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Design and Energy Analysis of Natural and Hybrid Ventilation Strategies for Norwegian Office Buildings

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Submission date: June 2016
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NTNU

Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2016-48

MASTER THESIS

for

Ingrid D. Halderaker

Spring 2016

Design and energy analysis of generic and adaptable buildings in Norway

Design og energianalyse av generiske og tilpasningsdyktige bygninger i Norge

Background and objective

Rehabilitation and reconstruction of buildings related to new tenants are often cost-driving. The buildings do not have sufficient flexibility and generality, and therefore often require adjustments and adaptations when new tenants move in. This requires resources and the result is cost demanding. Greater flexibility and generality of building functionality may provide an increase in value of a given property, both financially and resource-wise. Nevertheless, when a new building is designed, only standard energy requirements and low investment cost are considered. This means that solution and building are often not flexible for changes in ownership and use of the building. Therefore, it is important to consider how building elements such as floor plans, ventilation solution, space heating, energy, automation, and energy measurement can be made generic so that buildings can handle future changes. Implementation of a heating and ventilation strategy that exploits the interaction between the structure's thermal properties and a hybrid ventilation strategy may be relevant. Furthermore, it might be necessary to select an integrated heating and ventilation strategy. The purpose of the thesis is to analyze a generic and adaptable building solution for Norwegian conditions by using IDA-ICE simulation tool. A similar building where building installations and construction work together and provide good thermal comfort entire year without any mechanical ventilation or additional heating has been in use in Austria. The student will include necessary changes for Norwegian conditions into the building model. Different ventilation strategies such as natural and hybrid ventilation should be tested. Since achieving good thermal comfort may be challenging in this building, analysis of thermal comfort and defining suitable thermal comfort models to promote the solution will be beneficial.

The aim of the study is to analyze the generic and adaptable building from the Austrian project for the Norwegian conditions.

The following tasks are to be considered:

1. Literature study of the following topics: integrated building design, current and future energy requirements, thermal comfort models.
2. Develop building model in IDA-ICE. Extend the model to include natural ventilation, hybrid ventilation with different percetage of the natural ventilation, different heating systems such as radiators, floor heating or electric heater.
3. Analyze thermal comfort cosidering different models for the thermal comoft analysis.

4. Perform parametric and sensitivity analysis. In the parametric study, the following may be analyzed: percetage of the natural ventilation, construction properties, light level, installed power for appliances.
5. If possible include occupant behavior models into the building model. Perform analysis by considering occupant behavour on this solution.
6. Organized and present the results. Emphasize how such a building may perform in Norway, what may be advantages and disadvantages.

-- " --

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

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

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

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

Department of Energy and Process Engineering, 20. January 2016

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Abstract

Buildings' lack of sufficient flexibility and generality leads to the need of comprehensive adjustments when new tenants are moving in. In addition, many building owners experience faults and problems with the operation of advanced technical installations. The challenges implies a potential to reduce costs and resources by creating more adaptable buildings and limit the complexity of the technical installations.

In this thesis, examples of integrated ventilation strategies have been investigated by the use of the dynamic simulation tool IDA ICE. The strategies were inspired by the building "2226" in Austria by Baumschlager Eberle, and are systems where natural and hybrid ventilation interact with the thermal properties of the construction through automatic windows. A manual window solution with a user app was designed to model stochastic human behavior. A series of simulations were performed to predict the indoor climate and energy use of the integrated ventilation strategies in Norwegian conditions.

According to the results, all scenarios with automatic windows can provide satisfactory thermal conditions during spring, summer and autumn. The combination of night cooling and exposed thermal mass limits problems with overheating in summer, and gives a maximum temperature of 27°C with the given conditions. The main challenge, particularly with solely natural ventilation, is to provide thermal comfort during window airing in winter. In the naturally ventilated scenario, the temperature momentary drops down to 15°C on the coldest day. Results show that a hybrid strategy can provide a better indoor climate in winter, by limiting the number of pulse ventilations needed on cold days, and generally increasing the indoor temperature. The demand-controlled natural ventilation ensures satisfactory CO_2-levels of maximum 1100 ppm in all scenarios. Due to the required calculation method in NS 3031, buildings with only natural ventilation cannot fulfill the energy requirements in TEK. However, simulations results show a low energy use of 63 kWh/m^2 for a naturally ventilated and 54 kWh/m^2 for two hybrid ventilated scenarios. Furthermore, the naturally ventilated scenario is found to have a need for heating, while the need of and size of suitable heating systems for the hybrid strategies can be discussed.

The use of stochastic variables in building simulation is a suitable procedure to model different outcomes of human behavior. The design of a manual window control based on stochastic variables was however not successful in this thesis. Thus, further work is needed to develop a suitable simulation model in IDA ICE of occupant behavior with stimuli from an app.

Passive design strategies and the use of hybrid ventilation are shown to be promising tools to obtain a more sustainable building design with low life cycle costs, low energy use and a good indoor climate. The use of hybrid ventilation systems requires a different approach than conventional mechanical systems. It is crucial that conditions for natural ventilation and passive cooling are present. Furthermore, the system must be well controlled and integrated in the building design. The building's context, function, geometry, users, components and floor plans determines the feasibility of solutions and must be thoroughly assessed in every case.

Sammendrag

Rehabilitering og ombygging i tilknytning til nye leietakere er kostnadsdrivende. Bygningene har ikke tilstrekkelig fleksibilitet og generalitet, og det kreves derfor ofte omfattende justeringer og tilpasninger der nye leietakere flytter inn. Dette er ressurskrevende og lite effektivt. Utfordringene beskrevet indikerer at det er et økonomisk og ressursmessig potensial i å skape mer tilpasningsdyktige bygninger og begrense kompleksiteten i de tekniske systemene.

I denne oppgaven er ulike integrerte ventilasjonsstrategier blitt undersøkt ved hjelp av det dynamiske simuleringsverktøyet IDA Indoor Climate Energy. Ventilajonsstrategiene er inspirert av bygget «2226» i Østerrike av Baumschlager Eberle, og består av naturlig og hybrid ventilasjon via automatiske vindu i samspill med en tung termisk konstruksjon. En manuell vindusløsning ved hjelp av en «bruker-app» ble utviklet for å modellere stokastisk brukeroppførsel. Videre ble en rekke simuleringer ble utført for å predikere ventilasjonsstrategienes inneklima og energibruk i norske forhold.

Resultatene viser at løsningene med automatisk åpningsbare vindu kan sørge for tilfredsstillende temperaturer om våren, sommeren og høsten. Kombinasjonen av nattekjøling sammen med eksponert termisk masse forhindrer problemer med overoppheting om sommeren, og gir en maksimal operativ temperatur på 27°C. Hovedutfordringen, spesielt med ren naturlig ventilasjon er å få sørge for termisk komfort i forbindelse med lufting om vinteren. I det naturlig ventilerte scenarioet faller temperaturen tidvis helt ned til 15°C ved lufting på den kaldeste dagen. Resultatene viser at en hybrid strategi kan sørge for et bedre inneklima og lavere energibruk ved å begrense det nødvendige antallet pulsventileringer om vinteren i tillegg til å generelt øke innetemperaturen. Den behovsstyrte naturlige ventilasjonen sørger for tilfredsstillende CO_2-verdier på maksimum 1100 ppm i alle scenario. På grunn av den påkrevde beregningsmetoden i NS 3031 kan ikke rent naturlig ventilerte bygg oppnå de gjeldende energikravene i den reviderte TEK10 (2016). Simuleringer viser allikevel lave energiforbruk på 63 kWh/m^2 for den naturlig ventilerte løsningen og 54 kWh/m^2 for de to hybride. Det naturlig ventilerte scenarioet viser et behov for oppvarming, mens behovet for og valget av oppvarmingsløsning i de hybride strategiene kan diskuteres.

Bruken av stokastiske variabler i bygningssimulering kan være en god metode for å fremstille mulige utfall av menneskelig oppførsel og påvirkningen på inneklima og energibruk. Den manuelle vinduskontrollen som ble utviklet med bruk av stokastiske variabler viste seg å ikke fungere som planlagt, og det kreves derfor videre arbeid for å utvikle en passende simuleringsmodell i IDA ICE som kan modellere brukeroppførsel med stimuli fra en app.

Passive designstrategier og bruk av hybrid ventilasjon viser seg å være lovende verktøy for å oppnå mer bærekraftig bygningsdesign med lav livssykluskostnad, lavt energibruk og godt inneklima. Bruken av hybrid ventilasjon krever en annen tilnærming enn tradisjonelle mekaniske systemer. Det er avgjørende at byggets form og omgivelser muliggjør bruk av naturlig ventilasjon og passiv nattekjøling. Videre er det viktig at det hybride systemet er bygningsintegrert og optimalt kontrollert. Bygningens kontekst, funksjon, geometri, brukere, materialer og planløsning avgjør mulighetene for forenkling av de tekniske systemene og må vurderes grundig i hvert tilfelle.

Preface

This master thesis was written during the spring 2016 at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology. The thesis is written in cooperation with the organization Grønn Byggalianse, and is the continuation of a specialization project written autumn 2015.

I would like to thank my supervisor Natasa Nord for good guidance and advice. Thanks to my research advisor Arne Førland-Larsen from Asplan Viak/Grønn Byggalianse for helping me with the model in IDA ICE and for always being available to answer my questions. I would also like to thank Grønn Byggalianse for the opportunity to write this thesis, and to participate on their workshops and study trip to Austria and Switzerland. To all friends and family, I am grateful for your encouragement and support.

Ingrid Dagsland Halderaker

Ingrid Dagsland Halderaker
Trondheim, June 23, 2016

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Abbreviations

2226
The name of a passive building in Austria by Baumschlager Eberle.

ACH
Air changes per hour.

AHU
Air handling unit.

BREEAM
Environmental assessment method and rating system for buildings.

CAV
Constant air volumes.

Clo
Unit for the thermal insulation of clothes. 1 clo = 0,155m^2*K/W. A typical summer outfit corresponds to 0.5 clo, and a winter outfit to 1 clo.

IDA ICE
IDA Indoor Climate Energy. A dynamic building simulation tool.

IED - Integrated Energy Design
A design procedure where a multidisciplinary design team develop integrated energy and environmental solutions in the building architecture and construction

LCC
Life cycle cost. The total investment and operational cost of a building during its lifetime.

Operative temperature
The average between the air temperature and the mean radiant temperature.

Met
Unit for the human metabolic rate. 1 met = 58.15 W/m^2 corresponds to sedentary calm activity. Sedentary mental activity constitutes 1.2 met.

***PMV* – Predicted Mean Vote**
Measure to predict how occupants experience the thermal environment in a building. The scale has the rankings:
-3 cold
-2 cool
-1 slightly cool
0 neutral
+1 slightly warm
+2 warm
+3 hot

***PPD* – Percentage of People Dissatisfied**
Measure derived from the PMV. Indicates the percentage of people dissatisfied with the thermal conditions.

TEK
Teknisk forskrift, Norwegian Building regulations of spring 2016.

1 Introduction

1.1 Background and objective

A greater flexibility and generality is estimated to give an increment value of a given property. Rehabilitation and refurbishment of office buildings due to new tenants are often cost driving [1]. Buildings' lack of sufficient flexibility and generality leads to the need of comprehensive adjustments when new tenants are moving in [2]. This is inefficient and requires a lot of resources. In addition, many building owners experience faults and problems with the operation of advanced technical installations [3]. The challenges described implies a potential to reduce costs and resources by creating more adaptable buildings and limit the complexity of the technical installations.

One solution can be to choose an integrated ventilation and heating strategy. By integrating the ventilation and heating strategy in the building construction and choosing a technical solution that is simplified, the building can become more robust and flexible [4]. It is important to have a system that is simplified to a high degree without compromising a good indoor climate and a low energy consumption. Furthermore, the system should have an adequate complexity and automation solution. However, this choice affects the building geometry, floor plans and other building components.

In this report, examples of integrated ventilation strategies inspired by the building "2226" by Baumschlager Eberle are investigated by the use of the dynamic simulation tool IDA Indoor Climate Energy. "2226" is a passive office building in Austria, which documents an indoor temperature of 22-26 °C and a CO_2-level below 1000 ppm all year around, without the use of mechanical ventilation, cooling or heating. The solutions investigated are systems where natural and hybrid ventilation interact with the thermal properties of the construction through automatic openable windows. Since it is favorable to limit the complexity of technical systems, a manual window solution with a user app was designed to model stochastic human behavior. The aim of this thesis is to assess thermal comfort and energy use of integrated ventilation strategies in Norwegian conditions. Can a building based on the principles in 2226 provide a satisfactory indoor climate and low energy use in Norway? If so, the solution could be used as an inspiration for simplified and integrated ventilation strategies.

1.2 Structure of the report

The report will be divided into two parts, a literature study and a case study. In the literature study, the concept of integrated energy design is presented in chapter 2, followed by a discussion on ventilation principles with a focus on natural and hybrid ventilation, in addition to displacement ventilation in chapter 3. Furthermore, life cycle cost and complexity is briefly discussed in chapter 4 before an example of a generic building solution, "2226" in Austria is presented in chapter 5. An example of an integrated ventilation solution in Norway is discussed in chapter 6. Since thermal comfort can be challenging to assess in natural and hybrid ventilated buildings, a literature study of thermal comfort models has been performed and is presented in chapter 7. Finally, the literature study concludes with a discussion on modelling of energy-related human behavior and occupant's window opening behavior in chapter 8.

In the second part, a model of a generic building with an integrated ventilation solution in Norwegian climate is assessed using the simulation program IDA Indoor Climate and Energy. The model is extended to include natural ventilation and hybrid ventilation with different percentage of natural ventilation, and the results are discussed in chapter 11. Thermal comfort is assessed in 11.1.1 using comfort models based on the heat balance method, adaptive comfort and exceedance calculations. The indoor air quality is discussed in 11.1.2, and the need of heating and yearly energy use is evaluated in 11.1.3 and 11.1.4. Furthermore, a parameter study of passive night cooling, heat capacity and internal loads is performed in 11.1.5. Modelling of a manual window solution with the use of an app was tested in IDA ICE and results are presented in 11.2. Finally, the discussion rounds off with general remarks in 11.3.

1.3 Limitations

This report is limited to an analysis of the indoor climate and energy consumption of the solutions, based on simulation results from IDA ICE. Detailed studies of air flows patterns and air velocities in the occupant zone have not been performed, and thus problems with draft is only briefly discussed based on room temperature and window geometries. Furthermore, the results are assessed in light of thermal comfort and general recommendations for indoor air quality, not productivity. The enthalpy of the air might be of importance for the perceived air quality at lower air flow rates, but as CO_2 was chosen as an indicator for air quality in this thesis, the relative humidity in the scenarios has not been considered. Dimensioning and choice of heating system for the solutions was not the scope of this study and has therefore only been briefly discussed.

2 Integrated energy design

The annual energy consumption in the Norwegian building sector pose about 40% of the total national energy use. Reduction of energy consumption and the use of energy from renewable energy sources are important measures to reduce the energy dependency and the emission of greenhouse gases. The Norwegian Government's Climate Agreement of March 2012 and the revised building act of November 2015 sets passive house standard as a requirement for new buildings from 2016 and indicates nearly zero energy level by 2020.

On EU-level, the project MaTrID - Market Transformation Towards Nearly Zero Energy Buildings Through Widespread Use of Integrated Energy Design - aims to support the implementation of Nearly Zero-Energy Buildings by 2020 using an Integrated Design Process [5]. Integrated energy design (IED) is a holistic design approach where the aim is to optimize the building as a whole throughout the lifecycle. In contrast to the linear conventional design process, IED is more an iterative process where multidisciplinary design team develop and discuss solutions from the initial design phase and throughout the entire process.

In an integrated energy design procedure, the focus is to optimize the architecture by passive design measures that reduce the energy consumption during the operation of the building. Firstly, the shape, facades and materials should be chosen to utilize solar energy and daylight as well as natural air flow for ventilation and cooling. Secondly, a simple technical system should be chosen to supplement the passive measures and reach the requirement specifications [5].

Experience from building projects where integrated energy design has been applied shows an increase in investment cost of about 5 %. However, the annual running costs are reduced with as much as 40-90 %, and the amount building faults is reduced [5]. The use of integrated energy design shifts the workload to an earlier stage, where the impact on the performance is increased at a lower cost, as seen in Figure 1.

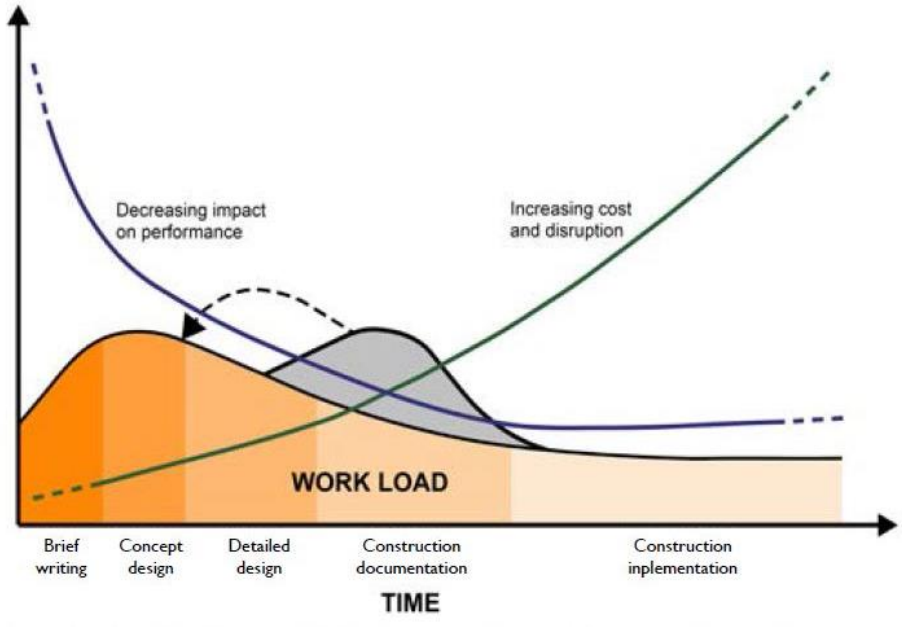


Figure 1 Integrated energy design implies a shift in the workload [5]

Benefits of an integrated energy design approach are many. Higher energy performance, reduced embodied carbon, lower running costs and optimized indoor climate are some of the gains. In addition, the use of IED can give more user involvement, a higher value and a green image of the building. Barriers towards implementing IED are however present. IED challenges conventional thinking, by changing the decision processes and design method. Many developers pay more attention to construction cost than life cycle cost and want to limit the time spent on the initial planning phase. Furthermore, IED requires a closer collaboration between experts from different fields of expertise, where compromises are necessary for a holistic approach [6].

2.1 Responsive building elements

Responsive building elements are emphasized as essential tools for exploiting environmental and renewable resources in an integrated energy design process. In the International Energy Agency's project 'ECBCS Annex 44 – Integrating Environmentally Responsive Elements in Buildings' a responsive building is defined as "a building component that assists in maintaining an appropriate balance between optimum interior conditions and environmental performance by reacting in a controlled and holistic manner to changes in external or internal conditions and occupant intervention"[7].

He report divides the environmental design and control of buildings into two approaches. The usual approach to create energy efficient buildings by excluding the outdoor environment from the indoor environment through the creation of a very air-tight and well insulated building construction. An acceptable indoor environment is then provided by automatic control of mechanical systems. This approach gives the need of a large heating installation during winter and mechanical cooling in summer.

An alternative approach is to create buildings that interacts more with its environment to make use of the surrounding resources, such as daylight, natural ventilation and passive cooling. In this approach, the building envelope is seen as an intermediate between the outdoor and the indoor environment, which should adapt dynamically to changes in the environment by the use of responsive elements and integrated design. An acceptable indoor environment is provided by a combination of user control of the building envelope and a mechanical system.

Thermal mass activation is an example of a responsive building element. Thermal mass has the capacity to store heat at times when there is excess and release it at times with heating demand [8]. Depending on the physical properties, such as the time constant of storage and the amount of energy that can be stored at a given temperature, thermal mass can store heat from a time scale of a day to a month or a year. By cooling the building structure during the night using natural ventilation, cooling demands, especially in office buildings, can be solved using thermal mass as a heat sink. According to Artmann et al. [9], there is a high climatic potential for using passive cooling by night-time ventilation in Northern Europe. A study by Høseggen et al. [10] show that exposed thermal mass in the ceiling can reduce the number of hours with excessive temperatures considerably and significantly increase the effect of passive night cooling. However, only a minor energy saving is achieved compared to a solution with suspended ceiling.

3 Ventilation principles

The choice of ventilation principle is of importance to create flexible and generic building solutions. A sustainable building should handle changes in tenants and different use of the building during its lifetime with a minimum of reconstructions and adaptions. By choosing a ventilation solution that is integrated in the building design, the building can be prepared for future changes in use.

3.1 Natural ventilation

Natural ventilation is a ventilation principle that make use of natural driving forces to transport the air in a building. The natural ventilation concept is constituted by three essential aspects, as seen in Figure 2 [11]:

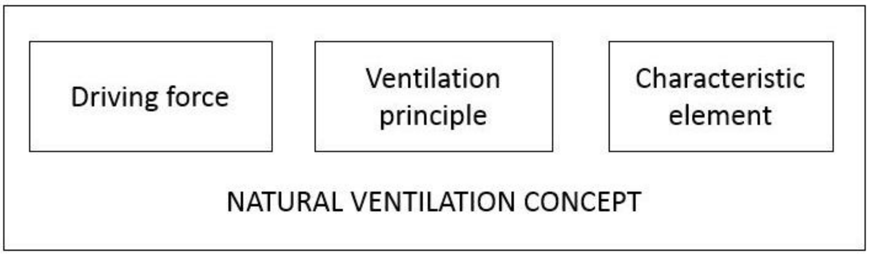


Figure 2 Aspects of the natural ventilation concept

The utilized driving force can be either wind, buoyancy or both. To exploit the driving force, single-sided ventilation, cross-ventilation or stack ventilation can constitute the ventilation principle. The characteristic element is the architectural solution in the building that allows use of natural ventilation. The most common characteristic elements are windows, wind towers, wind scoops, chimneys, double facades, atriums and embedded ducts. Modern use of natural ventilation includes control systems that regulate the venting according to the need and the driving force available.

3.1.1 Buoyancy driven flow

Thermal buoyancy, or the so-called chimney effect, makes use of the density differences between the internal and external air due to temperature differences between the inside and outside. Cold air enters openings in the lower part of the building envelope due to a local external over-pressure, while warm air exits the building through openings in the upper part due to local internal over pressure, as shown in Figure 3. The neutral zone is where the pressures equalize.

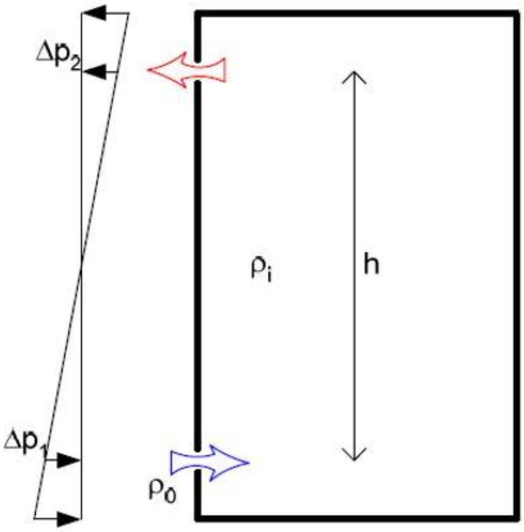


Figure 3 Buoyancy driven ventilation [7]

The pressure difference over an opening located in the height h is given by:

$$\Delta \mathrm{p} = \Delta \mathrm{p}_1 + \Delta \mathrm{p}_2 = (\rho_0 - \rho_i)gh = \Delta\rho \mathrm{gh} = \rho_0 \left(\frac{273}{T_o} - \frac{273}{T_i}\right) gh \qquad [1]$$

Where:

$\Delta p_1 = \Delta p_2$ – pressure difference over openings [Pa]
h – height difference between openings [m]
ρ – density [kg/m^3]
g – gravitational acceleration [m/s^2]

3.1.2 Wind-driven flow

Wind driven ventilation is a result of the pressure differences created on the building envelope due to wind. The pressure differences drive air through the building envelope on the windward side and out on the leeward side [11]. Figure 4 shows the effect of wind driven natural ventilation.

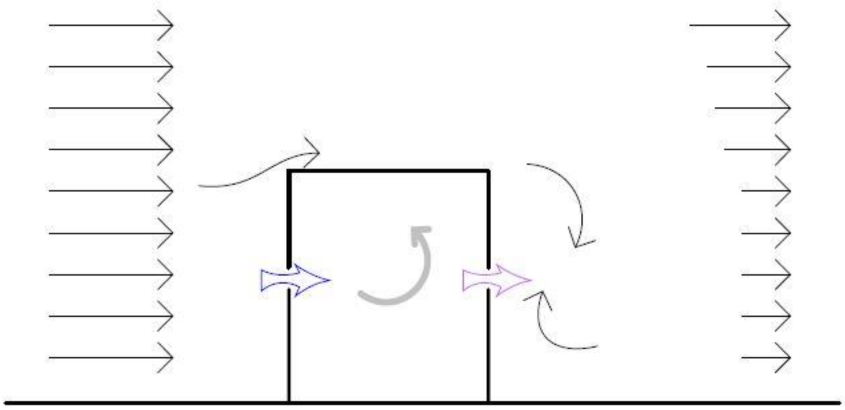


Figure 4 Wind driven ventilation [12]

The wind pressure on a given surface on the building envelope is given by:

$$p_w = C_p \frac{\rho_o {V_{ref}}^2}{2} \quad [Pa] \qquad [2]$$

Where:

p_w – wind pressure [Pa]
C_p – static pressure coefficient
V_{ref} - wind speed at reference height [ms^{-1}]
ρ_o – outdoor air density [kgm^{-3}]

3.1.3 Passive ventilation principles

As previously discussed, natural ventilation is based on a ventilation principle. The principle is related to the building shape and the location of the openings in the building envelope.

One-sided ventilation is created by openings on one side of the external walls in a room. An example is an office with an openable window and a closed door to the corridor. The contribution of the wind is caused by fluctuations in the wind speed and infiltration [13]. The contribution from thermal buoyancy depends on the area and height of the window opening. As a rule of thumb, the one-sided ventilation is effective when the room depth is lower than 2- 2.5 times the floor to ceiling height.

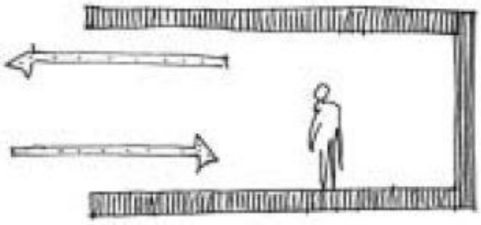


Figure 5 Sketch of one-sided ventilation [11]

Cross-ventilation is performed by having two openings or more in the external walls, as shown in Figure 6. The ventilation is mainly driven by the pressure differences on the surfaces where the openings are placed. Cross-ventilation is more efficient than one-sided ventilation and thus the room can have a depth of up to 5 times the room height.

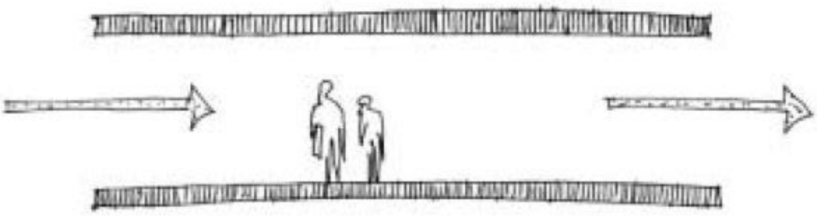


Figure 6 Sketch of cross-ventilation [11]

Stack ventilation is based on thermal buoyancy. The driving forces from buoyancy increases with an increasing height difference between the intake and exhaust openings. An increased height difference can be solved by increasing the floor height, create open sections between the floors in the building, create openings in the roof or include vertical ducts or chimneys.

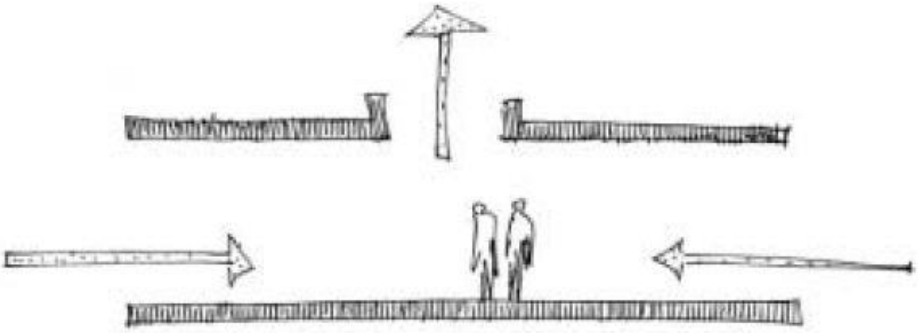


Figure 7 Sketch of stack ventilation [11]

3.2 Hybrid ventilation

Hybrid ventilation is a concept where natural and mechanical driving forces are combined in a building integrated solution. As the natural driving forces depends on weather and climatic conditions, they vary over time. Natural ventilation is an energy efficient ventilation principle in periods with need of cooling. However, during periods with need of heating it cannot provide heat recovery. Mechanical ventilation can ensure energy efficient heat recovery when this is needed. A hybrid solution combines the advantages of the two ventilation principles by utilizing both passive cooling and mechanical heat recovery.

3.2.1 Principles of hybrid ventilation

Hybrid ventilation can be performed in several ways [14] [15]. One solution is to use concurrent operation, where the mechanical ventilation supplements the natural driving forces or works as a base-ventilation. Another strategy is the use of change-over design. As the name implies, change-over design is an operation where the system changes between natural and mechanical ventilation on a seasonal or daily basis. The mode of operation can be decided by the building automation system regulating according to outdoor temperature, occupancy, a window sensor, or operator commands. Hybrid ventilated buildings can also be performed with some naturally ventilated and other mechanically ventilated zones.

The distribution between natural and mechanical ventilation in a hybrid-ventilated building can vary from 20 – 80 % [4]. Figure 8 shows typical hybrid solutions used in different Northern European countries. The solutions ranges from fan-assisted natural ventilation and use of culverts to balanced hybrid ventilation with heat recovery and filtering.

