First floor	Windbreaker 1	2	Start&end
	Windbreaker 2	1	Start&end
	Stairwell	2	Stairwell
	Bi-stairwell	2	Stairwell
	WC 1.1	1	All_day
	Wardrobe	5	Start&end
	Elevator	0,5	All_day
	Storage room	1	All_day
	Janitorial center	1	All_day
	Hallway	10	Hallway_1
	Canteen	30	Canteen
Second floor	Stairwell	2	Stairwell
	Bi-stairwell	2	Stairwell
	WC 2.1	1	All_day
	Copy room	0,5	All_day
	Elevator	0,5	All_day
	Hallway	1	All_day
	Meeting room 2.1	9	Meeting_room
	Multi-room 2.1	4	Multi-room
	Team-room 2.1	7	Team-room
	Team-room 2.2	8	Team-room
	Touch-down 2.1	4	Touch-down
	Twin cell 1	10	Worksapce
	Twin cell 2	10	Worksapce
	Twin cell tech.	0,25	All_day
Third floor	Stairwell	2	Stairwell
	Bi-stairwell	2	Stairwell
	Elevator	0,5	All_day
	Hallway	1	All_day
	WC 3.1	1	All_day
	WC3.2	1	All_day
	Meeting room 3.1	10	Meeting_room
	Multi-room 3.1	4	Multi-room
	Multi-room 3.2	4	Multi-room
	Open WS 3.1	6	Worksapce
	Open WS 3.2	10	Worksapce
	Open WS 3.3	10	Worksapce
	WS 3.1	5	Worksapce
	WS 3.2	8	Worksapce
	Touch-down 3.1	4	Touch-down
	Project room 3.1	10	Team-room

Fourth floor	Stairwell	1	Stairwell
	Bi-stairwell	1	Stairwell
	Elevator	0,25	All_day
	Hallway	1	All_day
	Auditorium	30	10:00-12:00
	Knowledge center	30	12:00-14:00
	WC 4.1	1	All_day

Table 7: Occupancy schedule values

Time	Stairwell	All_day	Start&end	Hallway	Canteen	Workspace	10:00-12:00	12:00-14:00	Meeting room	Multi-room	Team-room	Touch-down
00:00	0	0	0	0	0	0	0	0	0	0	0	0
01:00	0	0	0	0	0	0	0	0	0	0	0	0
02:00	0	0	0	0	0	0	0	0	0	0	0	0
03:00	0	0	0	0	0	0	0	0	0	0	0	0
04:00	0	0	0	0	0	0	0	0	0	0	0	0
05:00	0	0	0	0	0	0	0	0	0	0	0	0
06:00	0	0	0	0	0	0	0	0	0	0	0	0
07:00	1	1	0,25	0,25	0	0,5	0	0	0	0	0	0
08:00	1	1	0,5	0,25	0,1	0,75	0	0	0,5	0	0	0
09:00	0,25	1	0,25	0,25	0,1	1	0	0	0,5	0	0	0
10:00	0,25	1	0	0,25	0,1	1	1	0	0	0,5	0,5	0
11:00	1	1	0	0,5	1	0	1	0	0	0	0,5	0,5
12:00	1	1	0	0,5	1	0	0	1	0	0	0	0,5
13:00	0,25	1	0	0,25	0,1	1	0	1	0,25	0	0	0

14:00	0,25	1	0	0,25	0,1	1	0	0	0	0	0,75	0
15:00	0,25	1	0,25	0,25	0,1	0,75	0	0	0	0,75	0,75	0
16:00	1	1	0,25	0,25	0,1	0,5	0	0	0	0	0	0
17:00	0	0	0	0	0	0	0	0	0	0	0	0
18:00	0	0	0	0	0	0	0	0	0	0	0	0
19:00	0	0	0	0	0	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0
00:00	0	0	0	0	0	0	0	0	0	0	0	0

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