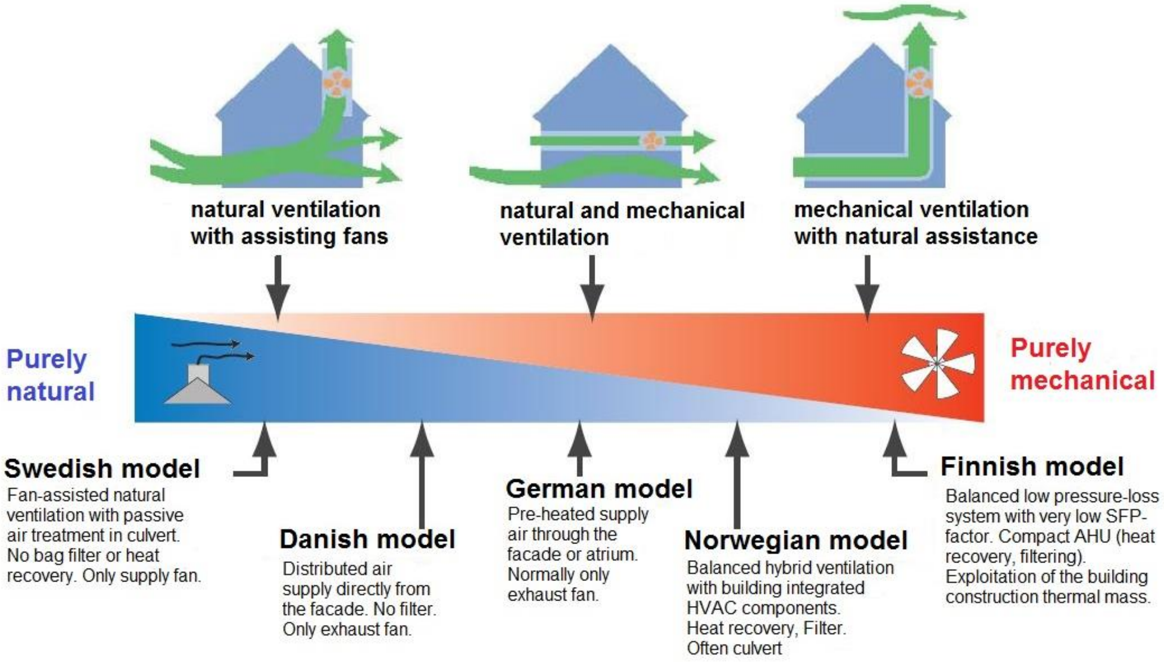


Figure 8 Range of hybrid ventilation concepts [16]

The driving pressure and the pressure drop in a hybrid system is low, in order to exploit the natural driving forces when desirable. By integrating the solution in the building construction, and using natural paths for the air flow, the amount of ducts can be reduced and areas can be freed for other use. Hybrid systems are dimensioned with lower air flow rates than conventional mechanical systems, as it is supplementary to, or supplemented by natural ventilation. The lower air flows rates and use of natural ventilation gives reduced energy use due to reduced fan power and absence of mechanical cooling [15].

The main advantages with a hybrid system is the possibility for individual control, flexibility, low noise level and increased occupant satisfaction [15]. The user satisfaction is related to the system being more comprehensive and intuitive, giving them greater personal control to open windows [17]. The mechanical system can be dimensioned smaller and passive night cooling can be exploited. Additionally, the reduction of ducts and technical rooms has an economic potential. During the design phase of Romsdal upper secondary school, a building in massive wood and with hybrid ventilation, an economical comparative analysis was performed by Asplan Viak [18]. In general, the analysis concludes that there is a potential of reducing the use of area with 1 % of the gross area for hybrid ventilation and 3 % for pure natural ventilation.

3.3 Possibilities and limitations with natural and hybrid ventilation

The use of natural and hybrid ventilation systems requires a different approach than conventional mechanical systems. It is crucial that conditions for natural ventilation and passive cooling are present and that the system is well controlled and integrated in the building design. Local climate, building geometry, choice of windows, risk of draught, and the quality of the outdoor air determines the feasibility and must be evaluated to find a suitable solution in every case. As discussed in section 2, the use of integrated energy design and passive measures can be challenging, but projects where it has been implemented shows promising results [5].

3.3.1 Building geometry

The building geometry is important for the natural ventilation principle. As discussed in section 3.1.3, the efficiency of different ventilation principles is limited by the room depths. Thus, the floor plan and width of the building creates possibilities and limitations for the use of natural ventilation [4].

Figure 9 shows how the possibility for cross- and one-sided ventilation is determined by the width of the building. Cross ventilation is a more efficient ventilation principle, as it utilizes the effect of wind and pressure differences on two facades. Wide buildings will have areas that cannot be ventilated naturally (grey areas in Figure 9). Regarding natural ventilation, rectangular buildings have an optimal width of 12-18 m, while quadratic buildings can have a width of 22-24 m. With hybrid solutions, the design of the floor plan becomes more flexible. Ventilation of the grey areas can then be solved using a small mechanical system to supply these zones.

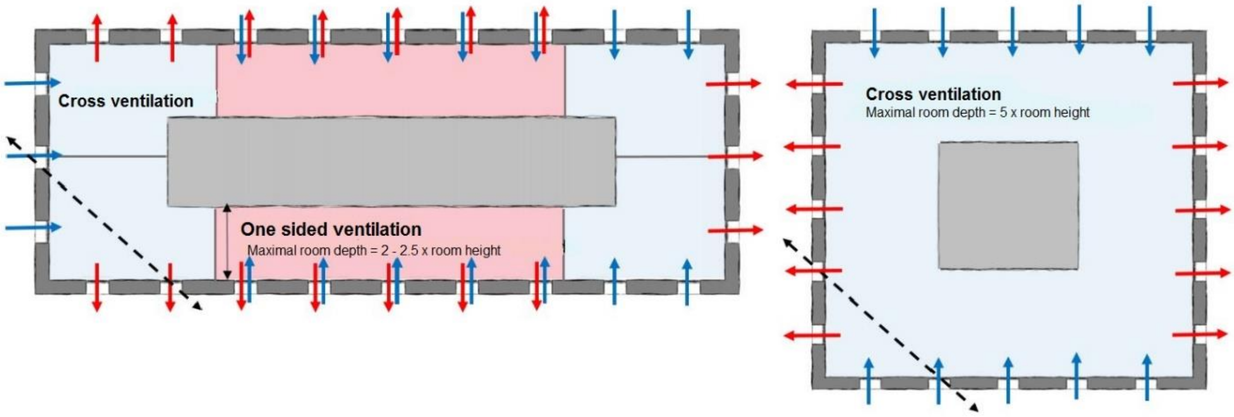


Figure 9 Natural ventilation possibilities and limitations - floor plan

The use of natural and hybrid ventilation limits the space needed for ventilation ducts below the ceiling. The liberated space can give higher floor height, better sense of space and add an esthetic quality to the building. In addition, large floor heights are important for displacement ventilation, as will be discussed in section 3.4.

3.3.2 Window geometries, control system and complexity

The choice of façade openings are important to create well-functioning buildings with natural or hybrid ventilation. In many naturally ventilated buildings, windows are chosen as the characteristic element. The choice of window type, size and location on the façade affects the airflow, ventilation efficiency and thermal comfort in the occupant zone. Furthermore, the windows can be manually or automatic controlled in different degree, resulting in different cost and level of complexity [19].

The airflow patterns through windows with different geometries was investigated in a laboratory experiment in [20]. The study investigated the airflow patterns with side-hung and bottom hung windows under different conditions using smoke tests. Figure 10 and Figure 11 shows the airflow through the two window types with a temperature difference of 20°C for both single sided ventilation and cross ventilation.

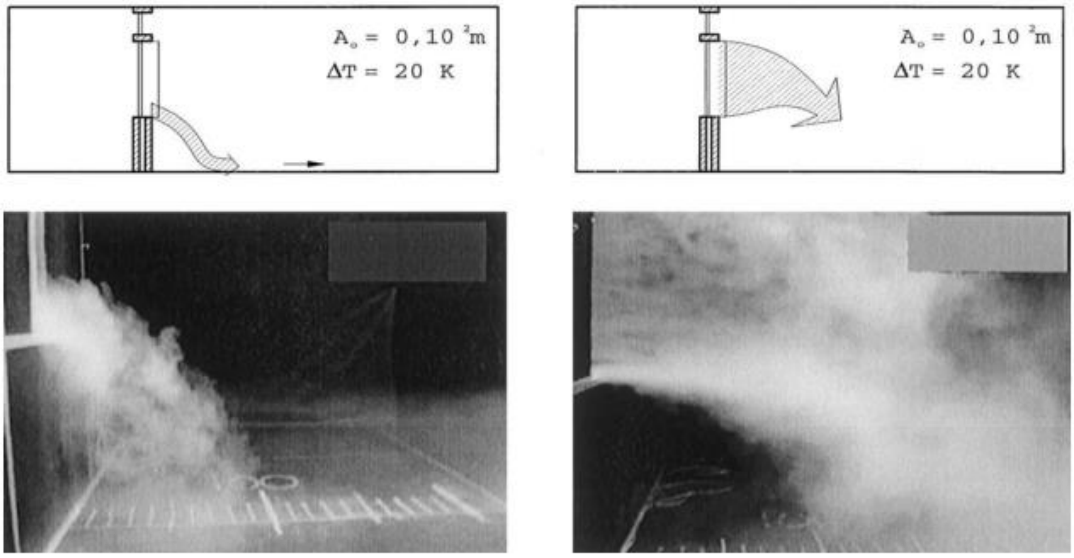


Figure 10 Airflow through side-hung window. Single-sided ventilation (left), cross-ventilation (right) [20]

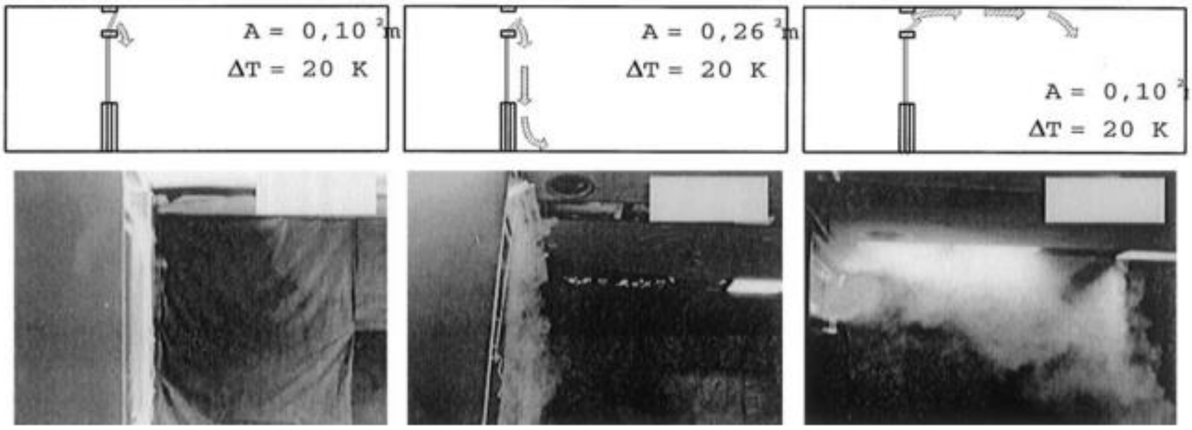


Figure 11 Airflow through bottom hung window. Single-sided ventilation for small and large opening angle (left and middle), cross ventilation (right) [20].

With single-sided ventilation, the airflow from the side-hung window flows directly into the occupant zone, as seen in Figure 10, Depending on the temperature difference and the open window area, the air reaches the floor 0.5 to 1.5 m from the window. The airflows are large and have a high velocity even with small opening angles. With cross ventilation the pressure difference across the windows are higher and the air is supplied further into the occupant zone. The air quantities are larger than for single-sided ventilation.

In the bottom hung window, only small amounts of air enters the room at small opening angles when single-sided ventilation us used, as seen in Figure 11. When the opening is increased, the air flow and velocity increases, and in both cases the air is directed downwards along the wall from the window to the floor. However, with cross ventilation the air jet will attach to the ceiling due to the coanda effect, and drops into the room further into the occupied zone.

The study concludes that to create thermal comfort in the occupant zone, different window geometries are optimal for different outdoor temperatures. For both single-sided ventilation and cross ventilation, a bottom hung window is best in winter because it limits the air supplied directly to the occupant zone. Moreover, the amount of air can be regulated by the opening angle of the window. A side-hung window on the other side, supplies large amounts of cold air directly into the occupant zone, inducing great discomfort in winter. Using cross ventilation on a bottom hung window, the air will be distributed further into the occupant zone and the sensation of draft can be reduced. During summer, the bottom hung window will not be able to supply enough air to the room with single-sided ventilation, since the temperature differences are small. Using single-sided ventilation, the bottom hung window will then have to be combined with a side hung window to supply a sufficient amount of air.

To control the natural ventilation through windows, different system options are possible. The options vary from single or multi-element manual windows to automated systems with varying complexity. The choice of system affects the cost, complexity and personal control, as will be discussed in section 4 and 8.1. Table 1 shows an overview of window system options in relation to cost and complexity.

Table 1 Window system options and complexity for natural ventilation [19]

	System	Comments
Increasing cost and/or complexity →	Simple manual operable window	Manual operable windows are the most basic way to allow for natural ventilation in an office space.
	Multi-element operable window	Windows with more than one opening element are more expensive, but allows for better control and flexibility. A window with two elements can have a high element open on temperate days for a general ventilation of the room and a lower element under control of the nearest occupant who might be bothered with draft.
	Automated operable window	Introducing automatically controlled actuators allows for automatic control of the airing. With a two-element window, the upper window can be automatically controlled and utilized for night ventilation while the lower window can be in control of the occupant.
	Advanced natural ventilation	Buildings with sophisticated natural ventilation systems that are automatically controlled. Such solutions require heavy analysis during the design phase, and optimal tuning of the control system when the building is in operation.

3.3.3 Quality of the outdoor air

In buildings with natural or hybrid ventilation with the use of windows, the air is supplied directly from the façade without filtering. This solution requires a sufficiently good outdoor air quality and limits the sites where naturally ventilated buildings can be constructed. The Norwegian building regulations TEK requires to filter the incoming air if the ambient air lacks sufficient quality [21]. The regulation enhances the importance of conducting a thorough evaluation of the surrounding traffic and industry during the planning process. The sensitivity of the users must also be taken into consideration.

3.3.4 Demand specifications and risk of draft

The demand specifications from the users have a great influence on the feasibility of different solutions. Many tenants set strict requirements to the indoor climate conditions in terms of temperature limitations. A natural- or hybrid system requires a higher degree of acceptance and adaptability, since the risk of draft may occur in shorter periods and the indoor temperature will have variations over the year. For tenants with a strict formal dress code, this might be challenging [15]. Natural ventilation during winter can cause draft during the airing, and the risk of draft affects the possible floor plans and position of workplaces relative to the air intakes at the façade. A hybrid solution can reduce the number of airings during winter and the choice of window type is of great importance for the thermal comfort, as discussed in section 3.3.2. Alternative measures to reduce the risk of draft can be to use diffuse ventilation or to pre-heat the supply air using a double façade [22] [23].

3.3.5 Norwegian building regulations

In addition to TEK, the working environment law – *Arbeidsmiljøloven* - is also valid for office buildings. The energy requirements in TEK sets an upper limit to the yearly energy use. For office buildings, the maximum value in the revised TEK (2016) is 115 kWh/m^2/year [24].

The main challenge facing passive buildings is a requirement to document the energy calculations according to the Norwegian Standard NS 3031:2014. NS 3031 gives a set of pre-set values that are required to be used in the energy calculations, including a set of minimum air volumes for ventilation during and outside of occupational hours [25]. The air flow rates are independent of the building emissions and actual need for constant ventilation. For a naturally ventilated building, it is vital to ventilate only when fresh air is needed to achieve a sufficiently low energy use and a comfortable indoor environment. The calculation method using constant air volumes both during and outside the occupational hours has a large influence on the energy use, and makes it very difficult to reach the required energy frame. It will not be sufficient to compensate with a reduced power consumption to fans, cooling and pumps [18]. If the night ventilation could be documented by another method, a controlled passive building could meet the requirements. The standard NS-EN 15251:2007 recommends venting of office buildings outside of the working hours to be done by supplying an amount outdoor air corresponding to two air volumes of the ventilated room before use.

In the report "Avanserte versus enkle tekniske systemer" by Grønn Byggalianse [4] three ventilation solutions based on the 2226-concept are investigated in a Norwegian climate. The first is a naturally ventilated solution, while the two others are hybrid solutions with CAV and different percentage of mechanical ventilation. Table 2 show how the energy use calculated according to project prerequisites differ from the energy use calculated based on NS 3031-calculations. As previously discussed, the passive solution cannot fulfill the energy requirements in TEK. However, the two hybrid solutions have a total net energy use below the maximum limit, and hence fulfill the energy requirement in TEK.

Table 2 Energy calculations of natural and hybrid ventilation according to NS 3031 and project requirements [4]

Energy post	**Alternative 1**		**Alternative 2**		**Alternative 3**	
	Natural ventilation		**Hybrid ventilation**		**Hybrid ventilation**	
			(CAV 2 m^3/m^2 h mech. vent)		(CAV 4 m^3/m^2 h mech. vent)	
	Energy use based on project prerequisites	Energy use based on NS 3031 calculations	Energy use based on project prerequisites	Energy use based on NS 3031 calculations	Energy use based on project prerequisites	Energy use based on NS 3031 calculations
	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]
1a Room heating	17.0	104.4	6.1	46.6	4.7	27.6
1b Ventilation heating	0.0	0.0	0.5	4.9	0.3	5.0
2 Domestic hot water	5.0	5.0	5.0	5.0	5.0	5.0
3a Fans	0.0	0.0	1.4	3.9	2.8	4.2
3b Pumps	1.0	1.0	1.0	1.0	1.0	1.0
4 Lighting	9.8	15.7	9.8	15.7	9.8	15.7
5 Equipment	31.1	34.0	31.1	34.0	31.1	34.0
6 Cooling	0.0		0.0		0.0	
Total net energy use	**64**	**160**	**55**	**111**	**55**	**93**
Requirement in TEK		**115**		**115**		**115**

3.4 Displacement ventilation

The air flow pattern in a ventilated room is mainly divided into two types; mixing ventilation and displacement ventilation. In mixing ventilation, the air flow is distributed so that the air is fully mixed and the concentration of pollutants is the same everywhere in the room. Displacement ventilation makes use of the buoyancy forces and creates a stratification effect where the air in the upper part of the room contains more contaminants than the air in the occupant zone. In this way, displacement ventilation can generally provide better air quality in the occupant zone than mixing ventilation [26].

Displacement ventilation is characterized by the formation of horizontal air layers. The warmest and most contaminated air layers are on the top, while the cooler and cleaner layers are in the lower part of the room. Vertical air movement is created by convection flows from heat sources and sinks in the room. Cold air is supplied at the lower parts of the room and rises as it is heated by warm objects such as people and equipment. The convection flow will rise all the way to the ceiling or settle in a lower height, depending of the power of the source, as seen in Figure 13. The supply temperature must be lower than the room air temperature in order to avoid short-circuiting. Vertical convection flows can also be created by warm or cold surfaces, as seen in Figure 12. This effect is present in buildings with exposed thermal mass.

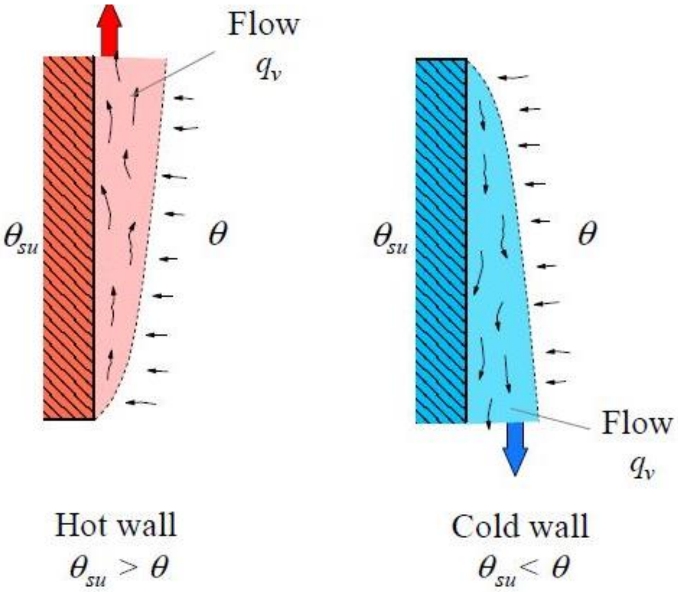


Figure 12 Convection flows at vertical surfaces [26]

Displacement ventilation creates a stratification effect, both regarding temperature and contaminant distribution. A practical approach to describe the vertical temperature distribution is to use the "50 % rule". The rule states that the air temperature at floor level is half-way between the supply and exhaust air temperature [26]. As cold air is supplied to the occupant zone, there is a potential risk of draught. The temperature stratification may also cause discomfort, as will be discussed in section 7.1.

The distribution of the contaminants depends on the position of the source and if the pollution source is a heat source. People are an example of warm contamination sources. In an ideal case, all contaminants from people will be transported into the upper zone by the convection flows created. Cold walls will create downward flows, bringing some of the contaminants back into the occupant zone. The contaminant distribution in a room with displacement ventilation can be seen in Figure 13.

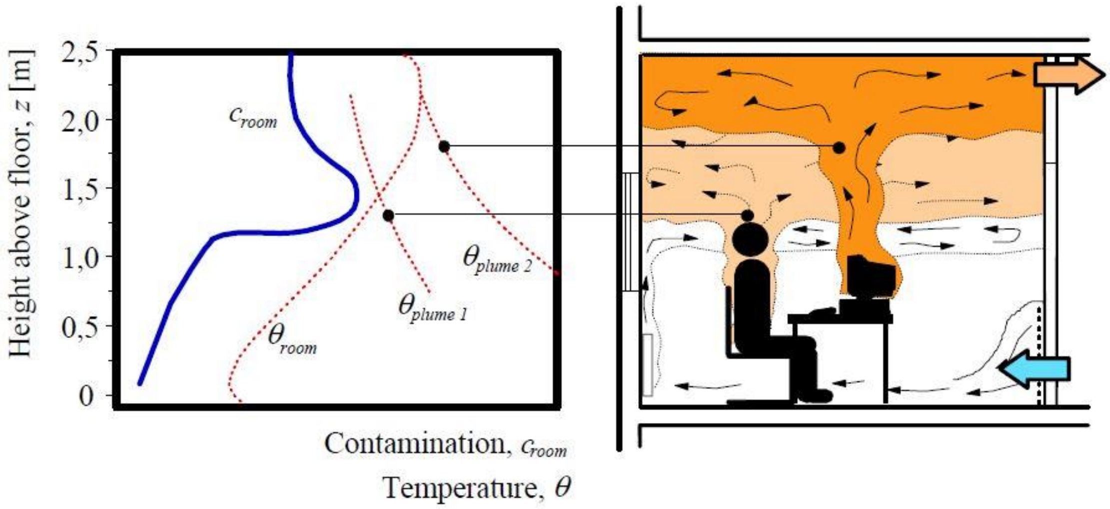


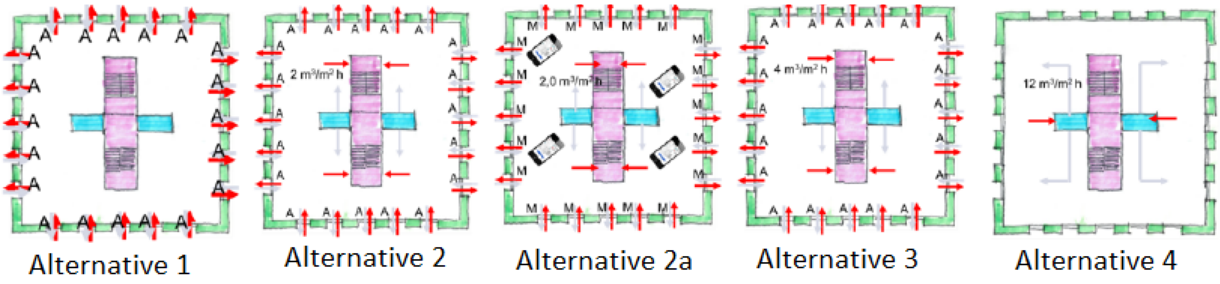
Figure 13 Contaminant distribution and air flow pattern in room with displacement ventilation [26]

The contaminant stratification is dependent on the relation between the rate of supply air and the convective flow rate. A sufficiently high air supply rate is important to keep a good air quality in the occupancy zone and maintain the horizontal layering. Displacement ventilation is only suitable for buildings with a sufficiently high floor height, normally of 2.5 m or more.

4 Life cycle cost and complexity

The choice of technical system affects the life cycle cost and complexity of a building. An advanced technical system can ensure low energy cost, but might have a high life cycle cost due to high investment and operating cost. Conversely, a less complex system might have a higher energy cost, but the total life cycle cost of the system is possibly lower.

A comparative study by Grønn Byggalianse [4] [27] show the difference in life cycle cost and complexity between five different technical solutions. The solutions evaluated are seen in Figure 14, and consists of a passive system corresponding to the solution in 2226 (alternative 1), two hybrid solutions with automatic windows (alternative 2 and 3), a hybrid solution with manual windows (alternative 2a) and a traditional mechanical system (alternative 4). Alternative 1-3 corresponds to the scenarios investigated in this thesis and are further described in section 10.1.



Alternative 1 Alternative 2 Alternative 2a Alternative 3 Alternative 4

Figure 14 Alternative technical systems investigated in [4]

An overview of the relative annual cost and energy use of the five solutions is seen in Figure 15.

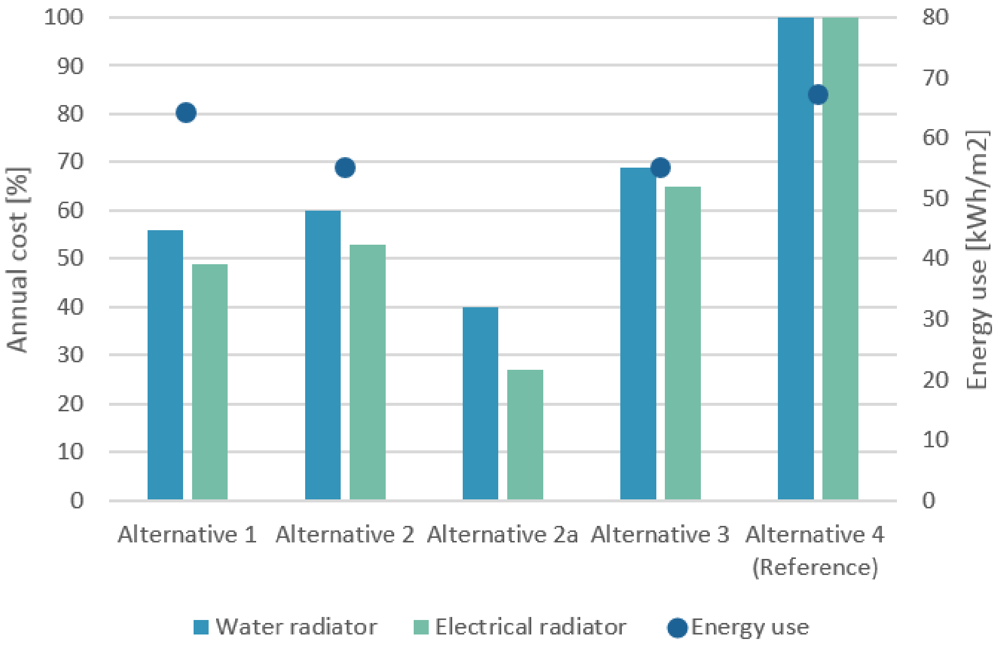


Figure 15 Annual cost and energy use of different technical systems [4]

The calculations show that the technical systems for natural and hybrid ventilation have a lower life cycle cost and annual cost than a traditional mechanical system in a 60 years perspective. The lower annual cost is a result of lower investment and operating costs. Regarding the energy use, the natural and hybrid systems have a somewhat lower energy use than the mechanical solutions, when the energy use is based on project prerequisites as discussed in section 3.3.5. Alternative 2a stands out as the least costly system in the analysis. The absence of window motors lowers the costs, but the energy use of the manual solution is difficult to predict, as it strongly depends on the behavior of the occupants and has therefore not been calculated.

In addition to the life cycle cost and energy use, the complexity of the technical systems is of importance. Systems with lower complexity are easier to operate and maintain since they are more comprehensible for the operational staff. Figure 16 shows the estimated total complexity and number of automatic components of the five technical solutions.

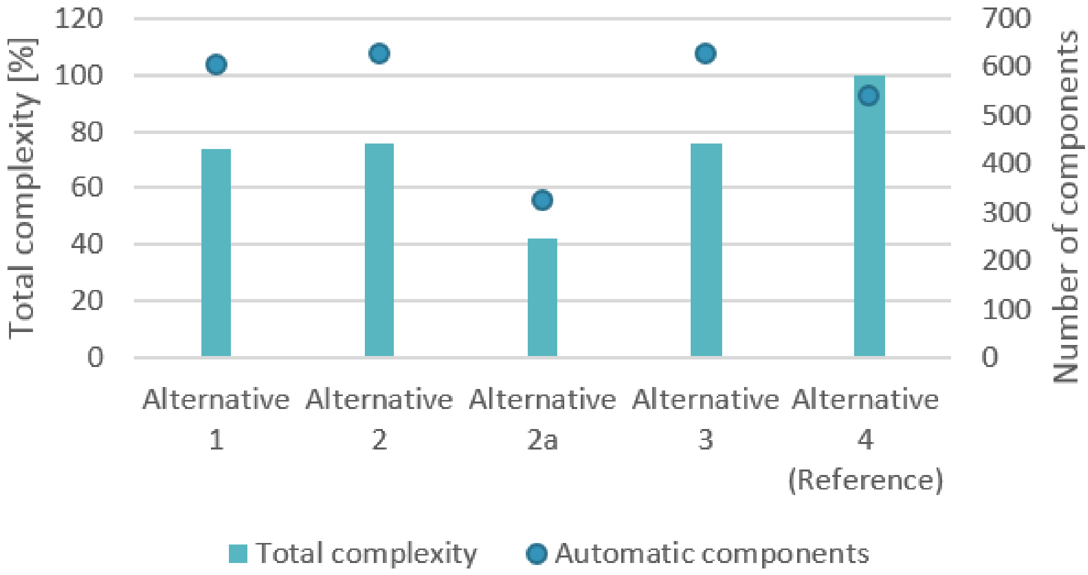


Figure 16 Total complexity and automatic components of different technical systems [4]

Alternative 1, 2 and 3 have a large number of automatic controlled windows. The window motors leads to a number of automatic components in the same scale as the traditional mechanical system. However, these control components are considered less complex than dynamic valves and dampers, as they are visible and more comprehensible. Consequently, the natural and hybrid solutions are estimated to have a lower total complexity. Alternative 2a with manual windows stands out as the less complex solution, having the fewest number of automatic components.

5 Example of 2226 building solution in Austria

5.1 The 2226 concept

In order to study a building with a simplified design of technical solutions, the building 2226 is an interesting case to study. 2226 was constructed by the architects Baumschlager Eberle, as a reaction to the increasing use of technology in modern buildings. Their goal was to prove it was possible to create a building with a good indoor environment without the use of mechanical heating, ventilation or cooling technology, but by clever use of architecture and exploitation of the environmental resources [28]. The building should be self-explanatory and give the user a sense of meaningful coherence between nature and technology. The name 2226 refers to the acceptable temperature range in the building. The system should ensure a comfortable operative temperature in the range of 22 to 26°C through the entire year [29], while keeping the CO_2-level below 1000 ppm.

Architects only know the first users of the building and cannot predict the behavior of the future tenants. Considering that a building should last between sixty and hundred years, it was important to make the building as flexible as possible. With the minimum use of technical installations and flexible floor plans, the building could easily be re-arranged and refurbished with a minimal amount of resources.

5.2 Location and climate

The building 2226 is located in Lustenau, a small town in the province Voralberg in the East of Austria. Lustenau lies in the Rhine Valley, at 400 meters above sea level. 2226 is positioned in an industrial area at the edge of the town, close to a residential area. The closest weather station to Lustenau is in Bregenz, a city located 15 km away. The area has a moderate climate with an average annual temperature of 9.3°C. The temperatures vary from an average of -3 °C on the coldest days of winter to an average of 24°C on the warmest days in summer. The annual average hours of sunshine in Bregenz is 1608 h [30].

5.3 Building construction and thermal design

The building geometry is cubical, with dimensions of 24 m. It is divided in six floors, with a gross floor area of 3200 m^2, and a net floor area of about 2400 m^2. The ground floor, which is used for expositions and a cafeteria, has a floor height of 4.6 m. The other floors, used as offices by Baumchlager Eberle and some other tenants, have a floor height of 3.75 m. All floors have the same floor plan, as can be seen in Figure 18. It is simple and open, with the flexibility to create different solutions.

Figure 17 Building Construction [29]

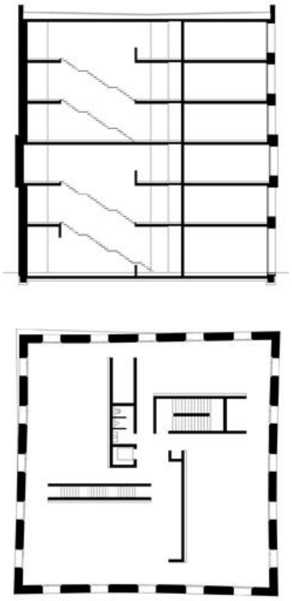


Figure 18 Floor plan 2226 [29]

The building envelope consists of two layers of brick. The inner layer is load bearing, while the outer part of the construction is isolating. The construction is massive and very air tight, with a wall thickness of 80 cm. This gives a high thermal inertia with the capacity to store heat over longer periods.

All vertical elements are in brick and the inner walls are load bearing. The structural floors are in concrete and a 20 cm elevated floor conceals the technical connections for water and electricity. Oak wood is used in doors and windows, while the walls are lime plastered. Passive design strategies are performed to create good daylight conditions and avoid over-heating from the sun. The windows are large and ranges to the ceiling. They are set flush with the interior walls, which shelters them from the direct sun radiation while adding additional diffuse daylight reflection. The good daylight conditions limits the energy consumption due to lighting in the building. There is no external solar shading, but curtains are installed to prevent glare and to improve the acoustic conditions.

As previously mentioned, 2226 is a building without traditional heating solutions. Being an office building, the internal loads are high, and the cooling need is dominant through large parts of the year. Heat from the computers and the users is the main heat source. Additionally, the lighting systems can be activated during cold periods or periods with low internal gains to create a “back up” of heat in the building. In combination with the exposed thermal mass, the building can store excess heat in the construction in periods with high internal gains and release it at times when there is a heating demand. This diminishes the temperature variations, and in combination with an optimized control system for ventilation, it eliminates the need of a traditional heating system. Cooling is solved by the use of natural ventilation and free cooling.

5.4 Ventilation solution

In 2226 the ventilation of the building is solved by using integrated energy design. Natural ventilation through vents in the façade works together with the thermal mass to create a good indoor environment throughout the year. Since the building has no mechanical ventilation or cooling system, it relies solely on natural driving forces for ventilation. Beside each window, a vent opens when fresh air is needed. The rural location of the building ensures a good ambient air quality, where fresh air can be taken directly into the building without being filtered or treated.

The façade ventilation is demand controlled by the indoor temperature- and CO_2 -level. The concept implies that the temperature should remain between 22 and 26°C while not exceeding a CO_2-level of 1000 ppm. The greatest challenge is to maintain an acceptable air quality in the extreme cases in summer and winter when the outdoor temperature is either very high or very low. The building control system was thoroughly developed and optimized before construction, to find the best possible adjustment points. During winter, the venting must ensure a sufficiently good air quality while not letting the room temperature drop below the comfortable range. Studies of the building show this is feasible if the temperature already is high before venting [28]. During summer, passive night ventilation is utilized to cool down the construction. The cooler surface temperatures of the construction help cooling the rooms during the day. Precise investigations of the airflow pattern in the building is needed to optimize and utilize effect of passive night ventilation.

The use of a CO_2-controller takes into account the dynamic behavior of occupants. The vents supply fresh air based on the need (the CO_2-level is a function of the number of people present) in contrast to conventional calculation of airflow rates, which is based on average density of occupation. By controlling the venting according to need, the air exchange rate is significantly reduced [28]. Sensors placed in sitting height in each room (about 1.2 m above the floor) register the levels of temperature, CO_2 concentration and humidity. Additionally, a weather station that records the external temperature, wind and light conditions is placed on the roof. The data is communicated to the software system that controls the vents. The temperature and CO_2 levels are displayed on a screen in each landscape, where daily, weekly and monthly variations can be monitored. A possibility to overrule the automatic venting with the software screen allows the user to control the environment to some degree. The vents will however be automatically closed after ten minutes. Pictures of the window solutions and vent openings are seen in Figure 19.

Figure 19 Windows and vents 2226

The ventilation concept is based on displacement ventilation. The high floor height creates a stratification effect where warm and polluted air rises to the ceiling. This gives better air quality in the occupant zone, and reduces the need for airing. The supply of air to each floor is done by a combination of cross-ventilation and one-sided ventilation. The cross ventilation performed by opening vents at the corners, while the one-sided ventilation is done by venting on only one of the facades. The two ventilation principles are illustrated in Figure 20 and Figure 21. During cold periods, the venting is conducted by pulse ventilation to reduce the risk of draught. Additionally, air is exhausted from the central wet core.

Figure 20 One-sided ventilation in 2226

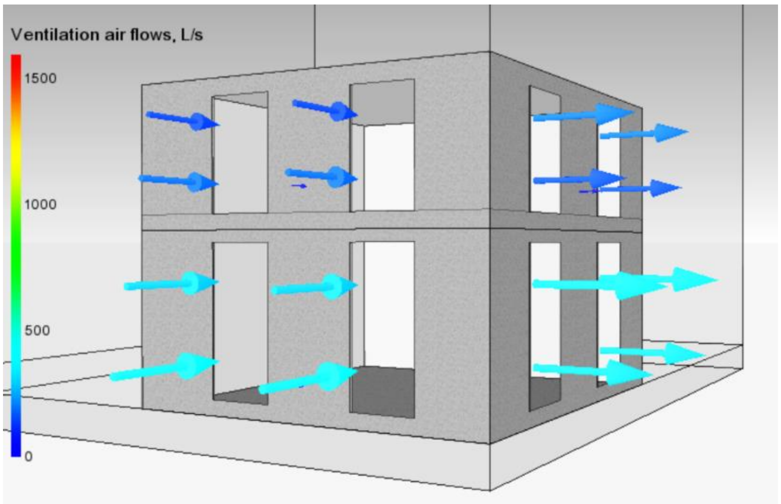


Figure 21 Cross-ventilation in 2226

The shape of the vents is vertical to make use of the stack effect. The temperature stratification leads to an overpressure at the upper part of the vent and an under pressure at the lower part. When the vents are opened and the ambient temperature is lower than the indoor temperature, the warm and polluted air is extracted from below the ceiling, while fresh and colder air is supplied to the occupant zone. The vents are placed on the northern part of the windows to avoid sun-affected air entering the building and they have a maximum opening of 45° to keep out unwanted objects such as leaves and birds.

Over a year after completion, the system shows an impressive stability. Measurements from the building during operation are seen in Figure 22 for four months during different seasons in 2014 and 2015. As seen in the figure, the indoor temperature remains within the 22 and 26°C even though the outdoor temperature varies much over the year. The concentration of CO_2 has a general level below 1000 ppm [28], and varies according to the occupancy of the building. During the two first years, the lime plaster will absorb some of the CO_2 from the room. Thus, the real CO_2-levels cannot be evaluated before the effect seizes to exist.

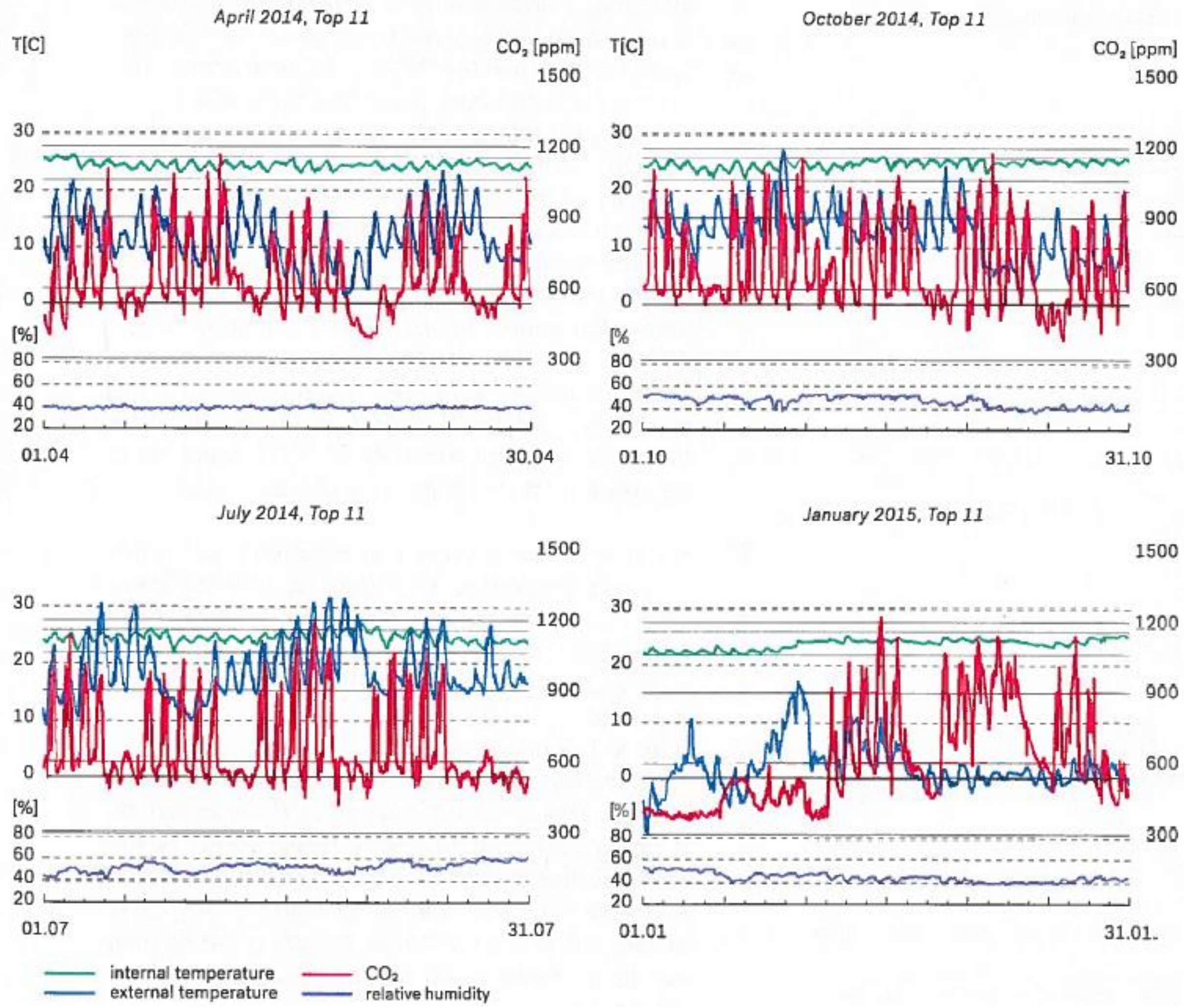


Figure 22 Registered indoor environment in 2226 [28]

5.5 Energy use

Since 2226 has no conventional heating, cooling or mechanical ventilation, the energy use in the building is limited to an electricity consumption. This includes electricity use for the elevator, kitchen, art gallery and offices. During the first year (December 2013 to December 2014), the specific energy consumption was 38 kWh/m^2 [28]. It must be mentioned that the two upper floors were hardly used during the first year, giving a somewhat lower energy-consumption in this period than what will be expected in the time to come. Furthermore, as the different parts of the building has different use (cafeteria, gallery and architectural offices) the energy consumption of the different parts varied a lot.

6 Example of an integrated ventilation solution in Norway

Powerhouse Kjørbo in Sandvika is an example of a building in Norway with an integrated energy design solution. The office building from the 1980's was refurbished into a building with a high level of energy and environmental performance, receiving a BREEAM Outstanding certificate for the design phase. Powerhouse Kjørbo does not have hybrid ventilation, but a simplified mechanical ventilation system that is coupled with thermal mass and can store heat, exploit passive night cooling, and allows the users to open the windows to some degree. Air is supplied through a central core, while the stairs are used as ventilation shafts. The ventilation solution is based on two main principles: the use of the building construction as supply ducts and the use of displacement ventilation. The heating system in the building is also simplified, with radiators placed at the central core. In the open offices, the heat is supplied directly to the zones, while in the single offices heat is distributed through the door to the corridor or the open landscape.

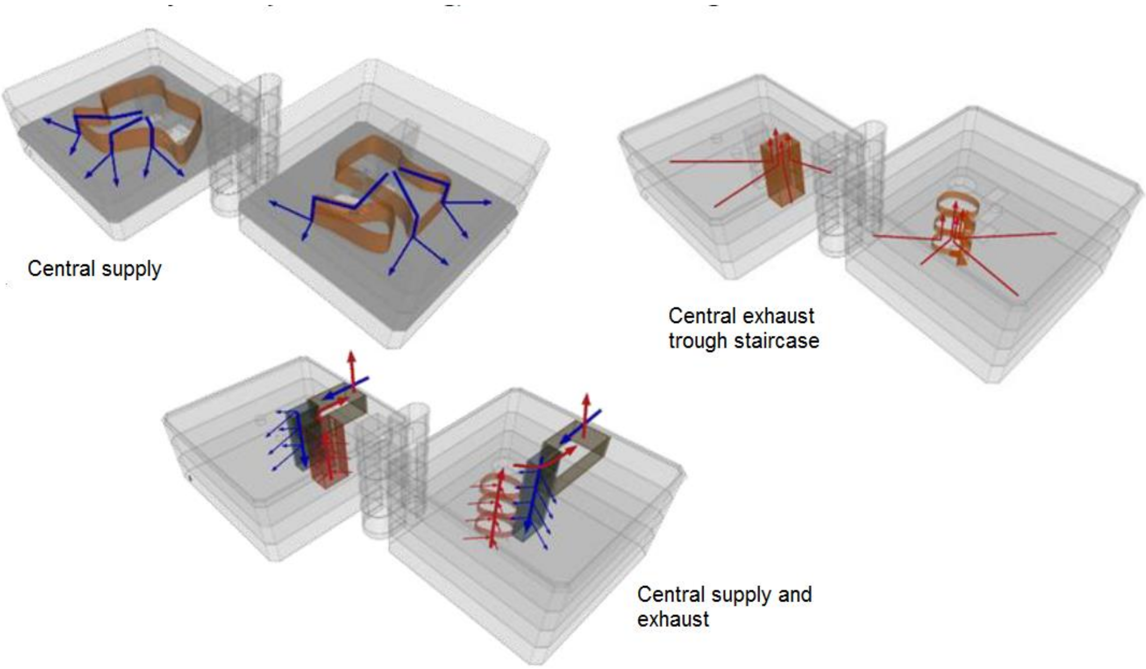


Figure 23 Integrated ventilation solution in Powerhouse Kjørbo [4]

After a year of operation, the solutions prove to give a good indoor environment and a high energy performance [31]. The measured total energy use is 54 kWh/m^2 when excluding the energy use related to the server room [32]. An overview of the energy budget and measured energy in Powerhouse Kjørbo is found in the appendix.

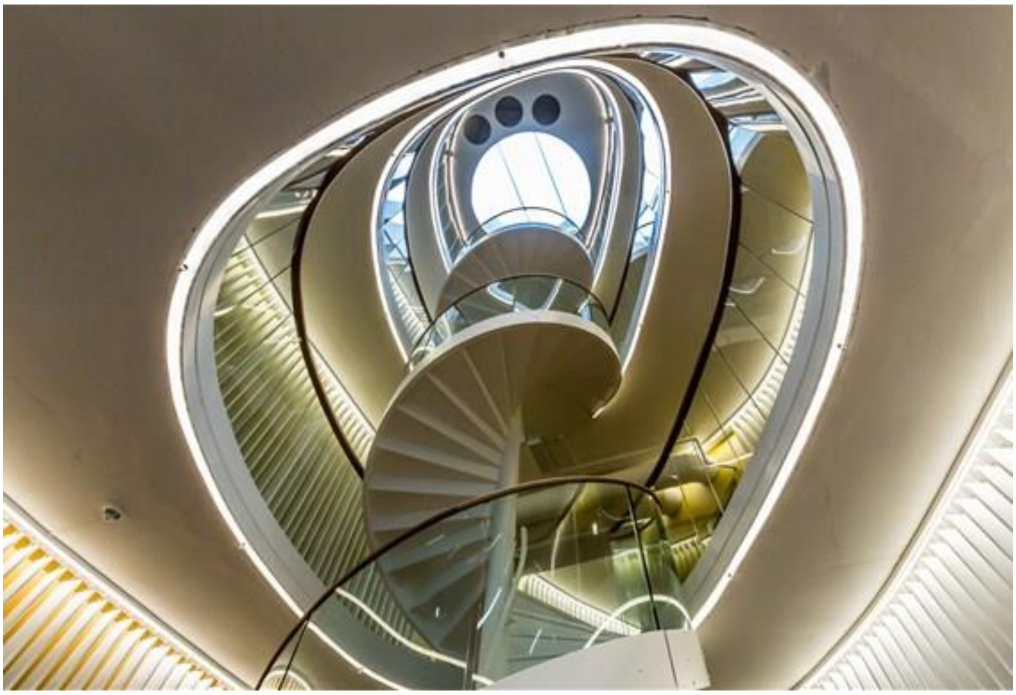


Figure 24 Integrated ventilation - exhaust and stair case [33]

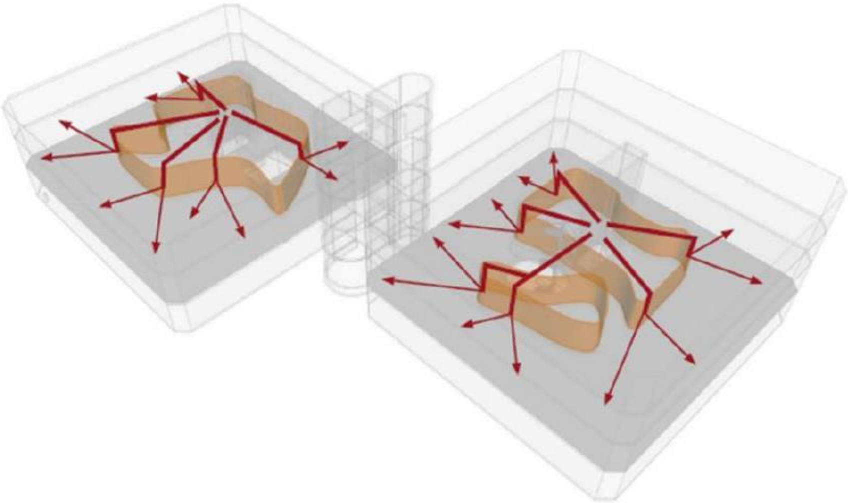


Figure 25 Simplified heating system, Powerhouse Kjørbo [4]

7 Indoor environment

Buildings are created to provide shelter and a comfortable environment for the users. A good indoor climate is important to ensure human comfort and health, and to provide good working environment in work spaces [34].

The indoor climate can be defined as a composite of five main elements:

- Thermal environment
- Atmospheric environment
- Acoustic environment
- Actinic environment
- Mechanical environment

As this report investigates generic building design in Norwegian conditions with focus on heating and ventilation strategies, the thermal and the atmospheric environment will be further discussed.

7.1 Thermal environment

The standard «ISO 7730:2005 Ergonomics of the thermal environment» defines thermal comfort as “that condition of mind which expresses satisfaction with the thermal environment” [35]. Thermal comfort is achieved when a person experiences thermal equilibrium between the body and the surrounding while having satisfied his/her expectations to the surroundings [36].

Two main models are described in comfort standards to evaluate the thermal comfort and the user satisfaction in buildings. The first model is the heat balance method developed by Fanger in the 1970’s, and the second method is the adaptive approach, which has gained attention in the recent years. Experts disagree on the accuracy and validity of the two models for different climates and building types. Some argue to use solely the heat balance method, while others claim the adaptive approach should be more emphasized.

7.1.1 The heat balance approach

The heat balance approach developed by Fanger is the most implemented approach. The method is based on the heat transfer mechanisms of the human body and extensive experiments conducted in climate chambers. The method describes the percentage of people who will be dissatisfied under different conditions given a certain air and mean radiant temperature, air speed, humidity, activity (metabolic heat production) and clothing level.

The heat balance of the human body is given by:

$$S = M\text{-}W\text{-}C\text{-}R\text{-}E_{sk}\text{-}C_{res}\text{-}E_{res}\text{-}K \ [W/m^2] \qquad [3]$$

where:

S	Heat storage in the human body
M	Metabolic heat production
W	External work
C	Heat loss by convection
R	Heat loss by radiation

E_{sk}	Evaporative heat loss from skin
C_{res}	Convective heat loss from respiration
E_{res}	Evaporative heat loss from respiration
K	Heat loss by conduction

When a person experience thermal equilibrium, the heat storage in the body is equal to zero. A negative heat storage indicates too cold environment (heat loss) and a positive heat storage indicates too warm environment [36].

Thermal comfort is described by the general thermal comfort and the local thermal comfort. The general thermal comfort is according to the heat balance method affected by the operative temperature, the air velocity and humidity. Local thermal comfort is determined by draught, vertical temperature differences and the surface temperature on the floor [37].

The heat balance method quantifies the thermal comfort using the parameters PMV and PPD. The predicted mean vote (PMV) predicts the mean vote from a large group of people on a seven-point comfort scale. The scale has the rankings -3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot. It is based on the activity- and clothing level as well as physical factors such as air temperature, mean radiant temperature, air velocity and humidity [35]. As the individual votes are scattered around the PVM, the PPD indicates the number of people who are dissatisfied under different conditions. The PPD is derived from the PMV and the two factors have the relation seen in Figure 26.

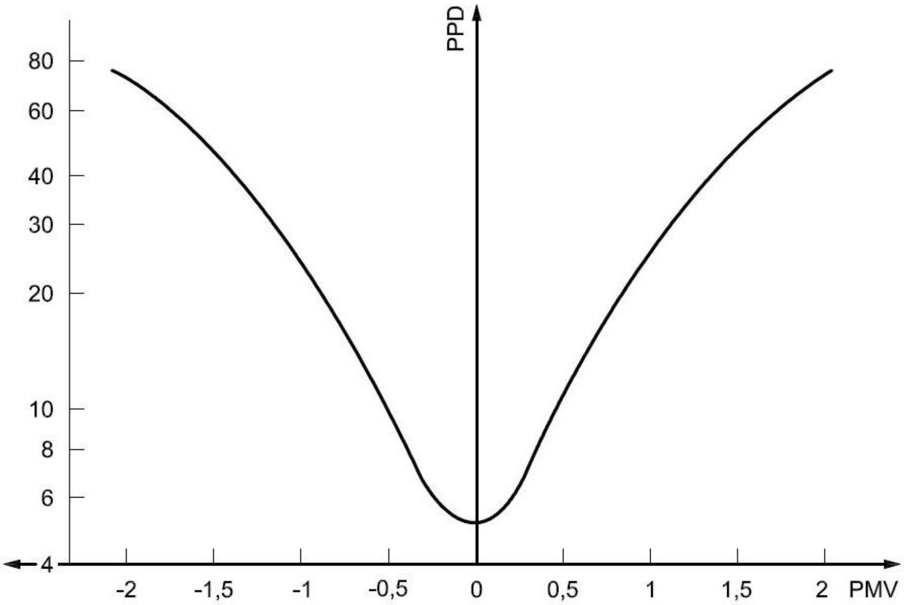


Figure 26 Relation between PMV and PPD [35]

As seen in Figure 26, PMV = 0 indicates that 5 % of the occupants are dissatisfied. Consequently, all occupants will be never be satisfied due to individual differences in preference and sensitivity. PMV = ± 0.5 corresponds to 10 % dissatisfied. A general overview of the relation between the activity level, clothing and comfortable operative temperature derived from the heat balance method is given in Figure 27.

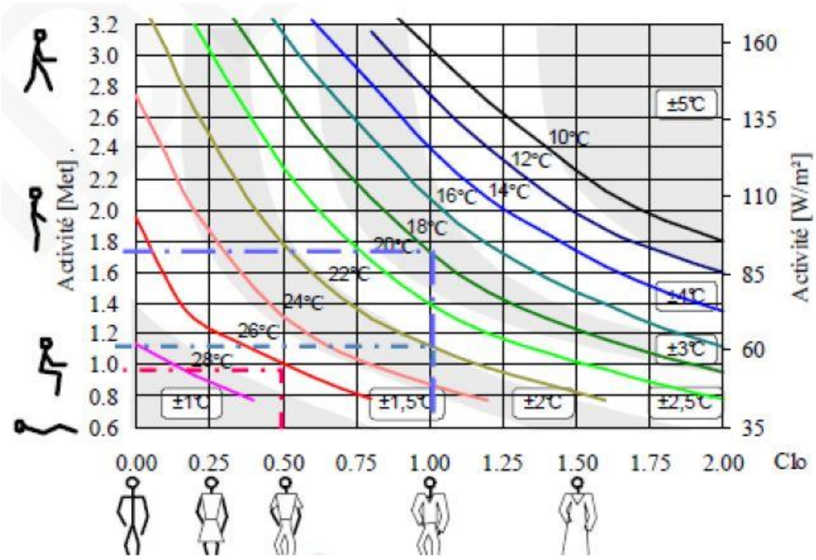


Figure 27 Relation between clothing, activity and operative temperature [38]

NS-EN 15251 gives recommendations for the dimensioning indoor temperature during summer and winter conditions. The recommendations are valid for buildings with mechanical heating and cooling systems. For an office building of category II (PPD < 10 % and -0.5< PMV< +0.5), the recommended minimum temperature in winter is 20°C (1.2 met and 1.0 clo) and the maximum temperature in summer is 26°C (1.2 met and 0.5 clo). With an exception of workplaces that have a specific dress code all year around, most people adapt to the changes in outdoor temperature by dressing differently during winter and summer. A more precise indication of a comfortable indoor temperature interval during summer and winter is given in the ASHRAE standard 55-1992. For an office building with the category B, corresponding to category II, the operative temperature is recommended to be 23-26°C during summer and 20-24°C during winter.

TEK10 does not distinguish between winter and summer conditions with corresponding clothing level. For light work, an operative temperature of 19-26 °C is recommended [21]. The temperature is allowed to exceed 26 °C for 50 h in a normal year. Furthermore, the Norwegian labor inspection authority recommends keeping the temperature below 22°C during the heating season to ensure a high degree of productivity [39].

The operative temperature and PMV-model indicates the thermal sensation of the body as a whole. A person can however experience discomfort due to cooling of a local part of the body. Draft is the most common reason for complaints on the thermal environment [34]. Draft is a combination of the air velocity and the turbulence intensity, which can give a local discomfort. It may occur when the mean air velocity exceeds about 0.15 m/s. In warm conditions, draft can however be perceived to give improved comfort [37]. Other factors that might cause local discomfort are vertical temperature gradients and radiant asymmetry. According to TEK10, a vertical difference in air temperature of more than 3-4 °C between head and feet should be avoided as it gives unacceptable discomfort. The same is valid for daily or periodically temperature variations of more than 4 °C [21].

7.1.2 The adaptive approach

Many studies have been conducted on the thermal comfort of buildings in operation. Some of the studies support the heat balance method, while others have found discrepancies between the heat balance theory and the thermal comfort response of the occupants [36]. Brager and de Dear presented an extensive literature review (1998) where they criticized the assumed universal applicability of the heat balance method in all climates and for all building types [40].

One of their main findings was a significant difference between the thermal responses from occupants in naturally and mechanically ventilated buildings. They found that occupants in naturally ventilated buildings had more relaxed expectations and accepted more fluctuations in temperature, while occupants in mechanically ventilated buildings were more sensitive and had more strict expectations to a uniform thermal environment. In addition, people in the naturally ventilated buildings preferred indoor temperatures that tracked the trends of the outdoor temperature to a higher degree during the summer season. Brager and de Dear concluded that these differences most likely results from the past thermal history of the naturally ventilated buildings (people have accepted that the indoor climate varies to a larger degree) and their experience of a higher level of perceived control. As a result, de Dear and Brager argued for applying an adaptive approach to thermal comfort in naturally ventilated buildings [40] and have gained support by other researchers such as Nicol and Humphreys [41].

In contrast to the heat balance method where the occupant is considered as a passive recipient, the adaptive approach is built on the principle that people tend to adapt to changes in their environment. If a change occurs and produces discomfort, people tend to react in different ways to restore their comfort [41]. The adaptation can be behavioral (people can change clothing, open or close windows, or regulate ventilators), physiological (the human body experience acclimatization) or psychological (the occupant can change his/her expectation) [40]. The literature study performed by Brager and de Dear [40] indicated that thermal acclimatization is less relevant, while behavioral adjustment and expectation has a much greater influence.

The adaptive approach describes the indoor comfort temperature as a function of outdoor temperature only [42]:

$$T_{comf} = A*T_{a,out} + B \qquad [4]$$

where:

T_{comf} comfort temperature [°C]

$T_{a,out}$ monthly mean outdoor temperature [°C]

A,B constants

NS-EN 15251 has included the adaptive approach for the dimensioning of indoor temperatures in naturally ventilated buildings during summer conditions [43]. The approach is only valid for office buildings where people are performing sedentary activities and the users can easily regulate their environment by opening the windows. It is also of importance that the users can adapt their clothing according to the outdoor temperature. The extended temperature levels are dependent on the outdoor temperature and the chosen building category, as seen in Figure 28. For winter conditions and running mean air temperature below

15°C, the adaptive comfort model is similar to the heat balance model [36].

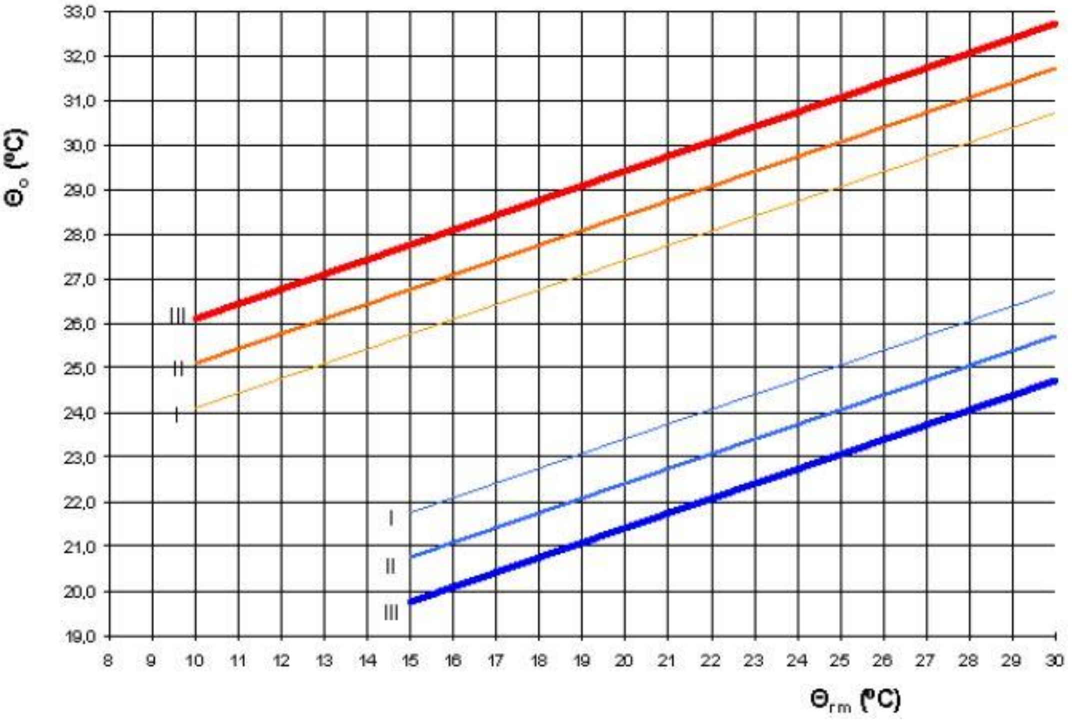


Figure 28 Dimensioning indoor temperatures, buildings with no mechanical cooling system [43]

Θ_{rm} = Outdoor running mean temperature [°C]
Θ_o = Operative temperature [°C]

The critics of the adaptive approach claim it oversimplifies the comfort charts by basing the indoor thermal comfort on outdoor temperature only, and that the psychological adaptation and expectation hypothesis lacks experimental or survey data [42]. Based on this extensive literature study, Halawa and Hoof raised the question if there is a need for a separate approach and separate standards for naturally ventilated buildings. They stressed that it is positive to have comfort standards based on findings in field studies, as people spend time in real buildings and not in laboratory environments. However, their opinion is that the findings from the adaptive field surveys should be used to improve the applicability of the heat balance approach by modifying the existing coefficients in the heat balance formula. By integrating the adaptive field studies in the heat balance method, Fanger's comfort indices could be extended to better comprehend thermal comfort conditions in naturally ventilated buildings.

7.1.3 Hybrid ventilated buildings and comfort standards

Buildings with hybrid or mixed mode-ventilation cannot be characterized as either mechanically or naturally ventilated buildings. They constitute a combination of the two, and can operate along a scale from almost 100 % mechanically ventilated to almost 100 % naturally ventilated.

Since the adaptive model is valid for naturally ventilated buildings during summer, it can be applied for hybrid buildings during times when they are not employing mechanical cooling. However, when the outdoor temperature drops below a certain level, the adaptive model is no longer valid and the heat balance method should be applied. It is challenging to perform an over-all comfort analysis where the two cases are taken into consideration during a year, as the outdoor temperature and the ventilation mode may vary during a day, week or month. There is a general lack of guidance in building standards on how to evaluate comfort in mixed mode buildings [44].

In buildings with natural or hybrid ventilation, the indoor temperature may exceed the comfort conditions at times, i.e. during periods with warm weather or during venting at cold days. To describe the general thermal comfort is important to predict the severity and duration of these episodes. A potential method to evaluate the discomfort is to calculate the comfort exceedance by accounting for the accumulated time where the indoor conditions exceed the defined comfort conditions [44].

7.1.3.1 Long-term evaluation of thermal comfort in NS-EN 15251

NS-EN 15251 proposes methods for long-term evaluation of the thermal comfort in buildings based on exceedance [43]. Annex F and G describes three methods and recommendations on acceptance:

A) *Percentage out of the range*
B) *Degree-hours criteria*
C) *PPD-weighted criteria*

Method A evaluates the percentage of occupied hours where the PMV or the operative temperature is outside of a specified range. Method B evaluates the exceedance of the operative temperature and weights it with a factor based on the number of degrees of the exceedance. Method C evaluates the exceedance uses a weighting based on PPD. The method B in Annex F of NS-EN 15251 is more thoroughly described in the following section as it is later used to evaluate the results.

<u>*Method B*</u>

The weighting factor *wf* is equal to 0 for times where the operative temperature Θ_o is within the limits for comfort temperature. At times where the temperature exceeds the limits, the weighting factor is calculated as

$$wf = \Theta_o - \Theta_{o,limit} \qquad [5]$$

when

$\Theta_o < \Theta_{o,limit,\ lower}$ or $\Theta_{o,limit,\ upper} < \Theta_o$

For a characteristic period of a year, the product of the weighting factor and the time is summed up, and the sum of the product is expressed in hours.

Warm period:

$\sum wf * tid$ for $\Theta_o > \Theta_{o,\text{limit, upper}}$

Cold period:

$\sum wf * tid$ for $\Theta_o < \Theta_{o,\text{limit, lower}}$

Acceptable values for exceedance are 3 % or 5 % of the occupant hours.

7.2 Atmospheric environment

Indoor air quality is a term with many definitions. According to Nilsson [34] the term indoor air quality is used as "a general denomination for the *cleanliness of indoor air*." ASHRAE, the American Society of Heating Refrigeration and Air conditioning Engineers, define an acceptable indoor environment as "air in which there are no harmful concentrations of contaminants as determined by cognizant authorities and with which 80 % or more of the exposed occupants do not express dissatisfaction" [45].

Factors affecting the perceived indoor air quality are:

- Olfatory sense
- Humidity and temperature
- Duration of exposure

The indoor air contains various groups of pollutants, and is affected by factors from both the external and the internal environment. External sources of pollution are natural sources, and human activity such as traffic and industry. Internal sources are pollution from humans, emissions from building materials and processes producing indoor pollution.

Due to large differences in the sensitivity of individuals, occupants may perceive the air quality in a room very differently. A commonly used indicator for air quality is the concentration of CO_2 in the room. The Norwegian labor inspections recommends an upper limit of 1000 ppm in the guide "Veiledning 444" [39]. NS-EN 15251 point out that it is the difference in concentration between indoor and outdoor that should be applied, not an absolute value. For a building of class II, the standard allows the CO_2-concentration to be 650 ppm higher indoor than outdoor.

The Norwegian Building regulation and the Norwegian labor inspections have set requirements for the minimum air flow rates allowed in office buildings. If there are no specific requirements due to processes, the necessary air flow rate is given by the sum of the rates due to humans contaminants and emission from materials (low emitting materials are required). The values of the required air flow rates in TEK are shown in Table 3. The Norwegian labor inspections distinguishes the air flow rates due to emissions depending on the type of material present. For well-documented low-emitting materials, air rates down to 0.7 L/s*m^2 are acceptable. If what the recommendation calls "normal materials" are used, an air flow rate of 2 L/s*m^2 is reasonable.

Table 3 Air flow requirements in Norwegian building regulations [16]

Air flow per person [m^3/(h*person)]	Air flow rate due to emissions [m^3/(h*m^2)]	
	During occupancy hours	Outside of occupancy hours
26	2.5	0.7

Table 4 Air flow requirements given by the Norwegian labor inspection authority [17]

Air flow per person [L/(s*person)]	Air flow rate due to emissions [L/(s*m^2)]
7.0	0.7 - 2

8 Modelling of energy related human behavior

Energy simulation tools are widely used to predict the energy consumption and indoor environment of buildings. They are mathematical representations of the building's physical properties and can predict the building's thermal behavior according to the chosen climate data and project prerequisites. A general problem with building simulations is that there is often a significant discrepancy between the predicted energy use and the energy use measured during operation [46]. The reason for this discrepancy may be due to human behavior and human interactions with building controls [47] [48].

Building simulation is a deterministic representation based on some key assumptions related to i.e. schedules for occupancy, window openings, set-point temperatures and use of equipment. In reality, people will not act according to fixed schedules, and their attitudes and preferences to the indoor environment will vary widely. People's behavior is of a more stochastic nature, with a certain probability for an action or an event. According to [46] the accuracy of building energy simulations are undermined by a poor representation of the stochastic variables that relate human interactions with the control of the indoor environment.

8.1 Occupant's window opening behavior

How can human behavior be modelled and predicted? Many studies have been conducted to examine how people interact with energy-related building control such as opening and closing of windows, adjustment of blinds and heating set points. The studies have examined occupant behavior in different types of buildings (office/residential) over variable observation periods (winter, summer, full year, short term, long term) and in various climates with the aim of describing the driving factors of occupant behavior [48]. As the use of natural ventilation is a main aspect in this thesis, occupant window-opening behavior in office buildings is further discussed.

As previously discussed in section 7.1.2, field studies have found that occupants in naturally ventilated buildings prefer higher indoor temperatures in summer than occupants in mechanically ventilated buildings. According to the adaptive hypothesis, a person who experience a change that produce discomfort will react in a way to restore his/her comfort. A field study [49] was conducted in a naturally ventilated building in California during two seasons (warm/cool), where the occupants had varying degrees of control over the windows. The occupants experienced the same thermal environment and had the same clothing and activity level. However, the study showed that occupants with different degree of personal control of had significantly different thermal responses. The occupants with a higher degree of control reported an ideal comfort temperature that was much closer to the temperature they actually experienced than those with less personal control. Hence, the study that the perceived direct control of a person's thermal environment is of great importance.

An extensive literature study in [47] highlights that occupant behavior related to opening and closing of windows are complex processes. Occupant behavior in buildings is influenced by many factors, such as external factors (e.g. air temperature, wind speed), individual factors (personal background, attitudes, preferences) and building properties (ownership, available openable windows). There is no general agreement of what are the most important driving forces for occupants window opening and closing behavior, and there is especially a discussion on whether the indoor or the outdoor is the best predictor in building simulation. Furthermore, there is a lack of understanding the relationship between indoor air quality and window opening, and the degree of opening is in most studies ignored.

Another literature study [48] found some general parameters influencing window opening and window switching. The season, temperatures, time of the day and previous window state seems to be of importance for window opening. According to the literature review, there is a strong correlation between of window opening behavior according to season. In naturally ventilated buildings, the percentage of windows open was found to be highest in summer, lowest in winter and intermediate in summer and spring. Moreover, there was a difference in the window opening frequency, where the highest frequency in change of the window opening status was found in spring and autumn while a lower frequency was found during summer, as the windows then stay open for longer periods. Concerning the time aspect, many field studies showed that window control activities most often occurred at the arrival of the occupants in office buildings.

Regarding window switching, [48] found that during the heating period the main reason why people open the window is to get more fresh air. The reason why people close the windows is then to prevent cold air entering the room. During non-heating periods, two reasons were found for window-opening; desire for fresh air and a wish to cool down the room or prevent further increase in temperature. The main reason to close the window during non-heating periods seemed to be to prevent hot outside air (with a higher temperature than the interior) entering the building, causing a further increase in room temperature.

Both [47] and [48] emphasize that most studies have been conducted in single offices, and question how people will behave in shared offices. In addition to the physical factors, social aspects such as the hierarchical relation between colleagues and the number of people controlling a given set of windows might also be of importance.

Based on field studies, several statistical models have developed to describe window opening behavior in office buildings using logistic regression analysis, Markov chains, continuous-time random process and Monte Carlo method [50] [51] [52] [53] [46]. Haldi and Robinson [51] examined statistical methods on a dataset from seven years of continuous measurements of window opening and closing behavior in office buildings in Switzerland and Fabi et al. [46] presented a procedure for modelling energy related human behavior which is further discussed in section 8.2.

8.2 A procedure for modelling energy related human behavior

A possible procedure for modelling energy related user behavior by introducing a probabilistic approach in simulation programs is described in [46]. The philosophy of the method is to have stochastic input parameters, which results in a probability distribution rather than a single simulation output. An overview of the proposed method is shown in Figure 29.

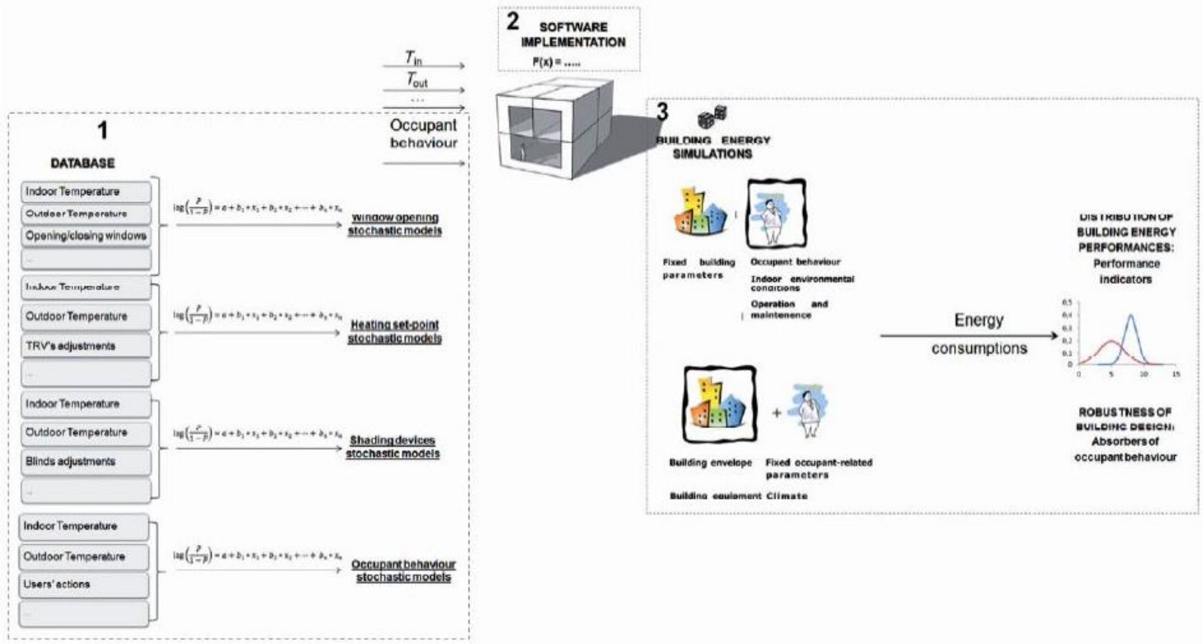


Figure 29 A probabilistic approach to model the human behavior in buildings [46]

Practically speaking, the method first requires the development of a database based on continuous measurements of a building. Indoor environmental parameters, external climate conditions and the behavior of the building occupants related to e.g. window openings, set-point values of thermostats and occupancy needs to be monitored and evaluated. Based on the measurements/surveys, a suitable user behavior model must be defined using statistical analysis. Examples of possible statistical analysis are logistic regression and Markov chain. The behavior model should then be implemented in a dynamic simulation tool (IDA ICE, Esp-r, etc).

As most simulation programs are deterministic, there is a need to translate the probability of an event into a deterministic signal. [46] proposes this can be done by comparing the probability of the event to a random number, to determine if the action will take place or not. If the value of the probability exceeds the value of the random number, the action will occur. Further, the simulation must be run multiple times to describe the possible outcomes of the human behavior. Finally, the building's energy consumption and indoor environment is described through a probability distribution.

9 Methodology

Four possible strategies to make buildings more flexible and generic in a Norwegian context have been investigated by the use of the dynamic simulation tool IDA Indoor Climate Energy. IDA ICE was chosen as simulation tool because it enables simulations of natural and hybrid ventilation through window opening control. In addition to basic modules, IDA ICE gives the possibility to develop own modules and create new window controls. Moreover, IDA ICE provides thermal comfort evaluations based on both the heat balance and the adaptive method. Matlab was used for post-processing of data.

A model of an office building with a simplified heating and ventilation strategy was developed together with the co-supervisor from Asplan Viak, and is thoroughly described in section 10. Simulations and parameter studies were conducted on three models with natural and hybrid ventilation having automatic controlled windows. In the parameter study, the effect of night cooling, heat capacity of the construction and internal loads were investigated. Furthermore, an attempt to model user behavior and manual control of windows was tested.

As discussed in section 8.2, a possible method to model human behavior in buildings is to introduce a probabilistic approach in simulation program. Ideally, human interaction with building controllers in a representative building should be monitored, and a behavioral model should be developed and implemented in a simulation program. In this thesis, an appropriate database for a similar office building in Norway has not been accessible, and thus a slightly different approach has been chosen. A window controller was developed in IDA ICE to model manual window openings of users being stimulated by an app. The controller included probabilities for window openings based on information derived from literature and is further described in section 10.5. To account for the stochastic behavior of occupants, versions with varying user profiles were run multiple times using different files of random numbers, as shown in Figure 30. As recommended in [46], this approach could generate results on the form of a probability distribution, indicating the possible outcomes of energy use and indoor environment conditions.

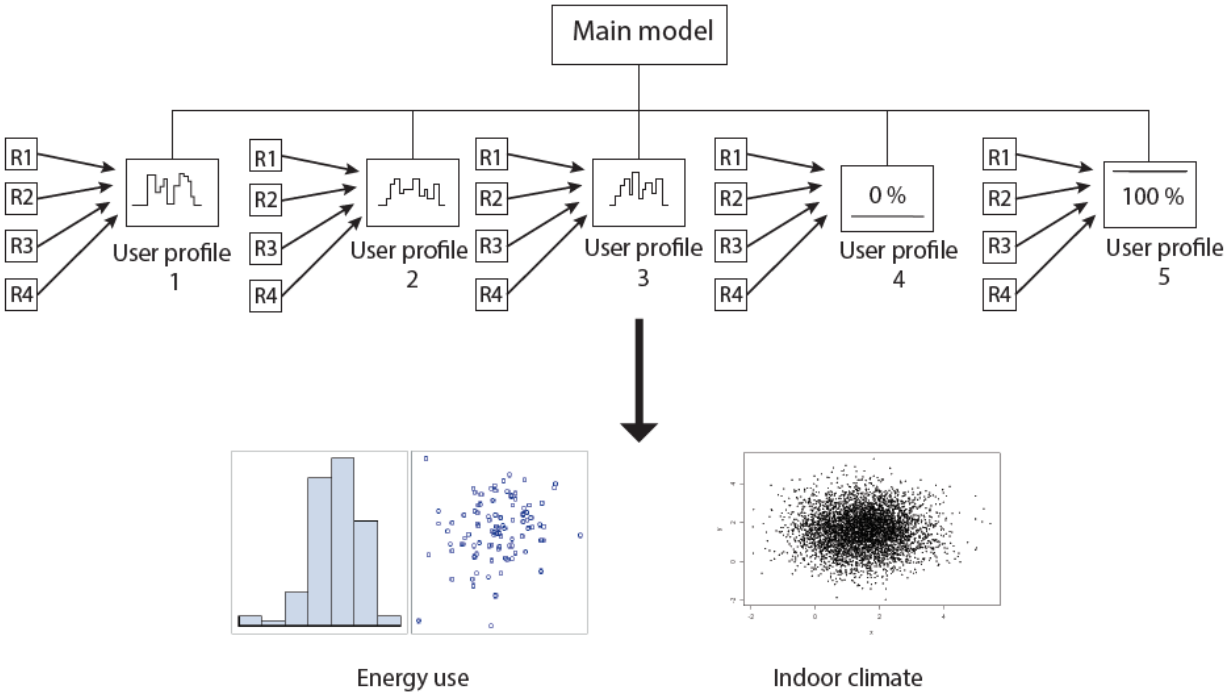


Figure 30 Simulation procedure, manual window control

Due to the rapid temperature changes with the use of natural ventilation, an analysis of the necessary data frequency of the simulation results was performed. An appropriate time step for output was found to be 1 min. The results and discussion of the frequency analysis are found in the appendix. Furthermore, different statistical analysis were performed on the results.

9.1 Evaluation of thermal comfort

As previously discussed in section 7.1.3, there is a general lack of guidance in building standards on how to evaluate thermal comfort in hybrid ventilated buildings. The heat balance method is developed based on thermal comfort in mechanically ventilated buildings, while the adaptive method is derived from field studies in naturally ventilated buildings where the occupants can regulate their thermal environment by opening windows. Since hybrid buildings with window venting constitute a combination of natural and mechanical ventilation, a suitable thermal comfort model is likely to be placed somewhere between the heat balance and the adaptive approach, depending on the degree of natural ventilation and personal control of the windows.

To evaluate the thermal comfort in the scenarios, different comfort analysis were performed. The indoor temperature was evaluated with the heat balance method, the adaptive method and the use of exceedance for long-term evaluation as proposed in the standard NS-EN15251 Appendix F [43]. As discussed in section 7.1.1, the comfort temperature varies according to season and the sensitivity of the users. Recommended temperature limits in NS 15251 for office buildings of class II with PPD < 10 % is 23-26°C during summer and 20-24°C during winter. As it is difficult to estimate the exact time of transition between seasons when evaluating the temperature, people are assumed to dress according to season, and the temperature limits used in the analysis of exceedance are 20 and 26°C.

The conditions in only one office was analyzed to perform an in depth analysis of the thermal indoor climate. The solar gains will vary according to the orientation of the offices. In this thesis, it is of interest to discuss adaptive comfort and the thermal conditions with increased outdoor temperatures in summer. Hence, the analysis was performed on the office facing South East on the second floor. The temperatures in the offices facing South East are a little higher than in the offices facing North West.

9.2 Limitations in the model

The operation of a building based on automatically controlled natural or hybrid ventilation requires a well-functioning control strategy to give the best possible indoor climate and energy consumption. The model developed and discussed in section 10.2 and 10.3 is an example of one specific ventilation strategy that could be further optimized. The results show how this specific solution with automatic controlled windows operates in a Norwegian climate.

The ventilation solution is based on the principles of displacement ventilation. IDA ICE can simulate the temperature stratification in the building, but do not model the stratification of CO_2. The program calculates a constant CO_2-level in the entire zone. As the systems are strongly reliant on an accurate and well-controlled natural ventilation that vents only when the temperature or CO_2-level exceeds the set point limits, the set point of CO_2 is of importance. In a room with displacement ventilation, the stratification of CO_2 is often approached with a two-zone model, where the room is divided in an occupant zone and a polluted zone. However, the formation of vertical air layers is dependent on a constant air supply, and uncertainty is related to how the stratification will be affected in a building with a varying air supply due to demand controlled natural ventilation. In addition, it is likely that the thermal mass will increase the creation of vertical air flows as it will periodically will operate as a cold and a warm surface. Due to the uncertainty of the stratification effect, the model was run with mixing ventilation and a set point of 1000 ppm. As the air quality in the occupied zone is assumed to be better, this can be seen as a conservative estimate.

User behavior related to window opening and control of natural ventilation is a complex process. As discussed in section 8.1, there is no consensus in literature on the most important driving factors. The window control modeled in this thesis is based on a number of key assumptions for window opening and closing. The chosen driving factors are indoor temperature and air quality (CO_2-level). Time of the day and window opening behavior related to arrival and departure have not been included. The probability for window opening is set to be constantly 70 % in the model. In literature, the percentage of windows open was found to vary over the year. The assumption of the probability for window closing lacks root in literature and should be evaluated to find a suitable value. By running simulations with closing probabilities of 0.3, 0.6 and 0.9, the most realistic closing behavior could be found. Furthermore, the effect of a user app lacks scientific proof, and the concept would need to be tested and verified in a 1:1 scenario to investigate the effect on user behavior.

10 Building and simulation model description

10.1 Presentation of scenarios

An overview of the scenarios investigated in this thesis is seen in Table 5.

Table 5 Description of the simulation scenarios, automatic control strategies

Scenario	Degree of natural ventilation	Degree of mechanical ventilation
Natvent 100	100 %	0 %
Hybvent 70_30	70 %	30 %
Hybvent 40_60	40 %	60 %
User app	70 %	30 %

The first three scenarios investigated are solutions with automatic windows and different degree of natural and mechanical ventilation. The first scenario is a passive building, relying 100 % on controlled natural ventilation, as 2226 in Austria. Since adaptations to Norwegian climate are assumed necessary, two scenarios with hybrid ventilation are investigated. The two systems have a small mechanical ventilation system operating as background ventilation, supplemented by natural ventilation through windows. The mechanical ventilation is supplied through a central core and stairs are used as ventilation shafts as in Powerhouse Kjørbo, described in section 6. The mechanical supply is chosen to be 2 m^3/m^2h in the scenario Hybvent 70_30 and 4 m^3/m^2h in Hybvent 40_60 based on a practical and economical evaluation [54]. Figure 31 show illustrations of the scenarios with automatic windows.

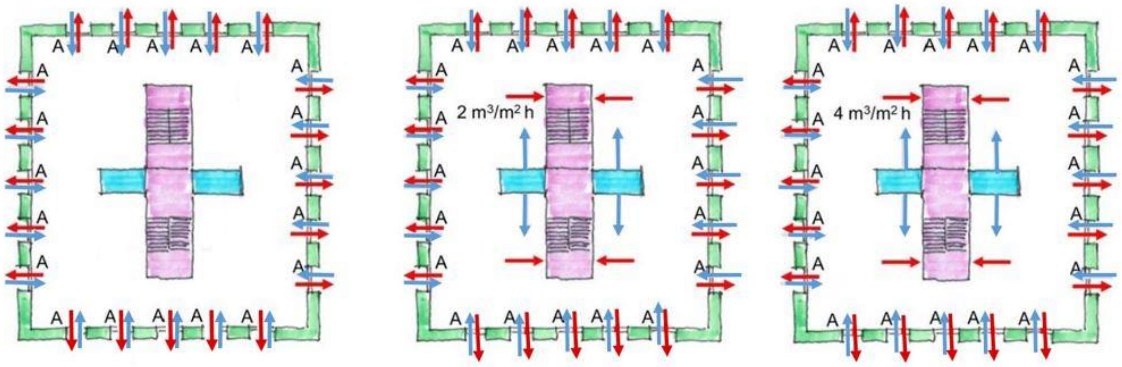


Figure 31 Automatic control strategies, different percentage of natural ventilation

The fourth scenario is an attempt to model human window-opening behavior. A system with manual window opening is less complex and less costly than the automatic systems, as discussed in section 4. The solution is a hybrid solution with a mechanical CAV supply of 2 m^3/m^2h. The windows are in this case manual and controlled by the user. The user is instructed by an app when the window should be opened or closed, according to the indoor and outdoor conditions. A window controller for manual opening of windows was developed in IDA ICE using random numbers to translate the probability of an opening or closing event into a deterministic value. Furthermore, multiple simulations were run to describe possible outcomes of the indoor environment conditions and energy use. Figure 32 shows an illustration of the manual control scenario, and the manual window controller is further described in section 10.5.

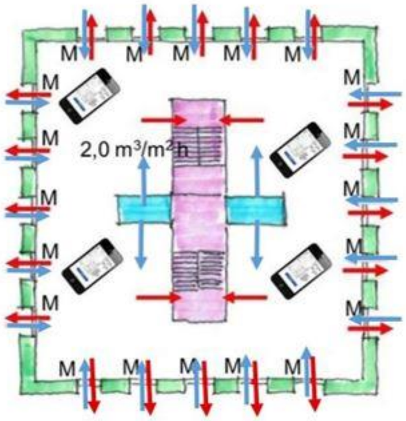


Figure 32 Manual control strategy

10.2 Description of the simulation model

It is important to emphasize that the simulation model created is not a model of the building 2226 by Baumschlager Eberle, but an office building with a simplified technical design based on passive strategies, placed in Norway. The model and the simulations performed are conducted independently, without knowing all the prerequisites of 2226. Hence, the results of the simulations in this project cannot be used to determine if whether or not Baumschlager Eberle's concept is feasible in Norway. It is only a general evaluation of how passive strategies and simplified technical installations can be developed in a Norwegian climate.

10.2.1 Location and climate settings

For location and climate settings in IDA ICE, Oslo was chosen with climate data from NS 3031. Oslo is geographically located at 59.5°N 10.5°E. The dry-bulb temperature for Oslo over a year is seen in Figure 33 and the direct and indirect solar radiation is seen in Figure 34.

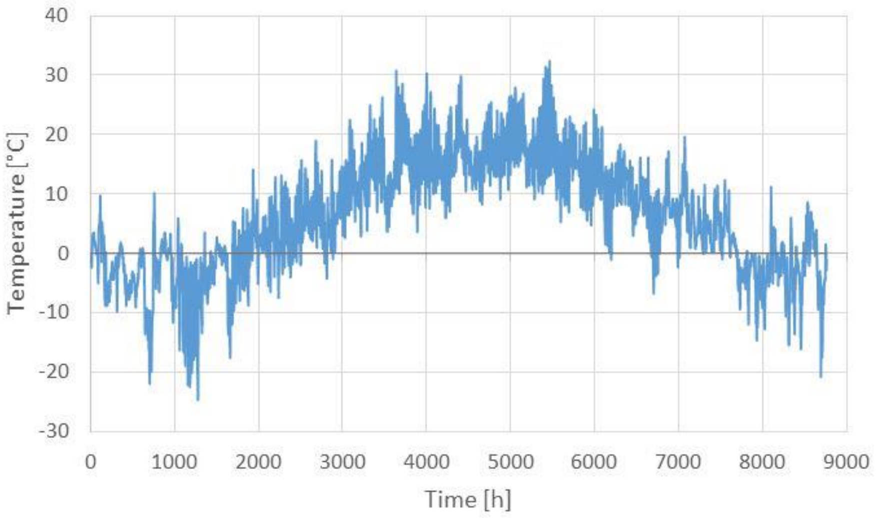


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Figure 33 Dry-bulb temperature Oslo

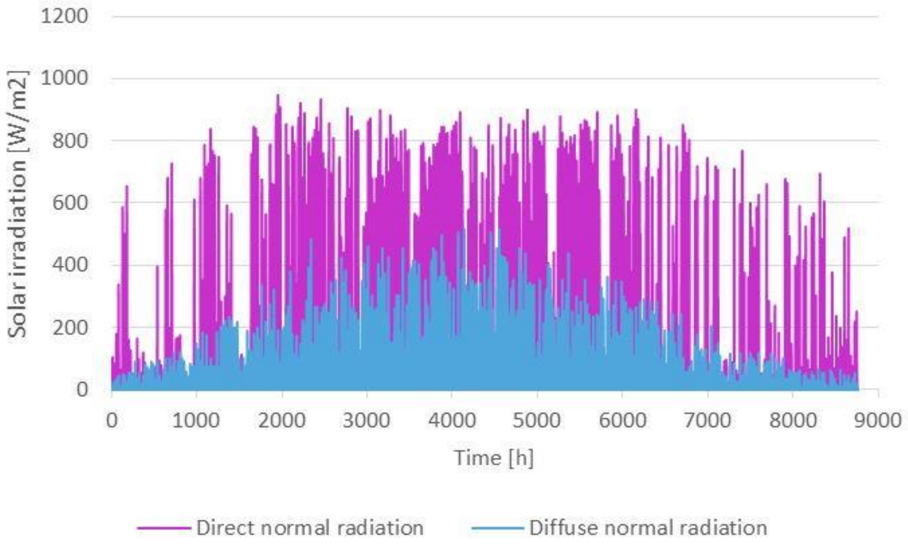


Figure 34 Direct and diffuse solar radiation Oslo

10.2.2 Building envelope and energy use

The construction developed in IDA ICE is an office building of six floors, with cubical measures of 24 m. In the simulation model, the building geometry was reduced to two floors and only the zones facing North West and South East were simulated to limit the simulation time. The two floors have the same floor plan, but different floor height. The ground floor is 4.6 m, while the second floor is 3.75 m. Figure 36 shows the floor plan in IDA ICE.

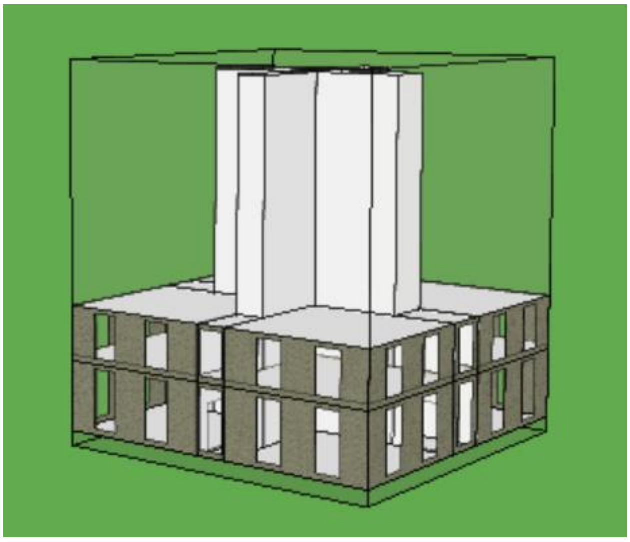


Figure 35 Building design in IDA ICE

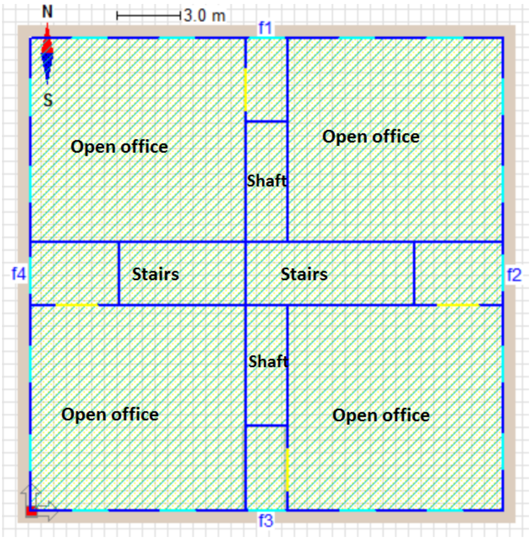


Figure 36 Floor plan in IDA ICE

Each floor consists of four open offices and a central core with stairs and shafts. Four additional small zones have been created, as IDA ICE needs rectangular zones to run simulations with displacement ventilation. The additional zones were connected to the surrounding office zones through a door. The doors were scheduled as “never open” and were included to create air movement between the zones.

The construction of the building body is very important as the passive and integrated design concept relies on the interaction between the ventilation system and the thermal mass in the building. The high specific heat capacity of the building body increases the thermal inertia and limits changes in the indoor temperature. Table 6 shows an overview of the building construction materials and corresponding U-values. Due to the high quality of the building construction, thermal bridges are assumed negligible.

Table 6 Building construction materials

Element	Materials	Thickness [m]	U-value [W/m^2*K]
External walls	Brick	0.8	0.13
Internal walls	Concrete	0.15	3.87
Internal floor	Floor coating, air gap, concrete	0.4	0.80
Roof	Light isolation, concrete	0.55	0.09
External floor	Floor coating, concrete, light isolation	0.67	0.09
Glazing	Pilkington Optitherm S3	-	0.6

Infiltration can be specified as fixed or wind driven flow in IDA ICE. As the model's ventilation solution is based on either natural or hybrid ventilation, the natural driving forces from wind are of great importance. Wind driven flow was therefore chosen, with pressure coefficients set as default with semi-exposure and an air tightness of 0.5 ACH at 50 Pa. Semi-exposure implies a rural position and the air tightness satisfies passive house standard [55].

The windows were mounted flush in the inner walls to provide solar shading. In IDA ICE this was done by inserting wall parts on the external walls with 0.1 m vacuum isolation having a very low U-value (U = 0.04 W/m^2*K). The internal part of the wall part has the same properties as the internal walls described in Table 6. The windows were then mounted on the internal wall parts, as seen in Figure 37. To create the opening vents, the window elements were divided in two pieces consisting of the same window type but having different control settings. The main window was scheduled as never open while the smaller part constituting the vent was scheduled to open according to the vent opening control described in section 10.3.

Figure 37 Windows mounted flush interior IDA

10.2.3 Heating and internal loads

Internal loads from occupants, equipment and lighting should cover part the heating demand in the building. In the simulations, the internal loads were set to 100% in order to include their heating contribution. An overview of the values of the internal loads are found in Table 7.

Table 7 Internal loads

Internal loads	
Occupants	100 W/person
Equipment	10 W/m^2
Lighting	5 W/m^2

A schedule of the occupational hours of the building was developed. As the building is an office building, the occupational hours were set from 7 AM to 5 PM during the working week. During this time, people are present and light and equipment are on. Outside of working hours and during the weekends there are no occupants present and all equipment and lighting is turned off. The set point values for heating, cooling and daylight were set as seen in Table 8.

Table 8 Control set points for the simulation model

	Minimum	**Maximum**
Temperature	20°C	Max temperature scheme
Daylight at workspace	500 lux	600 lux

An ideal heater is inserted in the zones to evaluate the need of heating. Whenever the indoor temperature drops below 20°C the ideal heater will activate. The set point temperature for cooling varies depending on the seasons in order to optimize the interaction between thermal storage of heat excess heat for colder periods and utilization of free cooling during warmer periods. To avoid cooling down the construction during winter, the set point was set highest from 1.November to 30.April and diminishing for the warmer months. Hence, there model has no night cooling during the winter months. An overview of the set point scheme for cooling can be seen in Table 9.

Table 9 Set point scheme for cooling

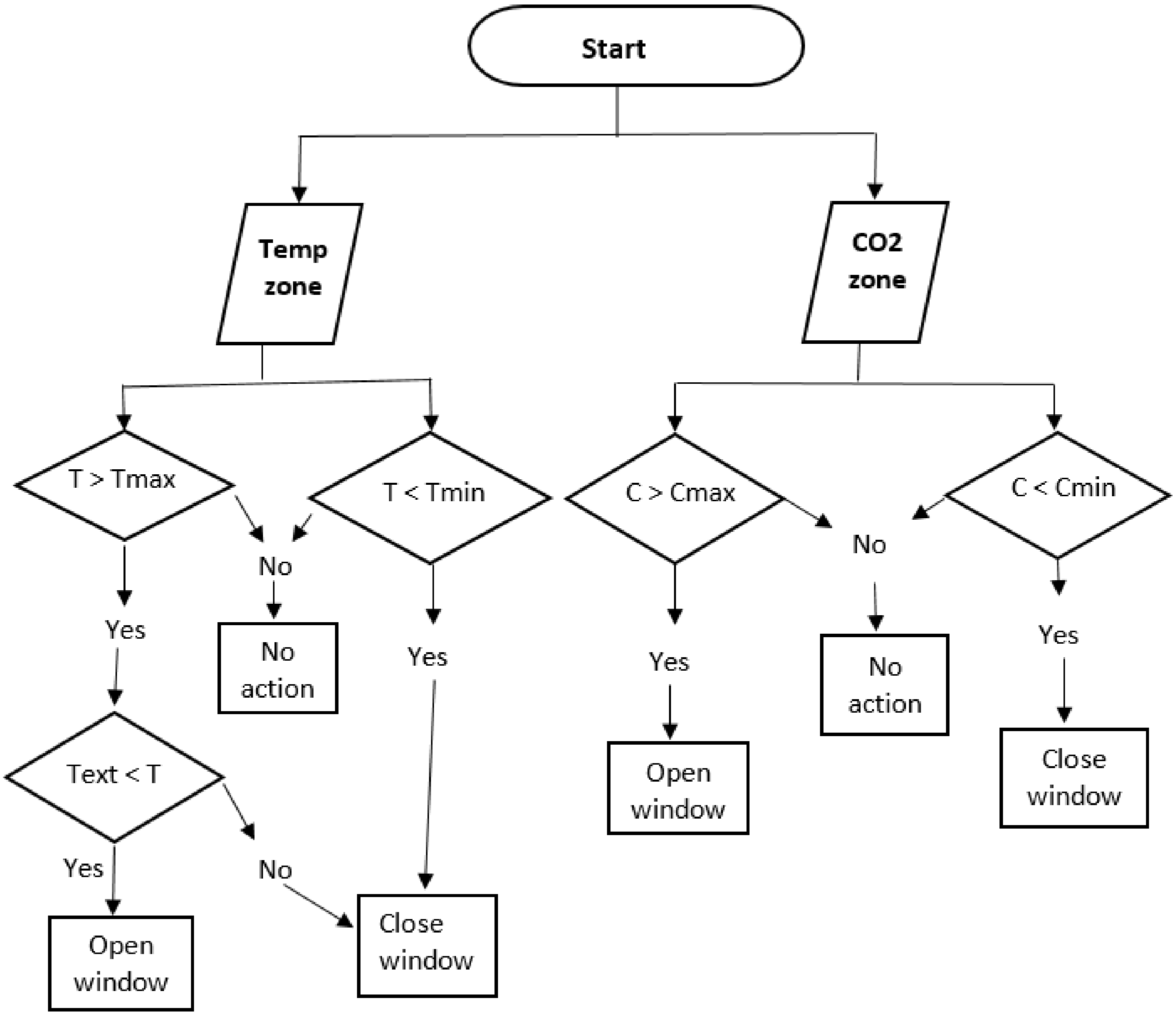
From	**To**	**Max value [07:00 – 17:00]**	**Max value otherwise**
1 June	31 August	22°C	21°C
1 May	30 September	23°C	22°C
1 March	31 October	24°C	24°C
All days		26°C	26°C

The workspace was placed six meters from the façade and the set points for turning the lighting on or off in the zone was given by the set point values for the daylight at the workspace, described in Table 8. Whenever the daylight at the workspace drops below 500 lux the lighting will switch on, and if the daylight value exceeds 600 lux the lighting will be turned off.

The domestic hot water consumption was not included in the model, as it does not affect the building’s heating demand or indoor climate.

10.3 Automatic ventilation solution

It is of great importance to create a well-functioning window opening scheme. This is a crucial part of the model. If the modelling of the airing is poor, it will strongly affect the quality of the indoor environment and result in a high energy use. The control scheme for the opening of the vents was created based on usual control schemes for natural ventilation. A temperature controller and a CO_2-controller regulates the opening of the vents. At a given time, the system will operate according to the maximum. An overview of the vent opening control can be seen in Figure 38.



T - Room temperature
T_{max} – Max room comfort temp.
T_{min} – Min room comfort temp.
T_{ext} – External temperature

C – Room concentration CO_2
C_{max} – Max room CO_2 concentration
C_{min} – Lower limit dead band

Figure 38 Automatic vent opening control

The CO_2 control regulates according to the set point values given. It compares the measured CO_2-level with the set point value. With a set point of 1000 ppm and dead band of 200, it will start the venting when the indoor CO_2-level zone values reaches 1100 ppm and shut down the venting when the CO_2-level in a zone is lowered to 900 ppm.

The temperature control is a proportional regulator that compares the temperature in the zone with the temperature set points for cooling described in Table 9. If the indoor temperature exceeds the set-point value with 0.5°C (dead band 1°C), and there is a need for cooling, the vents will open. The degree of opening depends on the outdoor temperature. When the outdoor temperature is lower than 5°C the vents will open with a degree of 0.1. The degree of opening increases gradually with increasing temperature and open fully at 15°C. The maximum value from the temperature control and CO_2-control indicates the opening degree of the vents.

In general, the vents will open according to the maximum signal in the comparison between the temperature- and CO_2 opening signals. At times when the ambient temperature exceeds the indoor temperature, the vents will not open. The system is then regulated only by the CO_2-levels and prevents hot ambient air entering the building. In winter, the system is mainly governed by the $CO2_2$-level in order to limit the amount of cold air entering the building, while in summer the indoor temperature regulates the venting.

Every morning before the office hours, the system will vent for four minutes between 06:56 AM to 07:00 AM. This fixed venting is included to satisfy the venting outside of office hours suggested in NS-EN 15251:2007 [43], as discussed in section 3.3.5.

Due to the limitations of modelling CO_2-stratification in IDA ICE described in section 9.2, the displacement degree is set to zero, and the simulations are run with mixing ventilation.

10.4 Parameter study

A parameter study has been performed to investigate the effect and importance of different parameters. The study was performed by changing one parameter at a time and comparing with the original results. The parameters investigated are:

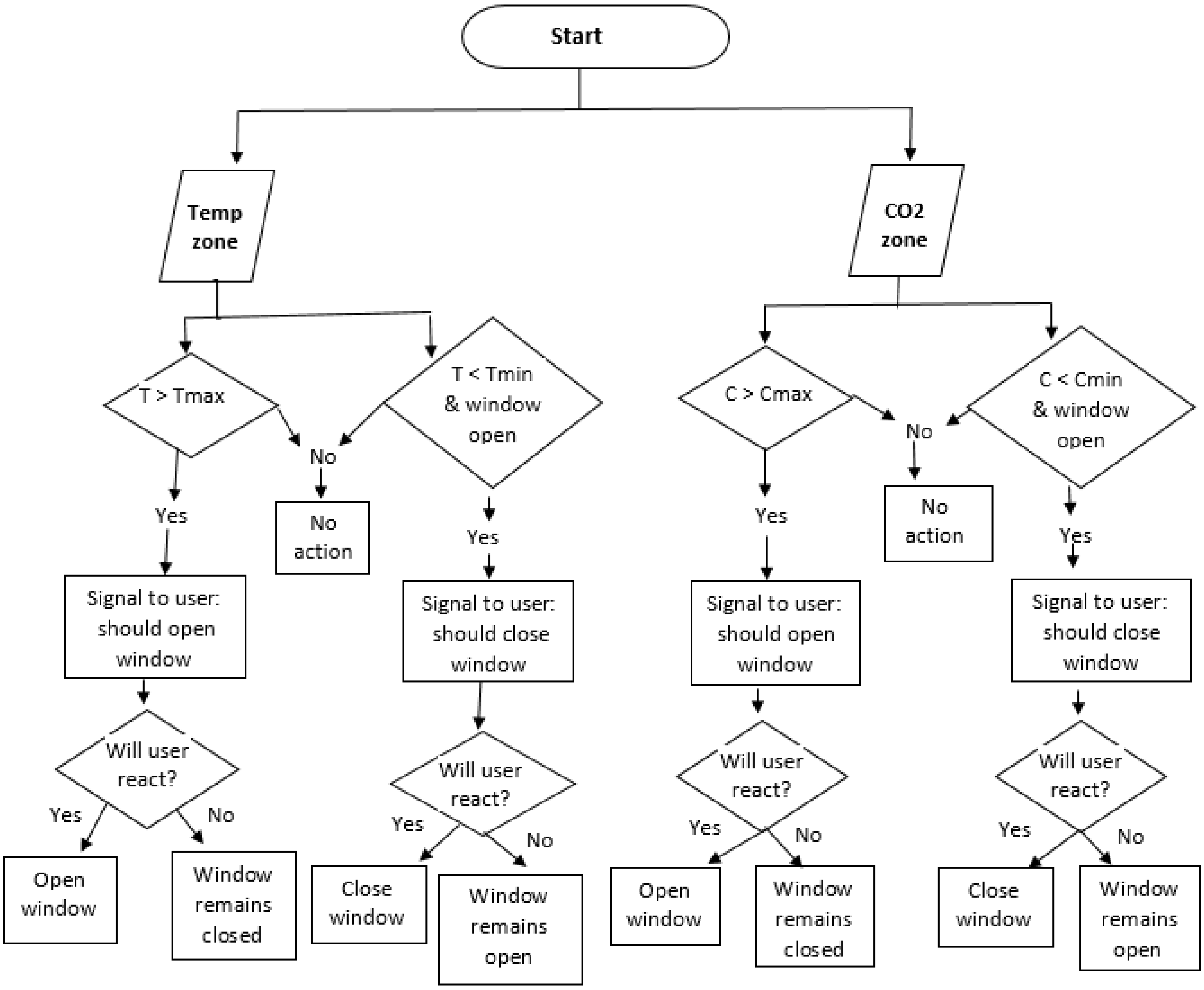
- *Night cooling*
  Simulations were run with schedule for window opening during working hours from 07:00-17:00 in all zones to evaluate the effect of night cooling on thermal comfort.

- *Exposed thermal mass*
  A suspended ceiling was inserted in the model to investigate the buffer capacity of the thermal mass. This was done by adding a layer of light insulation in the ceiling, corresponding to 50 mm of mineral wool. The light insulation had a heat conductivity of 0.036 W/(m*K) and a specific heat of 750 J/(kg*K). The exposed thermal mass in the original model consisted of concrete with heat conductivity 1.7 W/(m*K) and specific heat 880 J/(kg*K).

- *Internal loads*
  Variations in the density of occupants was simulated to evaluate the effect of changes in internal loads. As the amount of equipment is related to the number of occupants, internal loads from equipment was adjusted correspondingly. Simulations were run with three different occupant densities: 1 person per 20 m^2, 1 person per 10 m^2 and 1 person per 8 m^2.

10.5 Manual user controlled ventilation and stochastic user profiles

The idea of the manual user controlled scenario has been to expose the user to stimuli by an app, encouraging the user to regulate its environment by opening or closing the window. The message from the app is generated based on the automatic window control described in section 10.3. Thus, if the user would act ideally, the manual windows would be controlled as the automatic controlled windows during daytime. However, since human behavior is complex and great uncertainty is related to how the user will react to the stimuli, a probability aspect has been introduced in the window controller. The strategy of the manual window opening controller is described in Figure 39.



T - Room temperature
T_{max} – Max room comfort temp.
T_{min} – Min room comfort temp.
T_{ex} – External temperature

C – Room concentration CO_2
C_{max} – Max room CO_2 concentration
C_{min} – Lower limit dead band

Figure 39 Manual vent opening control

The user reaction to the stimuli from the app is modeled using a general probability for window opening at a certain indoor temperature compared with random numbers. To describe the general probability for window opening, the work by Haldi and Robinson [51] on window opening behavior in Swiss office buildings was used as a basis. The work showed that at an indoor temperature of 26°C, the proportion of windows opened by occupants without any stimuli were about 55 %. This was interpreted as a general probability of window opening of 55 % with an indoor temperature of 26°C. As the users in this case is exposed to stimuli, the probability was assumed to increase to 70 %, given the same indoor conditions. Every 5 minutes, random numbers are generated in the model and compared with the general probability of window opening. If the app sends an opening signal due to high indoor temperature or CO_2-level (value exceeds upper limit of max set point) and the random number is less than 0.7, the window will open.

If the user chose to open, the window will be held open until a user closes it. This is done by introducing a time-delay in the controller. The opening signal in the model will be held until it is relieved by a closing signal. Closing of the window will happen if the indoor conditions induce a closing-signal in the app (temperature or CO_2-level below lower limit of max set-point) and the user chose to act on the stimuli (closing probability compared with random number). A suitable probability for window closing was not found in literature, and thus the probability for a user acting on the closing signal was also set to be 70 %. In a real case, the probability is likely to be higher in winter due to draft and lower in summer due to a wish for elevated air flows.

The critical aspects in the control is if the user is too slow to close and the window remains open in the model, causing great discomfort. In reality, someone would close the window to minimize the period of discomfort. The time delay for window switching is set to 15 min, creating a period of 15 min between each time the window can be opened (if conditions for opening are present). This is assumed reasonable, as the window is not often opened in winter and with short venting intervals, while during summer the windows will be held open for a longer period due to higher outdoor temperatures. It is assumed it will take at least 15 min before the window again is opened in summer. Furthermore, the degree of opening is adjusted according to outdoor temperature. As the venting is user controlled, the manual venting will only happen during working hours, and there is no use of night cooling. A figure of the composition of the controller in IDA ICE is found in the appendix.

As users will behave differently, with a stochastic nature, the simulations were run numerous times with different sets of files with random numbers. Each set contained four files, one for user behavior related to opening due to temperature, one for opening due to CO_2-level, one for closing due to temperature and one for closing due to CO_2-level. In addition, variable occupancy was accounted for by creating five scenarios with different user profiles. For each user profile, the model was run with the different sets of random numbers, generating a number of possible outcomes for each user profile. To simplify the simulation procedure, the user profiles were created using model versions in IDA ICE. Three occupancy profiles were randomly generated, in addition to a scenario with 100 % presence and a scenario with 0 % presence. The user profiles are presented in the appendix.

11 Discussion of results

In building simulation, the choice of input climate data is of importance. The output of the simulations is a result of iterative processing of the climate data in the mathematical simulation model. In this thesis, the simulations were run with climate data from NS 3031. Since climatic conditions can vary from year to year, uncertainty is related to the simulation results. The use of multiple sets of climate data could further have improved the outcomes of the simulations.

11.1 Scenarios with automatic controlled windows

Energy simulations were run on the three scenarios with automatic window control, described in section 10.1. An ideal heater was first included in the model to estimate the necessary heat rates, and the maximum heat rate in zone South East in Natvent was found to be 2000W. The hybrid scenarios had higher maximum heat rate, but with significantly lower duration. Thus the simulations of the indoor environment were run with 100 % internal gains and an electric heater of 2000 W in each zone for all scenarios.

11.1.1 Thermal comfort

11.1.1.1 Indoor temperature over a year

An overview of the indoor temperature over a year in the scenario Natvent (100 % natural ventilation) is seen in Figure 40. The temperature lines indicates the dimensioning values by NS-EN 15251 for a building of category II. The lower line represents the recommended indoor temperature during winter, while the upper line indicates the upper recommended value in summer.

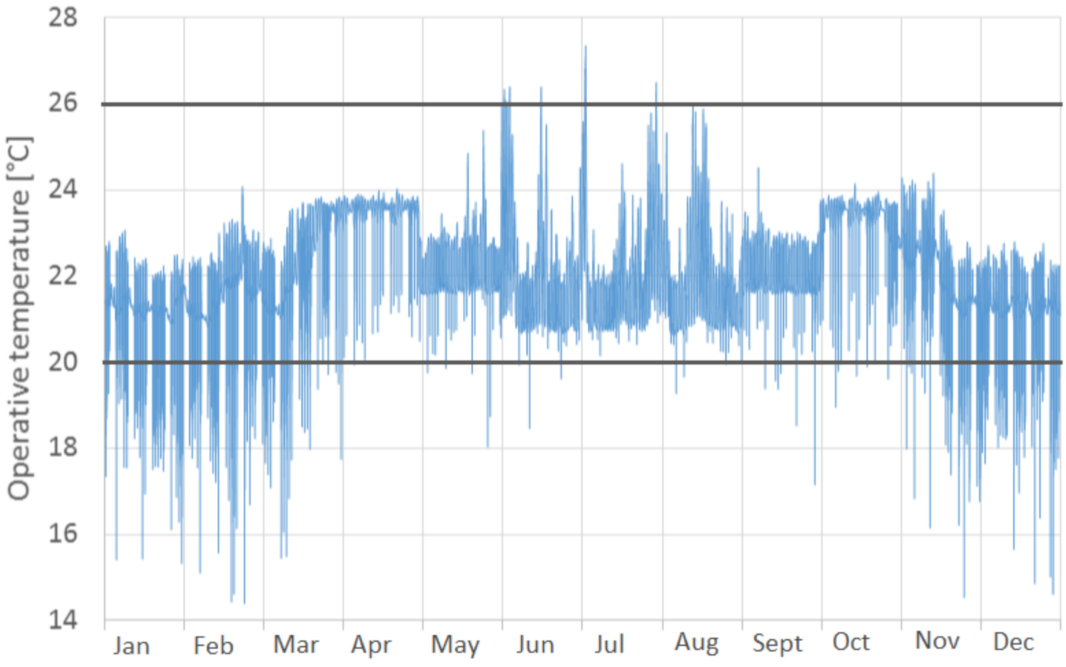


Figure 40 Indoor temperatures during a year, Natvent

Figure 40 shows great temperature variations during a day and the year. At first appearance, the indoor temperature seems to be unacceptably low in winter, as drastic temperature drops often occur. However, these large temperature drops mainly occur during the forced morning airing of four minutes before every working day, from 06:56 to 07:00. The temperature rapidly increases after the airing and has reached the lower recommended value of 20°C after approximately ten minutes. A more detailed study of the thermal comfort during a cold winter day is found in section 11.1.1.2. The two hybrid scenarios, Hybvent70_30 and Hybvent40_60 have similar yearly temperature profiles with great temperature variations, though with somewhat higher temperatures in general. Figures of the indoor temperature during a year for the two hybrid scenarios are found in the appendix.

Since the building investigated is an office building, the indoor temperatures during the working hours are of the greatest interest. The data was post-processed using Matlab to sort the temperatures during the working hours. To get a better description of the daily temperature ranges, a statistical analysis was performed, using two approaches. Figure 41 shows the mean operative temperature during each working day with two standard deviations. For a normally distributed data set, the values lies within the interval indicated in Figure 41 with 95 % confidence interval. Figure 42 shows the mean, minimum and maximum temperature for each working day.

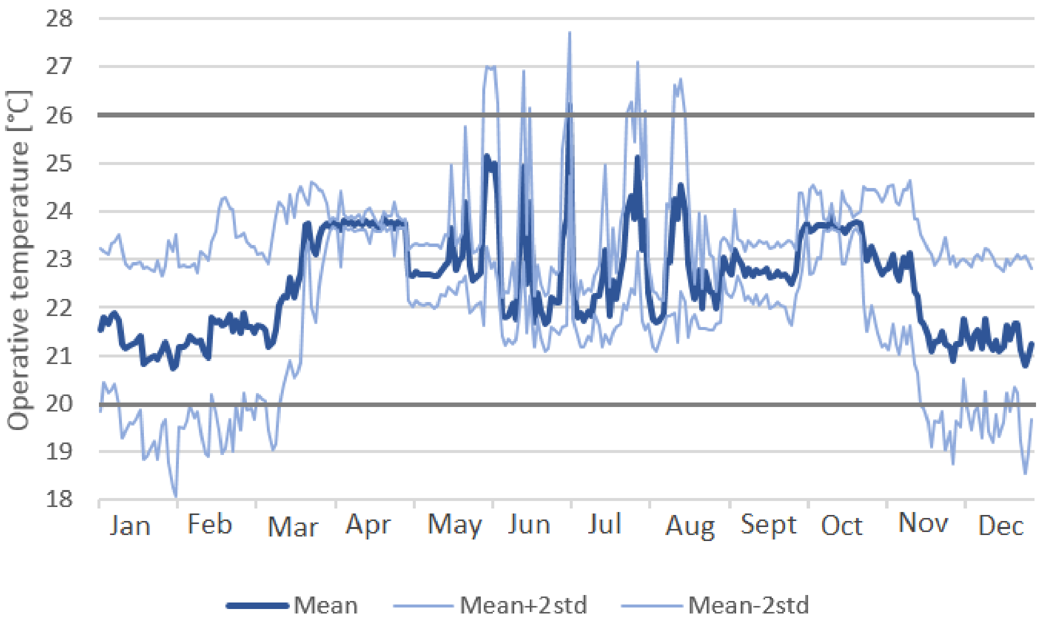


Figure 41 Mean daily temperatures and standard deviations during working hours, Natvent

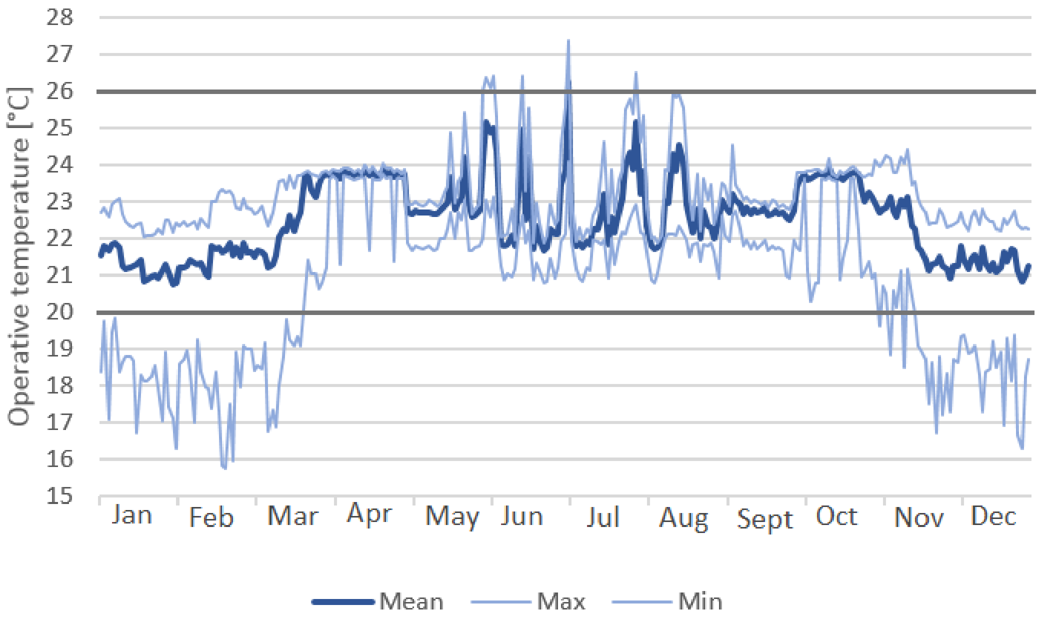


Figure 42 Mean daily temperatures, min and max during working hours, Natvent

The data of each working day are not perfectly normally distributed and thus it would be more technically correct to present the data using the mean daily temperature with the corresponding minimum and maximum values. However, due to the four minutes morning airing, very low temperatures are registered during the first ten minutes of the working day, causing very low minimum temperatures. The low minimum temperatures strongly affects the representation of the data and gives a misguiding impression of the general thermal conditions during the working day. It was therefore chosen to proceed using mean temperatures and standard deviations for the general evaluation of the daily temperatures during the working hours.

Using the heat balance method and the recommendations in NS-EN 15251 for category II, the temperatures should be 23-26°C during summer and 20-24°C during winter. As seen in Figure 41, the mean temperature remains within 20-23°C during winter and 23-24°C during spring and autumn. In summer, the mean temperature varies to a larger degree, between 22-26°C due to the use of night cooling. The temporary low mean temperatures in summer indicates that the control of the night cooling could be optimized to maintain 23°C during working hours. In this thesis, the set points for night cooling were generally set according to season, as described in section 10.2.3. An alternative approach to optimize the night cooling could possibly be to regulate the set point according to the predicted outdoor temperature during the following day. However, the night cooling is generally well functioning and succeeds in avoiding overheating in summer.

The critical aspects in all scenarios and especially in the scenario Natvent are the temperature drops during venting in winter. Even if the mean temperature remains above 20°C in Natvent, the temperature drops below the comfort limits for a short period at every venting. A more detailed analysis of the thermal conditions during a cold winter day is found in section 11.1.1.2.

Figure 43 and Figure 44 shows the mean operative temperature during each working day with 95 % confidence interval for the scenarios Hybvent 70_30 and Hybvent 40_60.

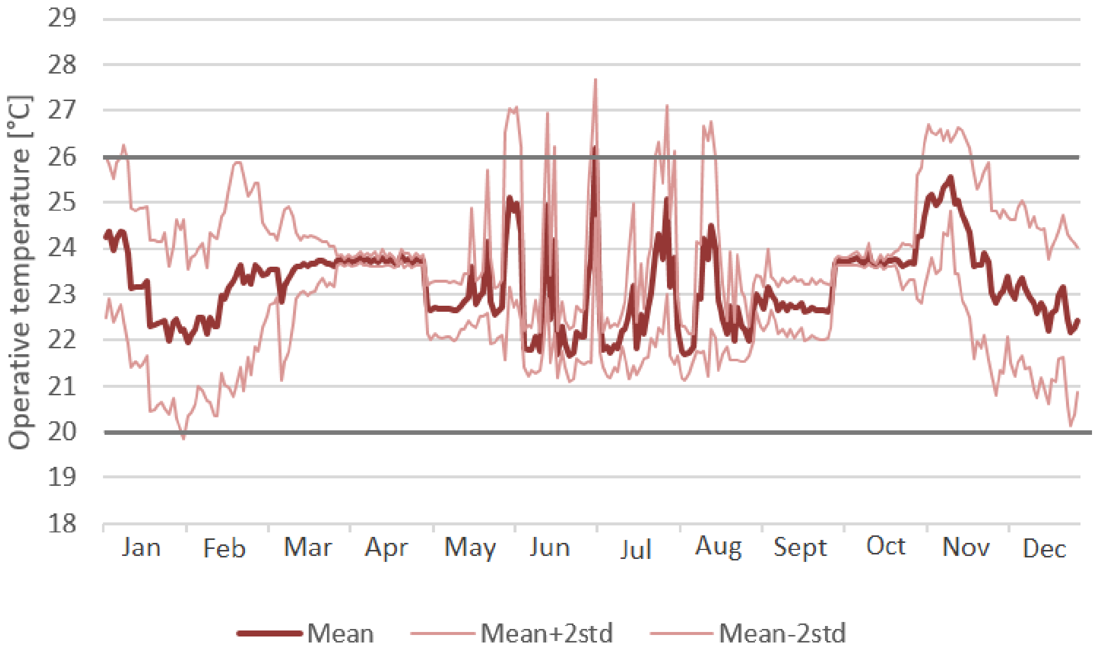


Figure 43 Mean daily temperatures and standard deviations during working hours, Hybvent 70_30

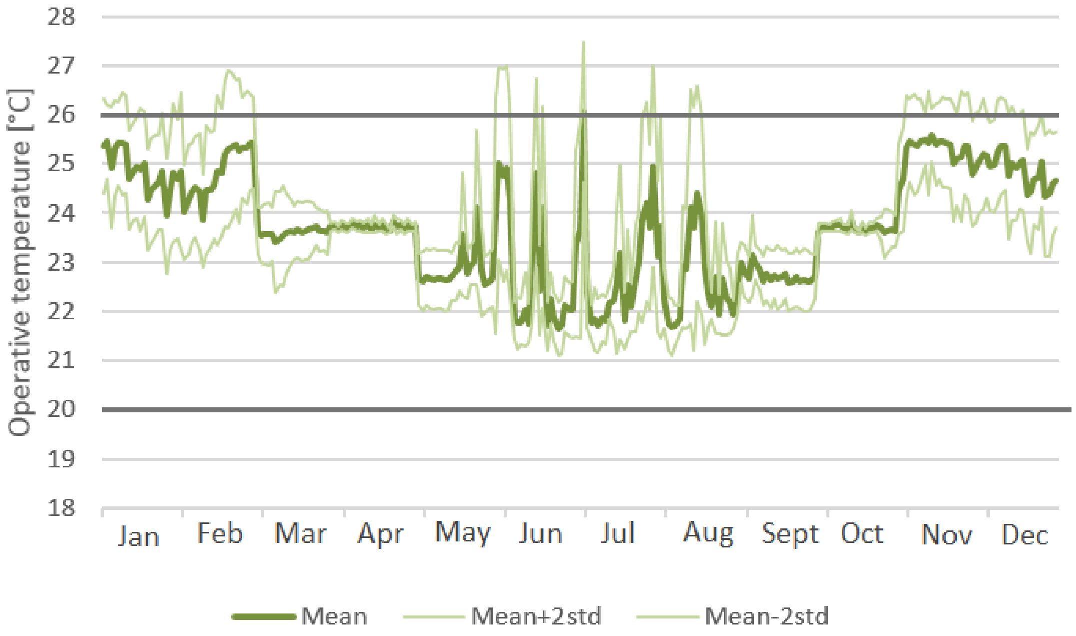


Figure 44 Mean daily temperatures and standard deviations during working hours, Hybvent 40_60

The use of hybrid systems can increase the temperature in winter, as the mechanical CAV-supply reduces the number of window openings. Hybvent 70_30 has a mean indoor temperature of 22-24°C in winter as seen in Figure 43. The temperatures in winter exceed the recommendations of NS-EN 15251, but limits the incidents where the temperature is below 20°C and thus ensures better thermal comfort in winter than Natvent. The high temperatures could be lowered by adjusting the cooling set point. Hybvent 40_60 has less variation in temperature than the two former scenarios. The reason is the higher mechanical air supply, which limits the natural venting to one forced morning airing during cold winter days. Figure

44 shows that Hybvent 40_60 also has higher temperatures than preferred in winter according to NS-EN 15251.

The spring, summer and autumn conditions are almost identical in all three scenarios. As previously discussed, the thermal conditions are good in spring and autumn, while the night cooling could be optimized to ensure a minimum temperature of 23°C in summer.

Figure 45 shows an overview of the share of the working hours having different temperatures.

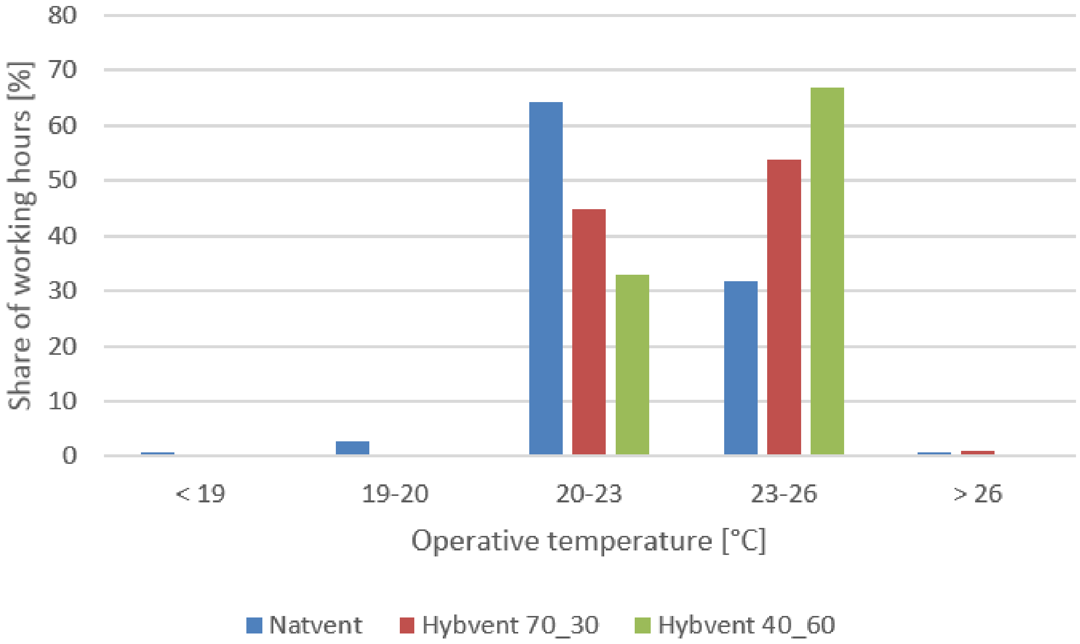


Figure 45 Temperature distribution during working hours

In total, all scenarios have temperatures mainly within 20-26°C, but with different distributions. The hybrid solutions ensures a minimum temperature of 20°C, while Natvent has a share of hours below. The main share of them are within 19-20°C, which fulfills the recommendation in TEK, but will be perceived as chilly by many occupants.

11.1.1.2 Extreme cases: Summer and winter conditions

To gain a more detailed understanding of the buildings performance, an analysis of the temperature, indoor quality and opening frequency was performed on a cold day in winter and a warm day in summer. The two scenarios describes the extremes of the indoor climate conditions.

Cold day

Figure 46 shows the outdoor temperature during a cold week in February. The day analyzed has an outdoor temperature ranging from almost -20°C at night to -2°C during the day.

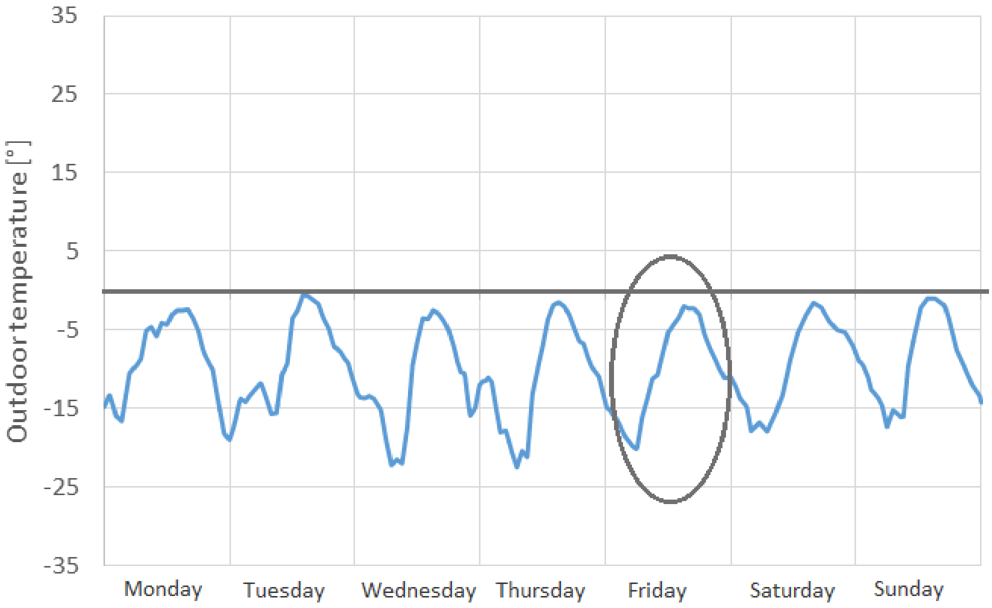


Figure 46 Outdoor temperature during cold week

The indoor temperature, concentration of CO_2 and window opening during the cold day for the scenario Natvent is shown in Figure 47 and Figure 48.

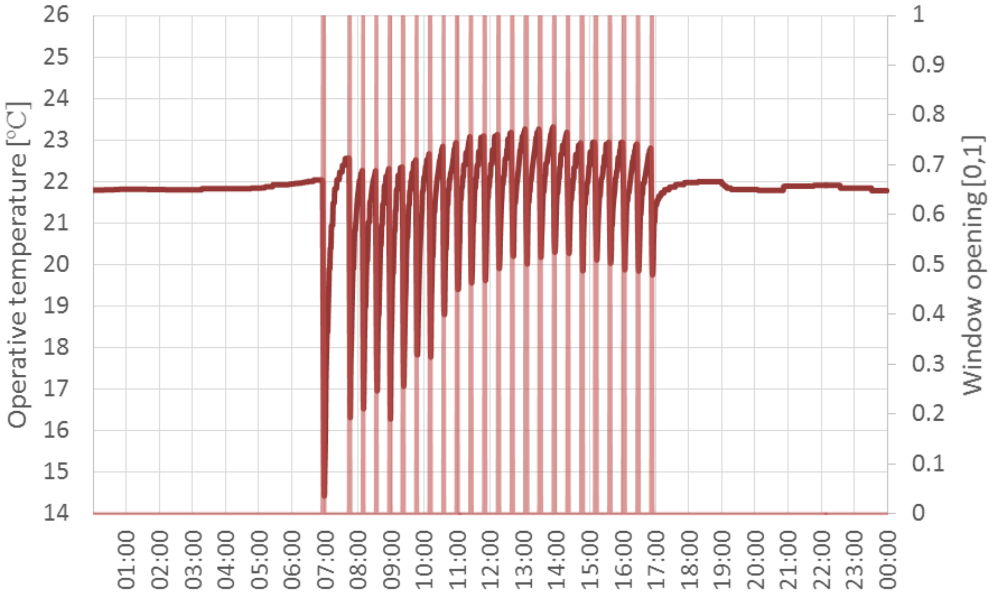


Figure 47 Indoor temperature and opening frequency on cold day, Natvent

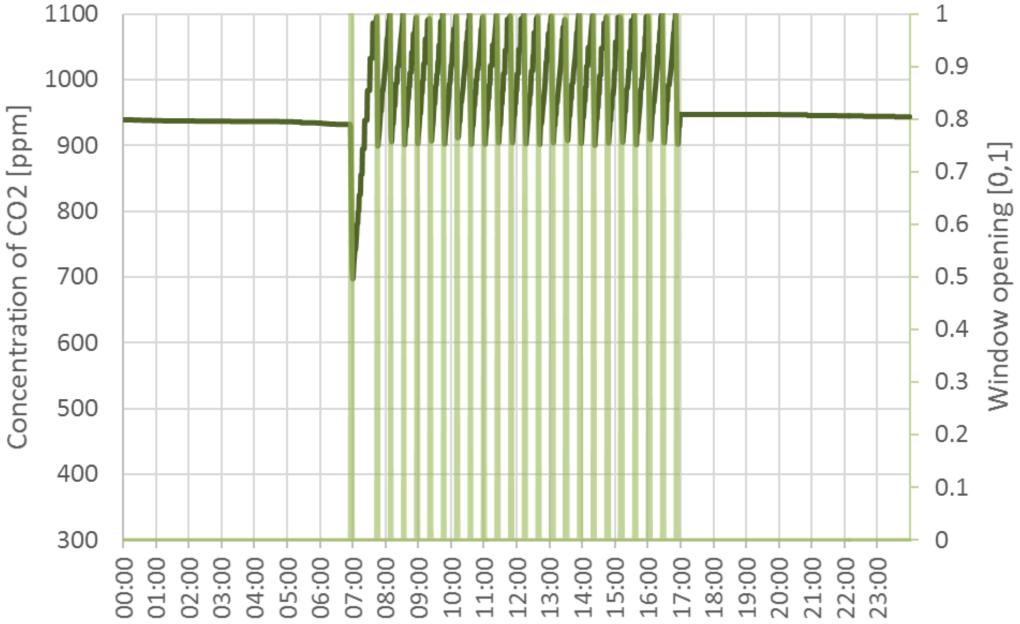


Figure 48 Concentration of CO₂ and opening frequency on cold day, Natvent

In winter, the air quality triggers the opening of the windows. As seen in Figure 48, the level of CO_2 remains high through the day and the windows open every time the level exceeds 1100 ppm, which is the upper set point limit. The windows needs to open every 30 minutes and activates in total 23 opening intervals throughout the day. Every window opening causes a drastic temperature drop where the temperature drops below 20°C and the user is likely to feel draft and be uncomfortable.

Figure 49 and Figure 50 show the indoor temperature, concentration of CO_2 and window opening during the cold day for the scenario Hybvent 70_30.

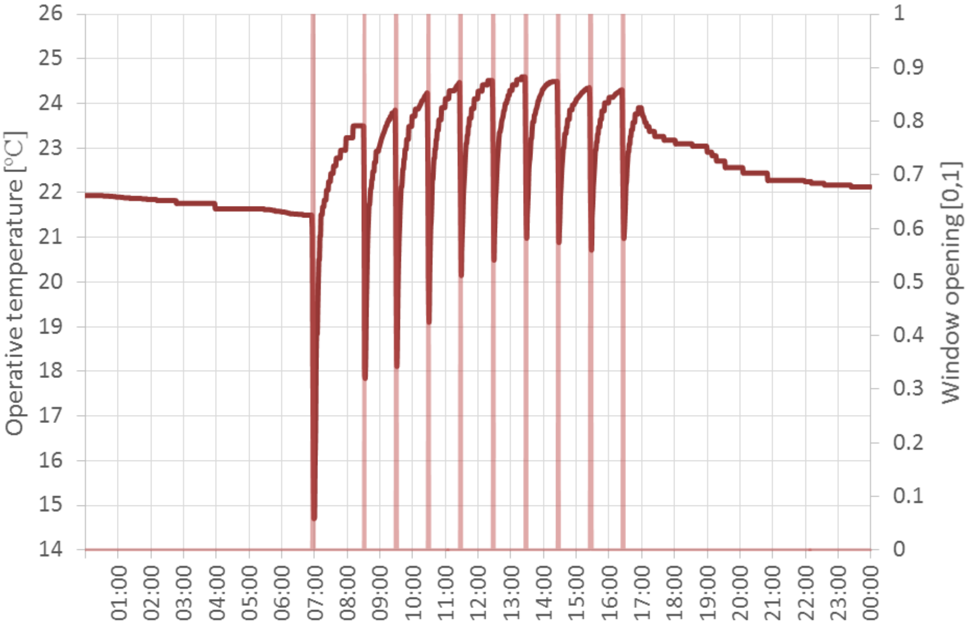


Figure 49 Indoor temperature and opening frequency on cold day, Hybvent 70_30

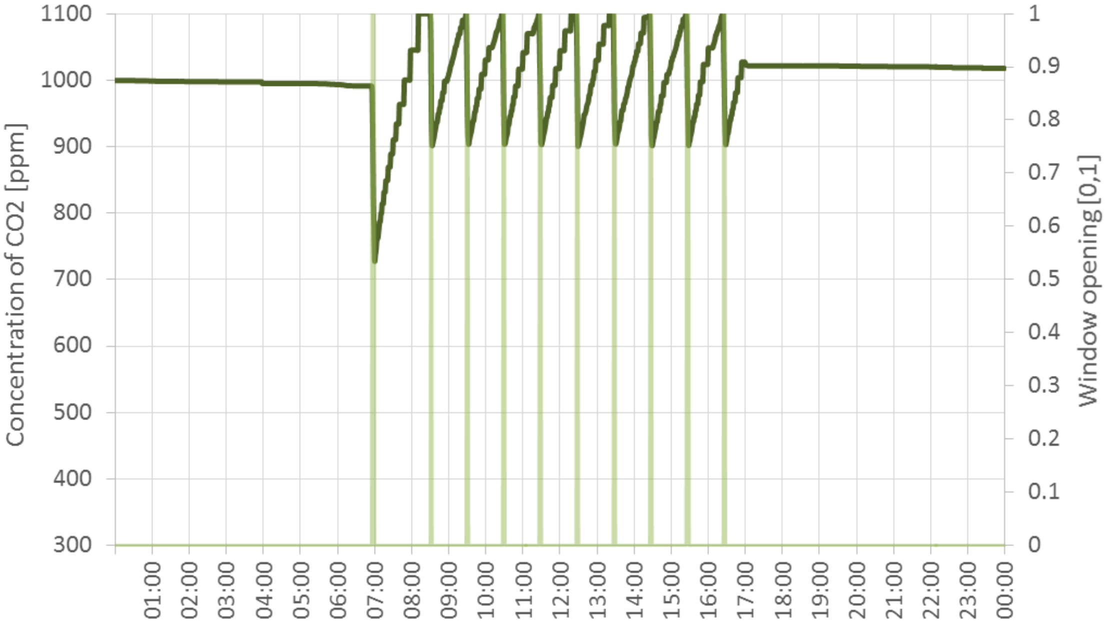


Figure 50 Concentration of CO_2 and opening frequency on cold day, Hybvent 70_30

The use of a hybrid solution reduces the number of window openings, as the mechanical system supplies the zones with a constant air supply. With a base ventilation of 2 m^3/m^2h, the number of window openings are reduced to nine, one venting every hour. This increases the thermal comfort for the occupant as the temperature drops occur less often and the operative temperature only drops below 20°C three times during the working day.

In the scenario Hybvent 40_60 with 4 m^3/m^2h, the window venting is mainly limited to the forced morning airing, as seen in Figure 51 and Figure 52.

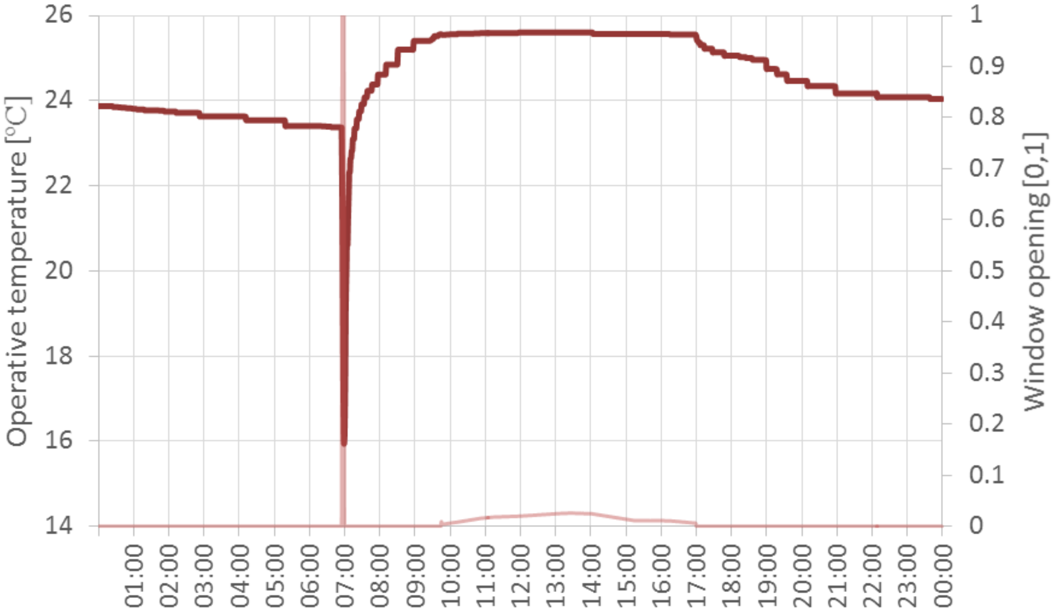


Figure 51 Indoor temperature and opening frequency on cold day, Hybvent 40_60

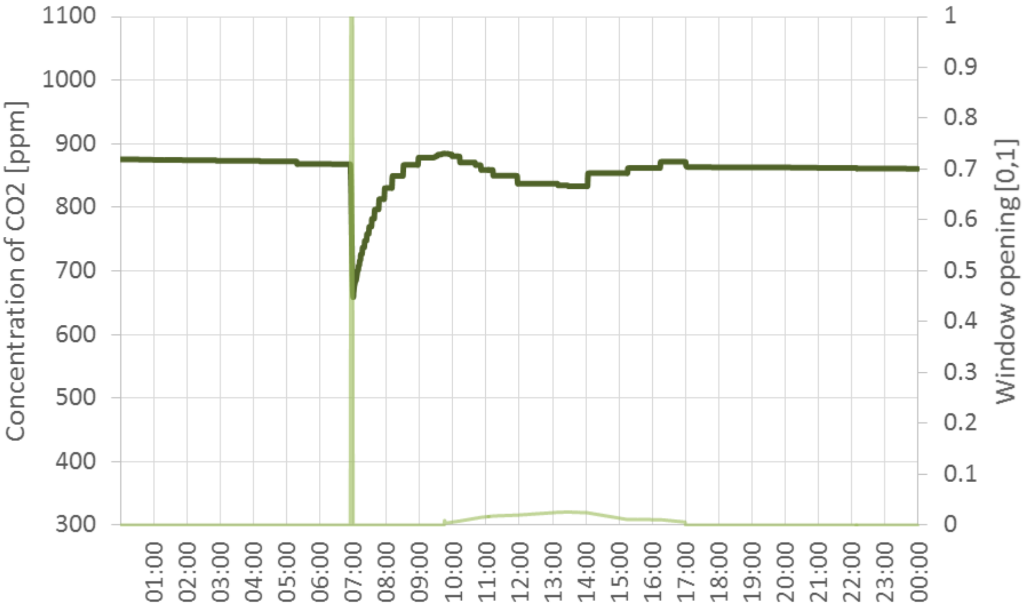


Figure 52 Concentration of CO_2 and opening frequency on cold day, Hybvent 40_60

The mechanical supply is in this case sufficient to maintain an acceptable level of CO_2 in the zone. In Hybvent 40_60 it is not the indoor air quality, but actually the temperature that triggers a tiny venting during the day. This could be avoided by lowering the supply air temperature, as discussed in section 11.1.1.1. When disregarding the high temperature, Hybvent 40_60 can provide good indoor conditions during the cold day. Due to the absence of airings during the working day, the room has constant supply and exhaust rates, and a stratification effect of the contaminants will occur as described in section 3.4. The effect is likely to cease with every pulse ventilation through the windows.

Generally, it is favorable to limit the number of airings on cold days, both to provide comfort and to save energy. A hybrid strategy can be a good solution to ensure a good indoor climate. The size of the CAV-system determines the number of airings on cold days and needs to be planned based on project prerequisites, user requirements and cost analysis. The geometry of the windows plays an important role, as discussed in section 3.3.2. In 2226 and the scenarios investigated in this thesis, the window openings/vents are side-hung and thus air is taken directly into the occupant zone. One measure to reduce the risk of draft could be to have multi-element operable windows, with a bottom-hung element for cross ventilation during winter and a side-hung element for larger air quantities during summer.

Warm day

Figure 53 shows the outdoor temperature during a warm week in August. The day analyzed is the Friday marked in the figure, with outdoor temperatures varying from 12 to 30°C.

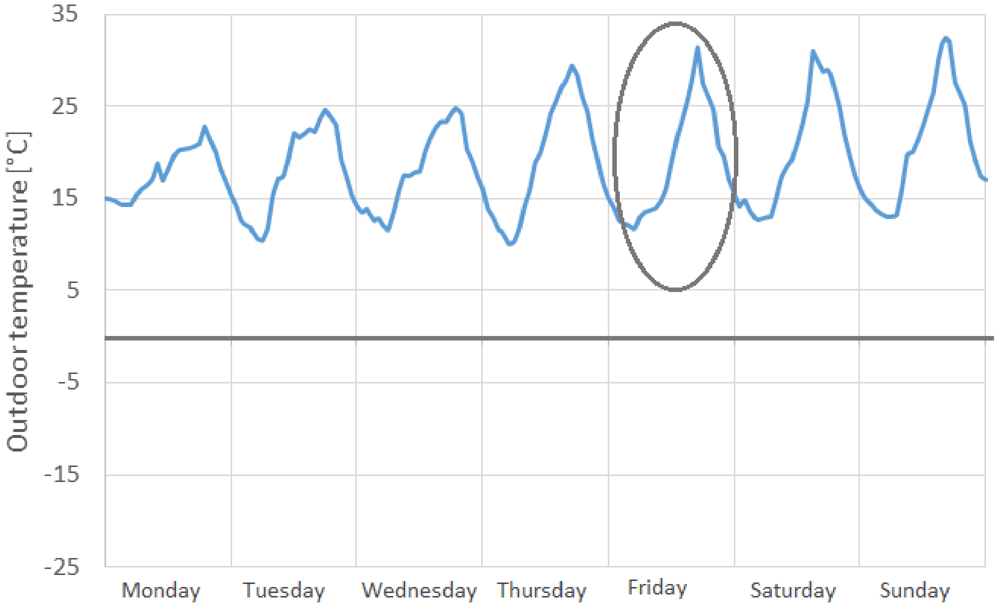


Figure 53 Outdoor temperature during warm week

During the warm day analyzed, the indoor temperature in the three scenarios are approximately identical. Therefore, only the conditions in Natvent are presented. Figure 54 and Figure 55 show the indoor temperature, window opening and indoor air quality during a warm day in August.

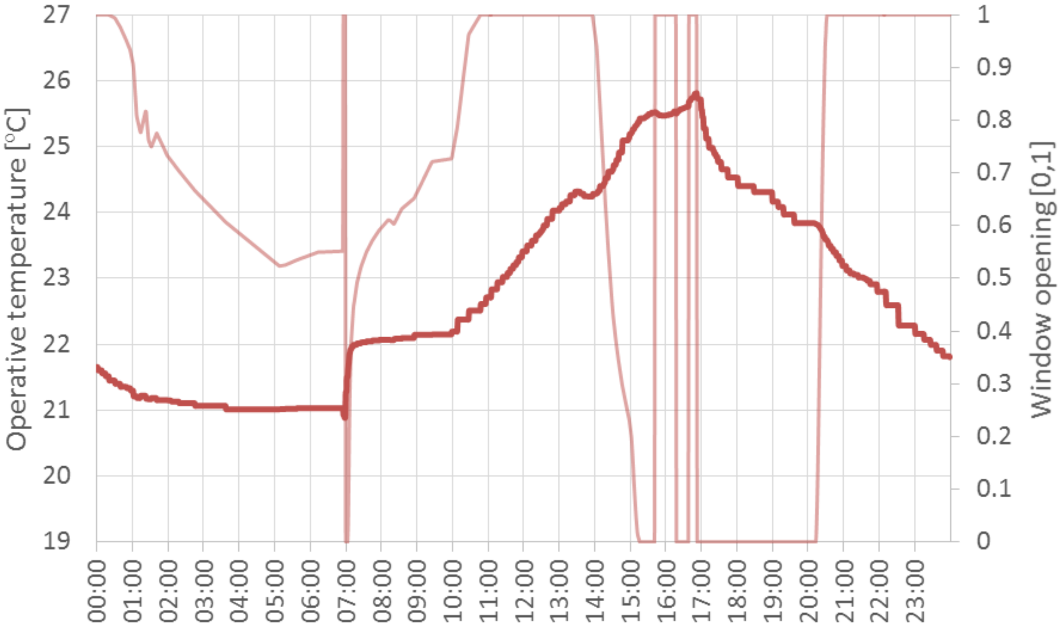


Figure 54 Indoor temperature and opening frequency on warm day

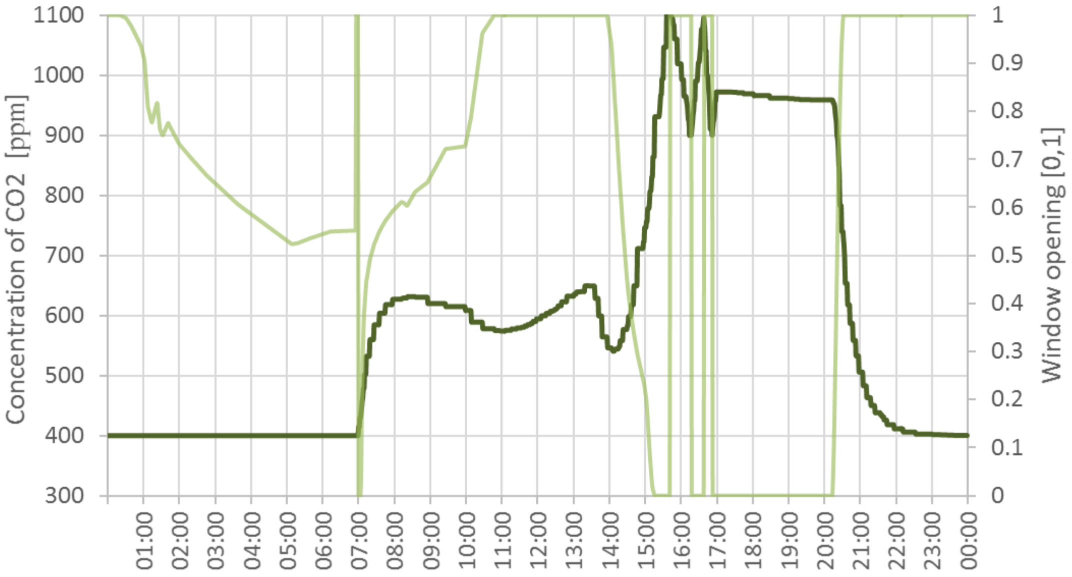


Figure 55 Concentration of CO_2 and opening frequency on warm day

In summer, the opening of the vents are mainly governed by temperature. The set points for cooling are 22°C during working hours (07:00-17:00) and 21°C for night cooling in August. As seen in Figure 54, the vents are open to lower the indoor temperature at night. The degree of opening depends on the outdoor temperature, and the opening diminishes as the temperature drops below 15°C during the night. At around 07:00 the morning airing occurs and the vents gradually open again as the indoor temperature increases. At 14:00 the vents closes because the outdoor temperature exceeds the indoor temperature. Further venting is avoided, as it would only contribute to a further increase in indoor temperature. The closing of the vents affect the air quality, as seen in Figure 55. The concentration of CO_2 rapidly increases and causes two short airings due to poor indoor air quality.

The analysis show no problem of overheating in summer because of the passive night cooling. On the contrary, the temperatures are lower than the recommendation in NS-EN 15251 during the first part of the day because of the low cooling set point for night cooling, as discussed in section 11.1.1.1. The recommendations in the standards assume people dress according to season. For tenants with formal dress codes a temperature of 20-22°C may be preferred all year around.

The temperature profile during the day show the importance of night cooling. As the temperature increases with 5°C during the warm day, it is vital to have a sufficiently low temperature in the morning to avoid overheating. If a warm period occurs, with night temperatures above 20°C and temperatures above 26°C during the days, the building will have problems with cooling the construction sufficiently and ensuring a comfortable environment. This is however not a usual scenario in Oslo, and the climate file used in the simulations did not contain a such period. According to TEK it is acceptable with 50 h over 26°C during a normal year. The effect of night cooling was further investigated in the parameter study, in section 11.1.5.1.

11.1.1.3 Adaptive comfort analysis

IDA ICE gives the possibility to perform a thermal comfort analysis based on both the heat balance and the adaptive comfort model. The simulation program performs the adaptive analysis based on the method in NS-EN 15251 described in section 7.1.2, using the outdoor running mean temperature. Figure 56 shows the distribution of the comfort categories during the working hours over a year for the adaptive and the heat balance model.

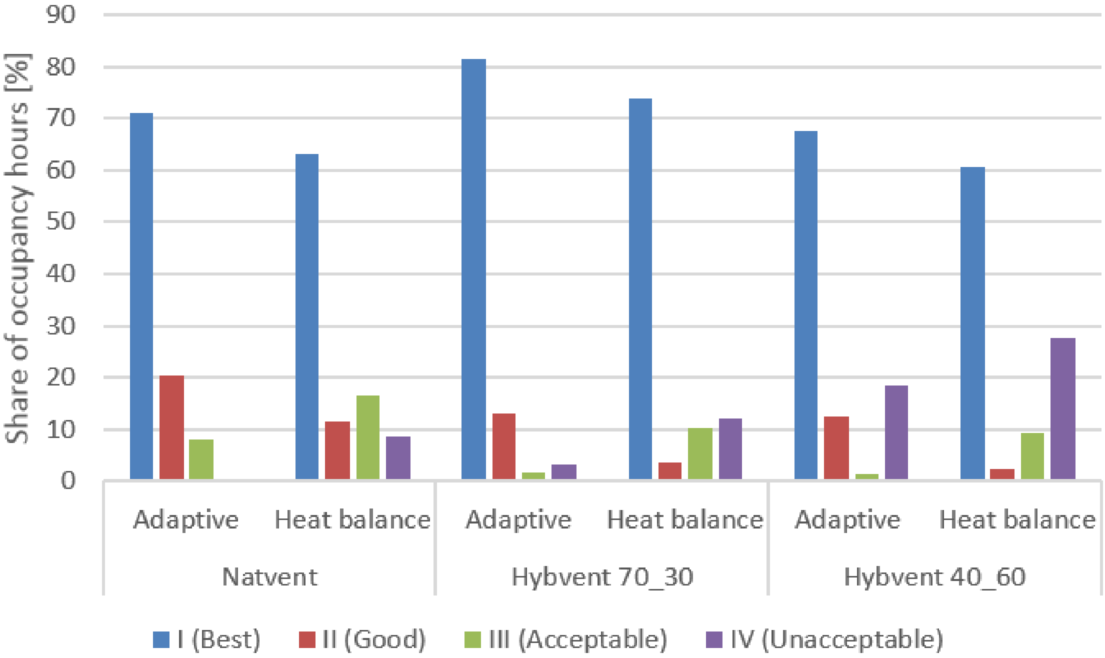


Figure 56 Comparison between adaptive and heat balance comfort analysis

The analysis show that all scenarios have their main share of occupancy hour in the comfort category I, corresponding to a PPD of < 6 and -0.2 < PMV < + 0.2 [43]. The distribution of the scenarios differ, but generally the adaptive model results in better thermal comfort than the heat balance method, as it allows for grater temperature variations. Hybvent 40_60 stands out having the largest share of occupancy hours in the category IV, unacceptable. The reason is likely to be the high temperatures in winter, as discussed in 11.1.1.1, which are out of the recommended range of 20-24°C. Figure 57 shows the share of occupancy hours where the thermal conditions in the scenarios are within comfort category I and II.

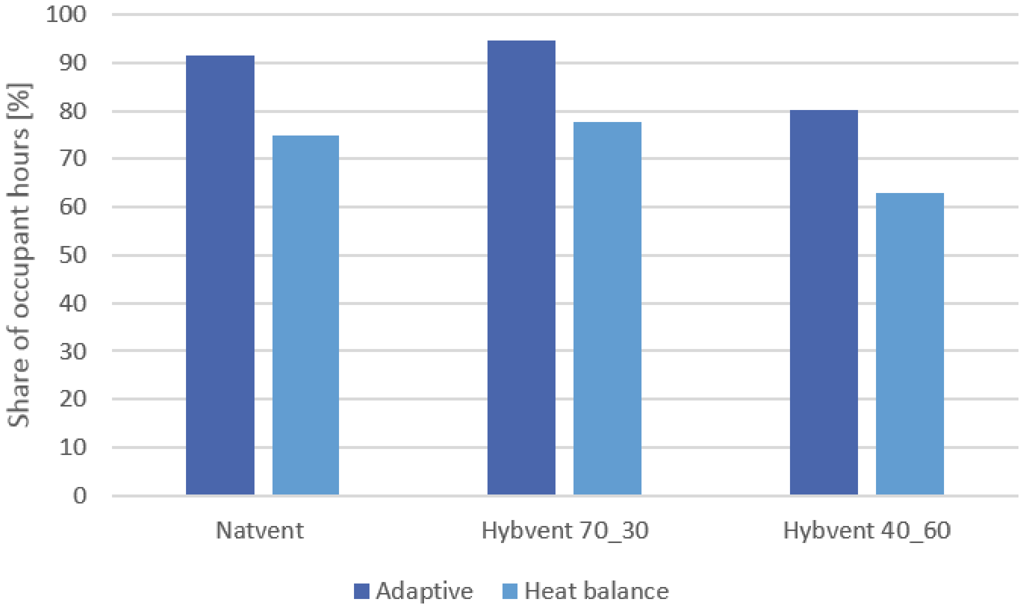


Figure 57 Share of occupant hours in category I and II

Based on Figure 57, it is favorable to use adaptive comfort to promote thermal comfort in naturally and hybrid ventilated buildings. However, the use of adaptive comfort requires a naturally ventilated building where the occupants have a high degree of personal control of the windows to regulate their thermal environment. The scenarios investigated in this thesis have automatic openable windows and the floor plan consists of open offices. Thus, the users do not have full personal control and possibility to regulate their environment as they desire. Furthermore, the hybrid solutions are running with CAV, and can only be counted as free running at times when the windows are open.

A suitable comfort model for office buildings with automatic openable windows and open offices will probably constitute a combination of the two models, depending on the degree of natural ventilation and personal control of the windows. Hybrid buildings with open offices are likely to be inclined towards the heat balance method, but have an element of natural ventilation that might affect the user's expectations and acceptance. The two comfort models indicate the extremities of thermal comfort, and in considerations of hybrid ventilated buildings, the heat balance method can be seen as a conservative estimate.

11.1.1.4 Long-term evaluation of thermal comfort

A long-term evaluation of the thermal comfort based on method B in NS-EN 15251 was performed as recommended in [44]. Method B evaluates the exceedance of the operative temperature and weights it with a factor based on the number of degrees of the exceedance. As people are assumed to dress according to season, the upper and lower limits for exceedance are chosen to be 26 and 20°C. Figure 58 shows the exceedance expressed as time and weighted time.

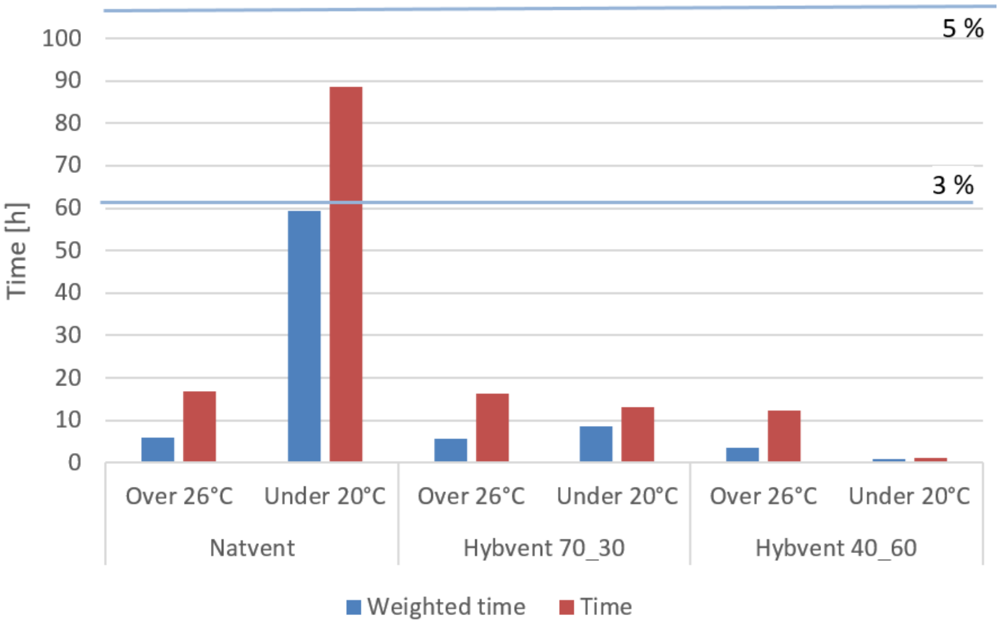


Figure 58 Exceedance calculations thermal comfort NS-EN 15251

Acceptable time of exceedance are 3 % or at the most 5 % of the occupied hours based on an eight hours working day, as indicated in Figure 58. The analysis of the simulation results was performed on the data during the occupied hours in the model. As the occupancy hours in the model are set to be 10 h during weekdays, the results appear somewhat worse than expected. All scenarios have acceptable exceedance above 26°. Natvent stands out by having a larger time below 20°C, exceeding the recommended 3 % of the occupied time. Hybvent 40_60 on the other hand has a very low exceedance below 20°C.

11.1.2 Indoor air quality

Indoor air quality is a term with many definitions, as discussed in section 7.2. Factors affecting the perceived indoor air quality are among other the olfatory sense, humidity and temperature, in addition to the duration of exposure. The concentration of CO_2 is a frequently used indicator for the indoor air quality, and is the chosen parameter to evaluate air quality in this thesis.

Standards differ between expressing the recommended CO_2-level in an absolute value and as the difference in concentration between the indoor and outdoor air. The Norwegian labor inspections refer to 1000 ppm as an upper recommended limit for the CO_2-level, while NS-EN 15251 recommends a difference of 650 ppm between the indoor and outdoor air for buildings of class II. With an ambient concentration of 400 ppm used in this thesis, the recommended upper value constitute a CO_2-concentration of 1050 ppm.

Similar to the indoor temperature profile, the concentration of CO_2 varies throughout the year in the three scenarios. To get a better understanding of the general atmospheric environment in the models, a statistical analysis was performed to find the mean and standard deviations the CO_2-level during every working day. The indoor air quality in the scenario Natvent is presented in Figure 59 with a confidence interval of 95 %.

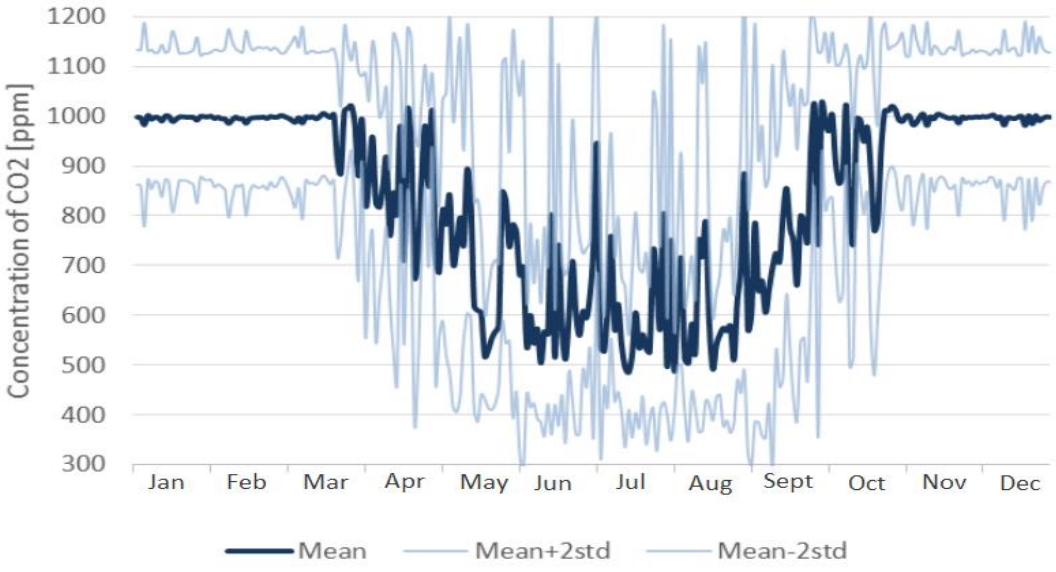


Figure 59 Concentration of CO_2 during working hours, Natvent

In winter, the control of the natural ventilation is governed by the CO_2-level in the scenario Natvent, as discussed in section 11.1.1.2. It is favorable to limit the numbers of window openings to reduce the energy use and incidents that might cause draft. The set point for CO_2 is 1000 ppm in the model, with a dead band of 200. Thus, the vents open when the concentration exceeds 1100 ppm and closes when it drops below 900 ppm. Figure 59 show that the indoor air quality mainly is a challenge during winter. In spring and summer, the mean level diminishes as the temperature increases and passive night cooling is utilized. During autumn, the mean level increases as the outdoor temperature decreases and there is less venting due to solar gains and high indoor temperatures. However, the indoor air quality is also a challenge during warm days as the vents close when the outdoor temperature exceeds the indoor temperature. This happens occasionally during the summer months, as seen in Figure 59. Since the occupancy was set to be 100 % and the simulations were run with mixing ventilation, the results of the indoor air quality can be considered as a worst-case scenario.

Figure 60 shows the indoor air quality during occupancy hours in the scenario Hybvent 70_30, with 95 % confidence interval.

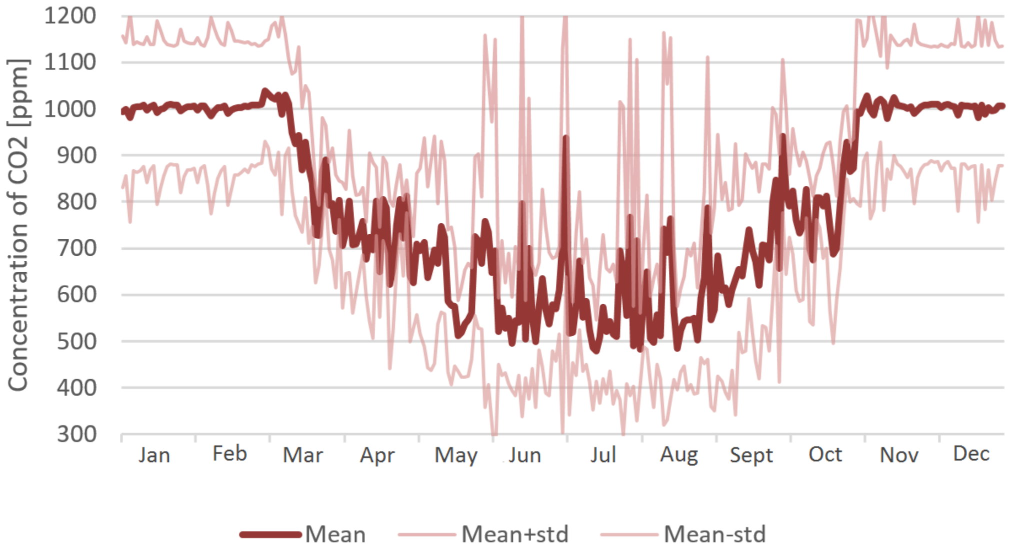


Figure 60 Concentration of CO_2 during working hours, Hybvent 70_30

The indoor air quality in Hybvent 70_30 has a similar profile to Natvent. The CO_2-level is high in winter, and diminishes during the warmer seasons. The difference between the two scenarios is the smaller variation in the daily CO_2-level during spring and autumn. The small air-handling unit constantly removes some CO_2 from the zone and thus limits the variation in concentration during the day.

Figure 61 shows the indoor air quality during occupancy hours in the scenario Hybvent 40_60, with 95 % confidence interval.

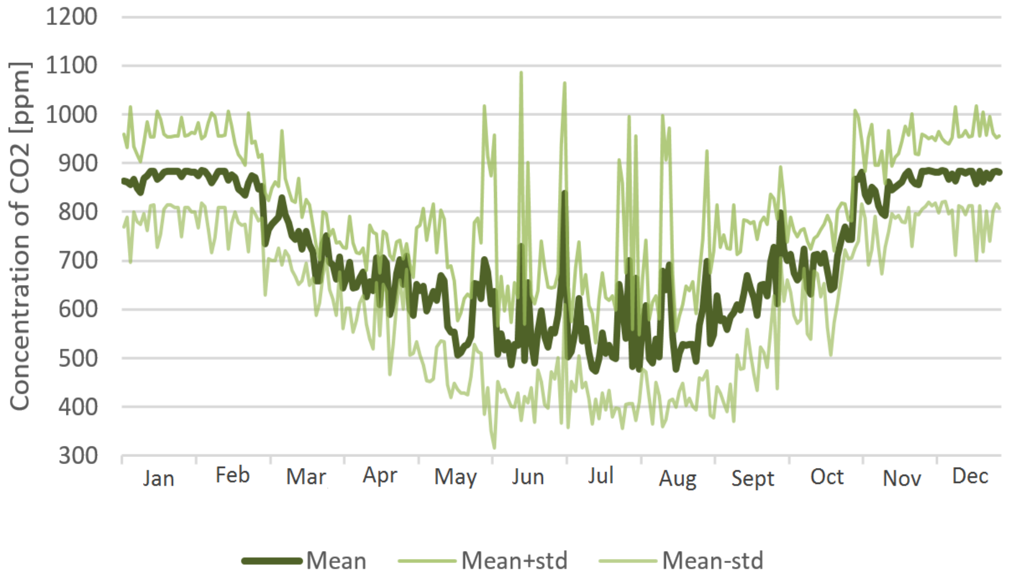


Figure 61 Concentration of CO_2 during working hours, Hybvent 40_60

The scenario Hybvent 40_60 stands out from the two others by not having any problems with the CO_2-level in winter. The air quantity provided by the mechanical system is sufficient to keep an acceptable indoor air quality without the use of natural ventilation on cold days. The higher degree of mechanical supply also leads to a lower degree of daily variations during winter, spring and autumn. In summer, the CO_2-level rises as the vents are closed due to high outdoor temperatures, but the mechanical air supply prevents the levels in rising too high during the day.

TEK has set requirements to the minimum supplied air quantities in office buildings during occupancy hours. An analysis of the supplied air to the zones in the different scenarios was performed to make a comparison between the air supply in the scenarios and the requirements in TEK. Figure 62 shows the distribution of supplied air in the zone facing South East during occupancy hours.

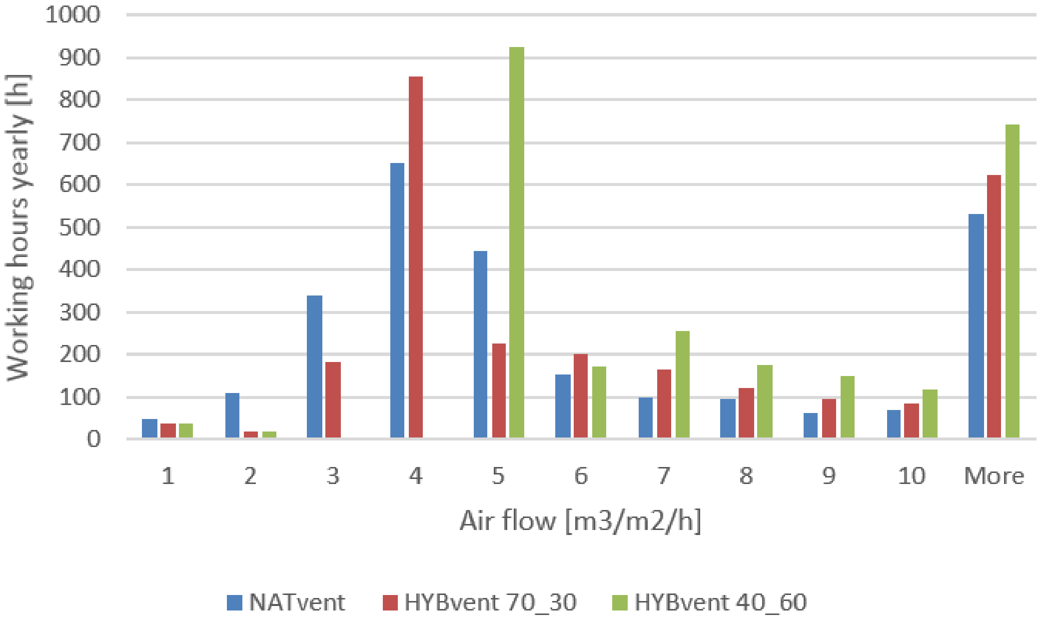


Figure 62 Distribution of air flows during occupied hours

The scenarios have different distribution of air quantities supplied to the zone. The trend is lower air quantities in the naturally ventilated scenario and higher air quantities with increasing amounts of mechanical air supply. Both Hybvent 70_30 (2 $m^3/m^2/h$) and Hybvent 40_60 (4 $m^3/m^2/h$) have some hours with low air supply related to the first minutes after the start-up of the air-handling unit at 07:00 every morning.

The minimum requirement in TEK for supplied air quantities in office buildings is 26 m^3/h per person and 2.5 $m^3/m^2/h$ due to emission from materials. Figure 63 show to which extent the scenarios fulfill the air quantity requirements in TEK, when simulating a density of one person per 10 m^2 in a zone of about 100 m^2.

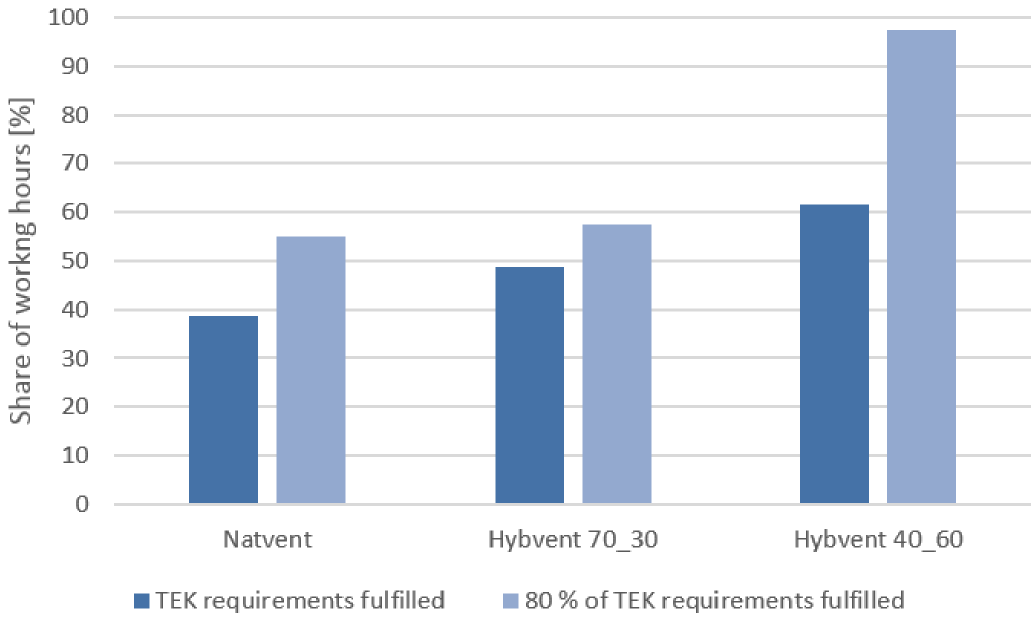


Figure 63 Share of working hours with air flow requirements in TEK fulfilled

The scenarios do not fulfill the air quantity requirements in TEK during all working hours, as seen in Figure 63.The naturally ventilated scenario fulfills TEK for about 40 % of the working hours, while the hybrid scenarios achieves a little higher percentage. Hybvent 70_30 (2 $m^3/m^2/h$) fulfills the requirements during almost 50 % of the occupied hours, while Hybvent 40_60 (4 $m^3/m^2/h$) achieves a little more than 60 %. The choices of mechanical air supply in the hybrid solutions were based on common sizes on AHU's in hybrid systems [54]. The main reason for the low achievement of the TEK requirements is that the atmospheric environment in this thesis has been assessed in a different manner than in TEK. Instead of assessing the atmospheric environment based on minimum air quantities, the assessment has been performed based on the air quality indicated by the CO_2-levels. An analysis of the distribution of CO_2-levels during occupancy hours is seen in Figure 64.

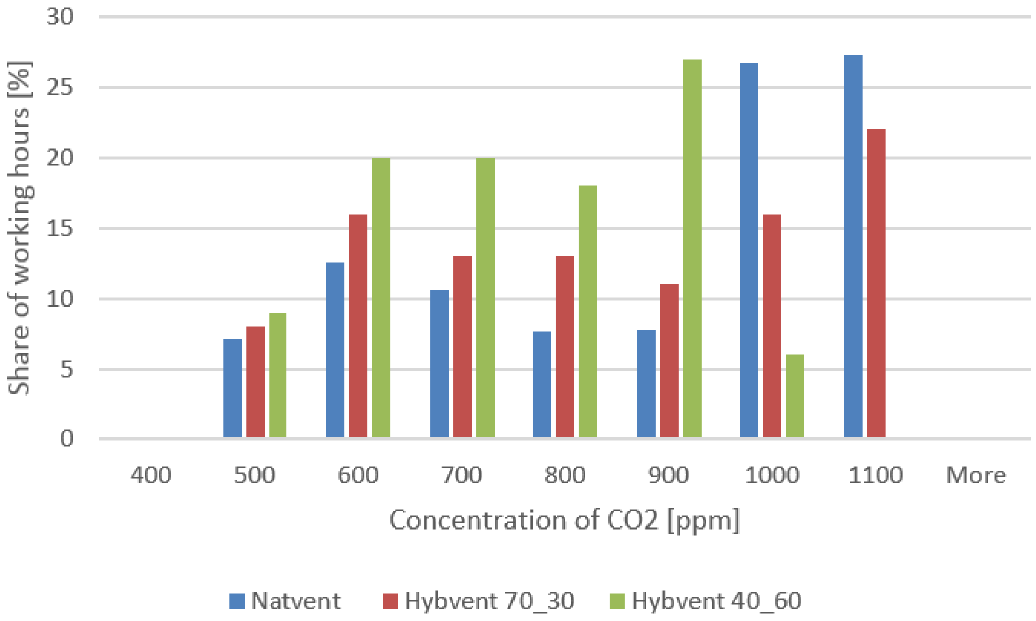


Figure 64 Distribution of concentration of CO_2 during occupied hours

When assessing the atmospheric environment based on CO_2-levels, all scenarios have acceptable indoor air quality. Hybvent 40_60 remains below 1050 ppm during 100 % of the occupancy hours. Hybvent 70_30 and Natvent have a slightly higher concentration during winter months when the windows are controlled by the upper set point for CO_2. In total, the CO_2-level in Natvent and Hybvent 70_30 does not exceed 1000 ppm for 73 % and 77 % of the working hours, and have less than 1 % of occupancy hours with more than 1100 ppm.

The differences between the analyses based on TEK and the CO_2-levels raises the question: what is good indoor air quality? The scenarios investigated do not have sufficiently good atmospheric environment according to TEK, but based on the simulated CO_2-levels, the indoor air quality in the building should be preferable. One aspect to be considered is that TEK accounts for emissions from materials in addition to pollution from occupants. In this thesis, the main objective has been to investigate how the solutions in 2226 could work in a Norwegian climate. In 2226 the ventilation is demand controlled based on CO_2-levels and accounts for varying occupancy in an office building due to meetings etc. during a day. Such approach requires the use of materials with low or very low emissions. The additional morning airing was included in the scenarios to ventilate emissions from materials before the occupants arrive at work in the morning.

One aspect not treated in this thesis is the effect of the air’s enthalpy on the indoor air quality. The combination of indoor temperature and relative humidity may be of importance for the perceived air quality when supplying with lower air quantities. The relative humidity in the scenarios have not been investigated in this thesis as CO_2 was chosen as indicator for air quality, but should be further investigated.

11.1.3 Analysis of heating systems

The building solution 2226 in Austria was created without a mechanical heating system, and manages to maintain an acceptable indoor temperature throughout the year due to clever utilization of thermal mass, heat from internal gains, solar gains and additional heat from lighting during cold days.

To investigate the need for heating in a Norwegian context, an ideal heater was inserted in each zone during the simulations. The simulation results showed a dimensioning heat rate of about 2000 W in each open office in the scenario Natvent. The hybrid solutions had higher maximum heat rates, but significantly lower duration. Thus, it was chosen to run simulations with electrical radiators of 2000 W in the analysis of the indoor environment in section 11.1.1 and 11.1.2. Further, an analysis of the size of and impact of hydronic heating systems was performed on the scenarios.

The simulation model was reduced to four zones as described in section 10.2, and Figure 65 shows the duration curve of the different scenarios with electrical heaters when the number of office zones have been scaled to full building size.

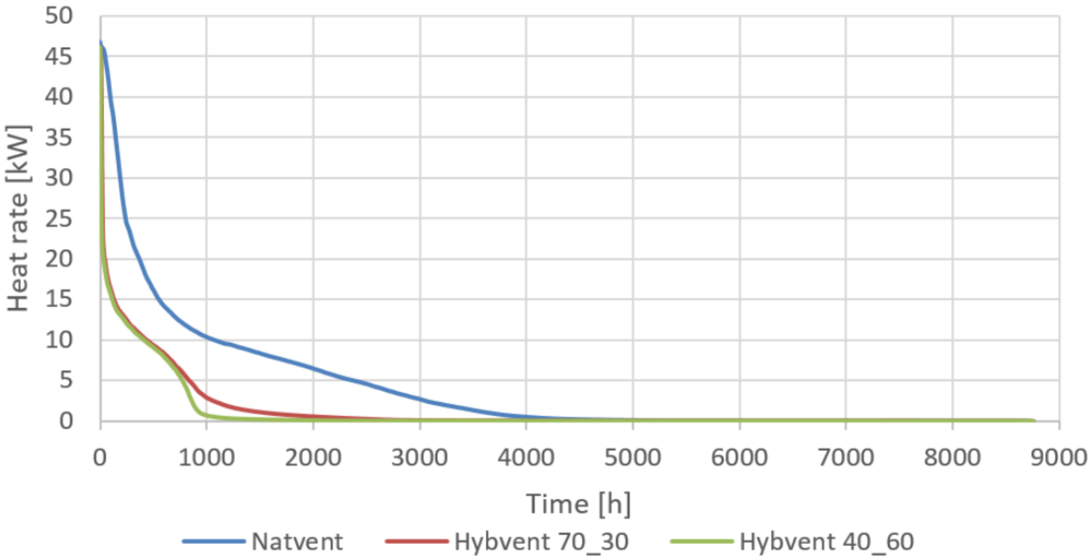


Figure 65 Duration curves full building scale

The duration curves in Figure 65 show that the scenarios have different distribution of heat rates during the year. The scenario Natvent has a need of heating during large parts of the year, while the hybrid scenarios have shorter duration with heating. To investigate the necessary size of a possible heating system, the electric heaters in each zone were replaced with water radiators with maximum heat rate 2000 W at 20°C, supply temperature 60°C and return temperature 40°C, at nominal conditions. A heating load was run with design outdoor temperature in Oslo (-19.8°C) and 0 % internal gains. Figure 66 shows the resulting heat rate and indoor temperatures at dimensioning conditions in the scenario Natvent.

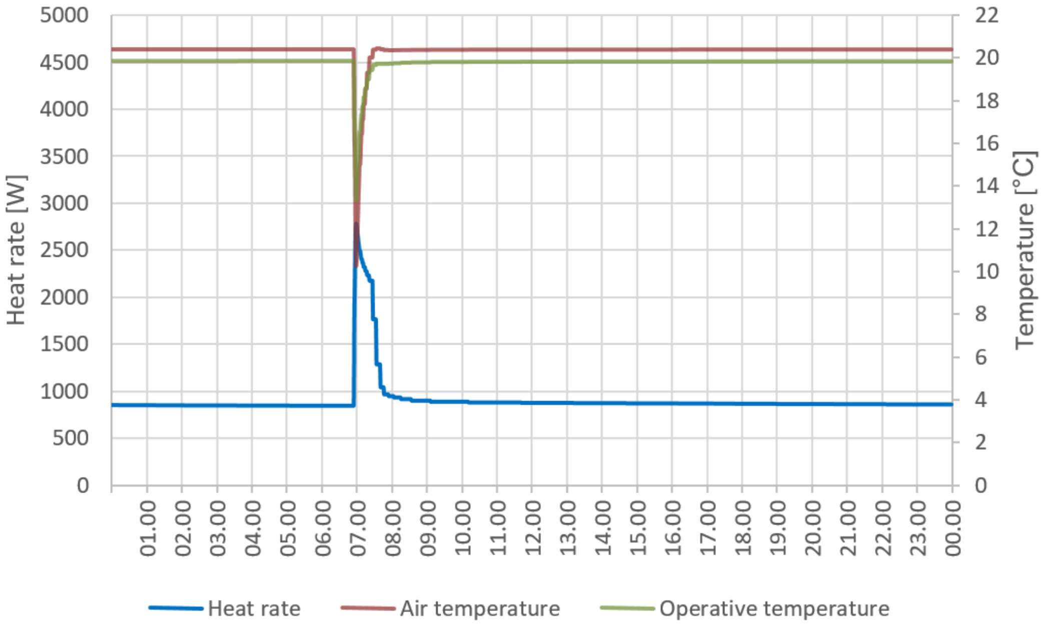


Figure 66 Dimensioning conditions Natvent - heat rates and temperatures, 0 % internal gains

The heat rate in has a general level of 800 W, with the exception of a peak value actuated by the forced morning airing around 07:00. The heat release from the radiator depends on the radiator constant, radiator exponent and mean temperature difference between the radiator and the room air. As the temperature in the room decreases during airing, the heating power output from the radiator increases. During normal conditions, a share of the occupants will be present during the day. Therefore, an additional simulation was run with 50 % internal gains to investigate the need of heating with people present. The heat rate and temperature profile with 50 % internal gains are seen in Figure 67.

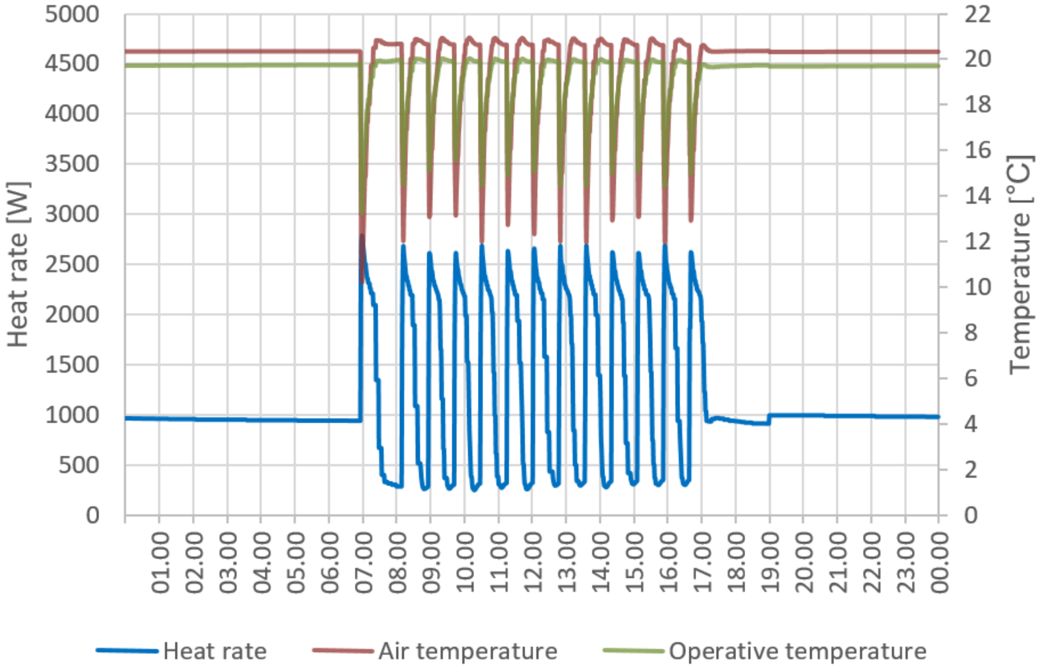


Figure 67 Dimensioning conditions Natvent - heat rates and temperatures, 50 % internal gains

When the number of occupants increase, the control system in Natvent needs to ventilate several times during the day due to high CO_2-levels. The opening of the windows creates peaks in the heat rate as the temperature drops during each airing, and heat is needed to lift the temperature up to the heating set point of 20°C. Figure 68 shows the distribution of heat rates with a water radiator of 2000 W in the zone and 60 % internal gains.

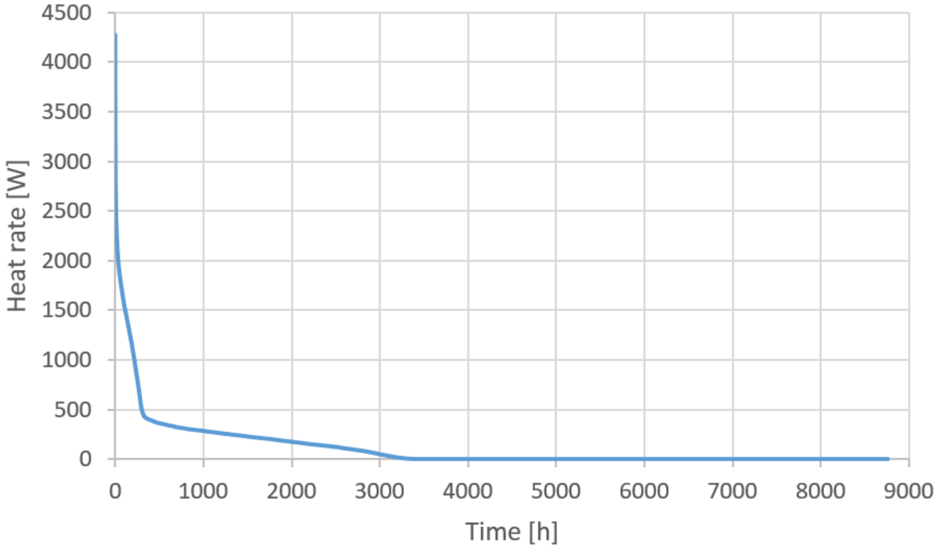


Figure 68 Natvent, Heat rates with water radiator 2000 W

The effect of different radiator sizes on the room temperature in Natvent was investigated at dimensioning conditions. The resulting temperature profiles during airing with water radiators of 2000 W, 2700 W and 4000 W are seen in Figure 69.

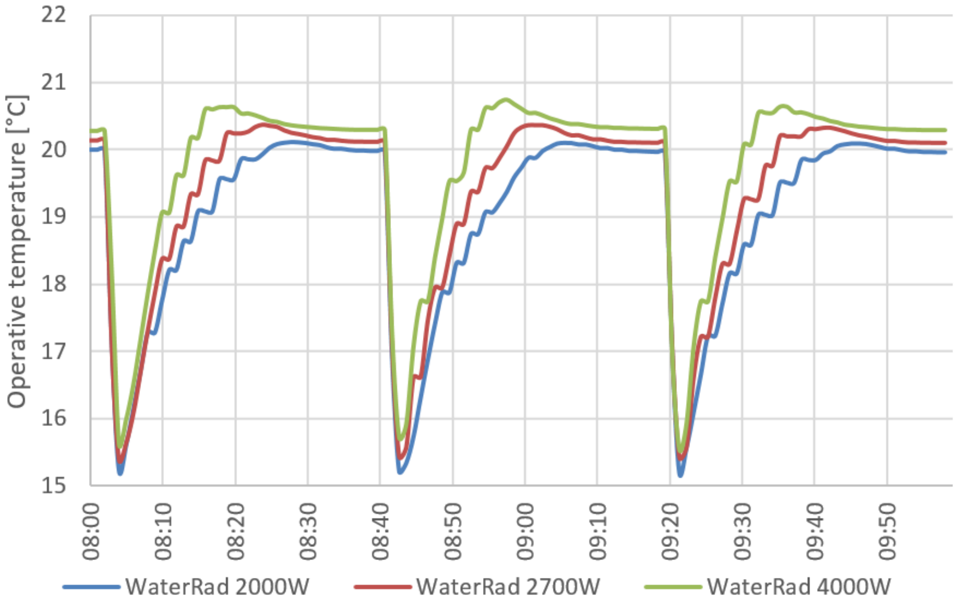


Figure 69 Effect of radiator size on indoor temperature, Natvent

The temperature drop is approximately the same in all scenarios because of the heating systems' inertia, as seen in Figure 69. However, larger radiator sizes give a quicker increase in temperature because larger heat rates can be provided during airing. The temperature profiles could additionally be improved by optimal control of the system. Sizing and good control of the heating systems are important factors for thermal comfort and should be further investigated, but was not the scope of this thesis.

A similar analysis was performed on the two hybrid solutions with a water radiator of 2000 W. The heat rate profiles of the two hybrid solutions were found to be identical at dimensioning conditions and are seen in Figure 70 with 0 % and 50 % internal gains.

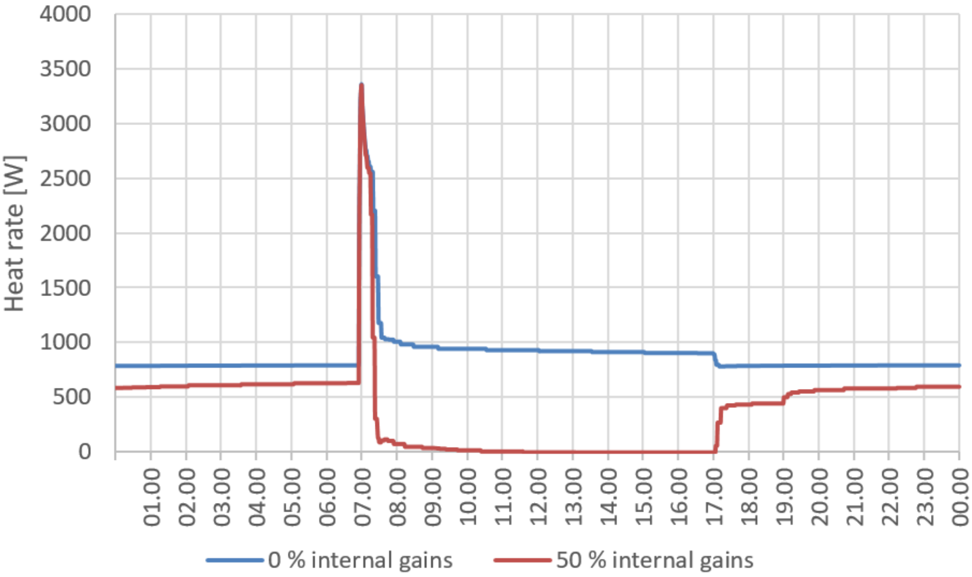


Figure 70 Dimensioning conditions Hybvent scenarios - heat rates and temperatures, 0 % and 50 % internal gains

In the hybrid systems, the background ventilation prevents the windows from opening as CO_2 is exhausted from the zone. The lack of airing prevents large temperature drops during the day and internal gains can cover large parts of the heating during daytime. Outside of occupancy hours the need of heating depends on the percentage of internal gains. For Hybvent 70_30 the 2 $m^3/m^2/h$ is sufficient until a certain level of internal gains, where window openings are necessary and additional supplied heat is needed to rise the temperature. As discussed in 11.1.2 Hybvent 40_60 does not have problems with CO_2-levels in winter, and thus internal gains could cover the heating need during the day. Further, energy simulations with 60 % internal gains were run with a larger and a smaller radiator size of 3400 W and 800 W. The resulting heat rates are seen in Figure 71.

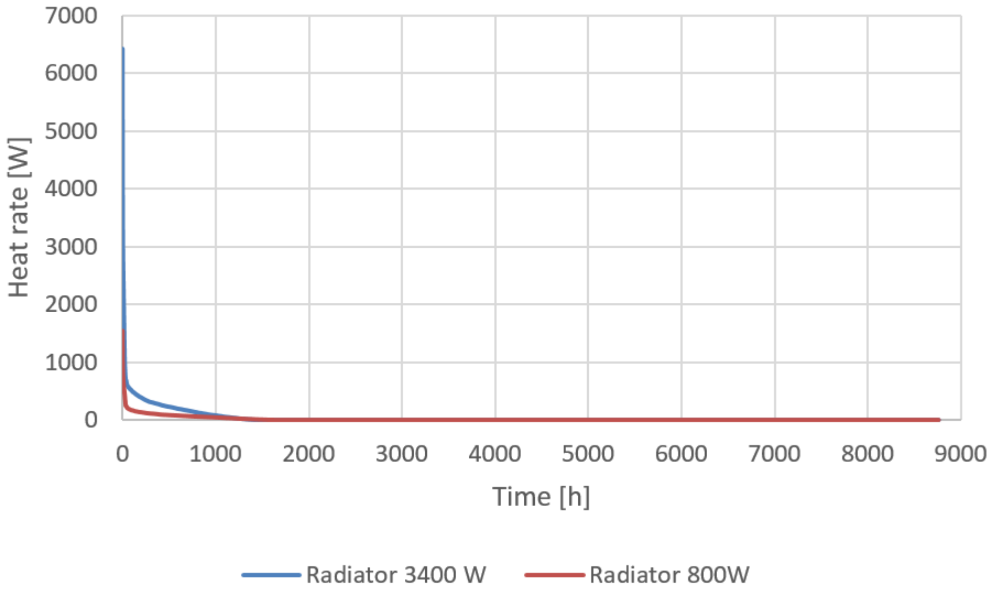


Figure 71 Hybvent, Heat rates with water radiators 3400 W and 800 W

The heat rates in Figure 71 show high maximum rates, but very low durations. Figure 72 show the effect of different radiator sizes and internal gains on temperature during the forced morning airing at dimensioning conditions (-19°C).

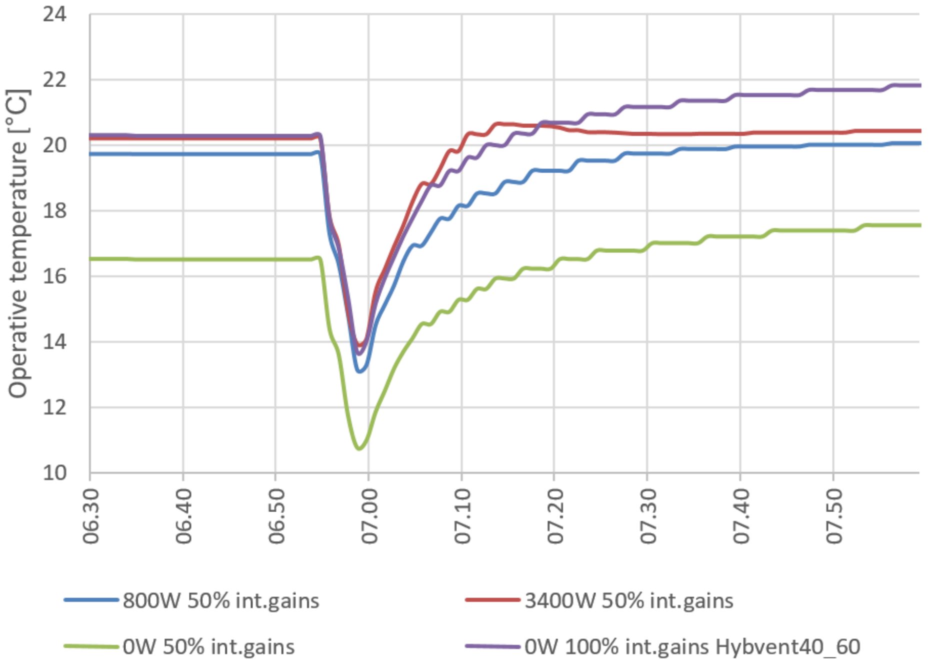


Figure 72 Effect of radiator size on indoor temperature, Hybvent

As in the scenario Natvent, the minimum temperature largely depends on the temperature level before airing because the heating systems need time to react when windows are opened. The larger radiator size increases the temperature more rapidly than the smaller size, and the radiator of 800 W struggles to maintain 20°C outside of occupancy hours during the coldest days. Furthermore, Figure 72 show the impact of internal loads. Low degrees of internal loads are not sufficient to maintain comfort temperatures during cold periods. However, with sufficiently high mechanical supply (Hybvent 40_60) and minimum airing on cold days, high internal gains could cover large parts of the heating demand.

Do a building based on the 2226-concept have a need for heating in Norwegian conditions? The analysis in this thesis show that it depends on the degree of natural ventilation and internal loads. The naturally ventilated scenario shows a need of heating during parts of the year, while the hybrid scenarios have a smaller need for heating during shorter time of the year. Possible sizes and optimal control of the heating systems in the scenarios can be discussed, and should be further investigated. The final choice of solution should be based on a cost-benefit analysis between size and comfort.

11.1.4 Yearly energy use

The yearly energy use of the three solutions with automatic windows is seen in Figure 73. The simulations were run with electrical heaters in each zone and the energy use for domestic hot water was set to be 5 kWh/m^2 in all scenarios based on recommended dimensioning values in NS 3031.

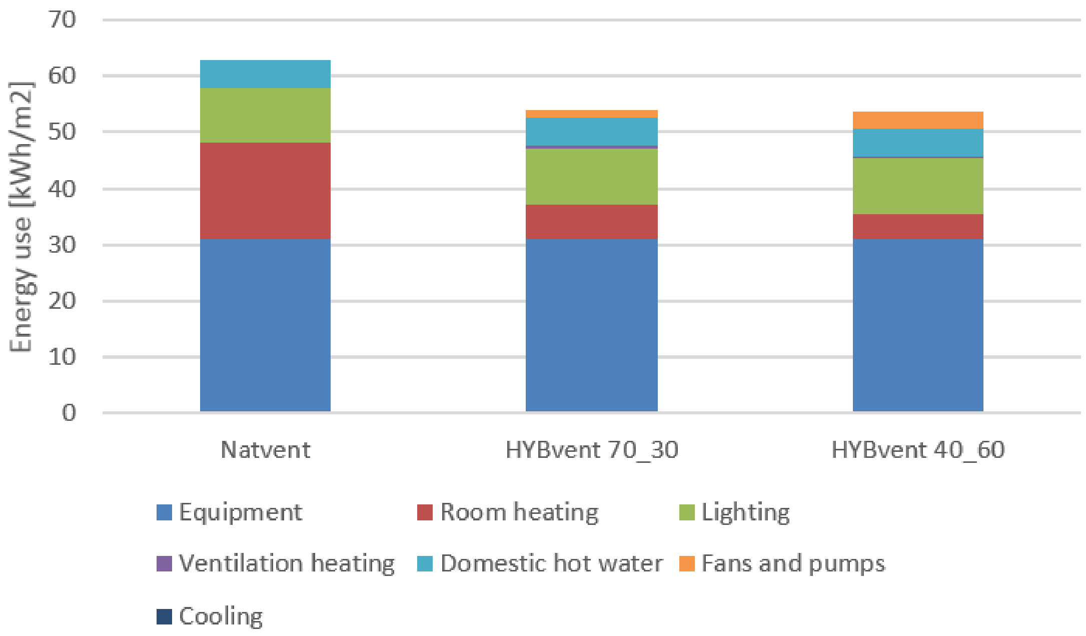


Figure 73 Energy use in the scenarios

The analysis of the energy use show that Natvent has the highest heating demand. The two hybrid solutions have lower heating demand due to heat recovery in the air-handling unit and less opening of windows in winter. When looking at the hybrid solutions, the energy use for fans in Hybvent 40_60 is higher due to larger air flow rates in the system, but energy use for room heating is lower because of fewer window openings.

The yearly energy demand of the scenarios is about 63 kWh/m^2 for Natvent and 54 kWh/m^2 for the two hybrid scenarios. For a comparison, the requirement in TEK is maximum 115 kWh/m^2 for office buildings and the energy efficient building Powerhouse Kjørbo has an energy use of 34 kWh/m^2 when excluding electricity use for the computer room. A discussed in section 3.3.5, buildings with only natural ventilation cannot fulfill the requirements in TEK because of the required calculation method. However, the energy use based on the project prerequisites show that all scenarios, both natural and hybrid, are well below the energy requirements in the Norwegian building regulations.

11.1.5 Parameter study

The main principle in 2226 is an integrated ventilation strategy, which interacts with the construction’s thermal properties. The solution is based on the use of night cooling, a construction with high heat capacity and internal gains for heating. The effect of these three design parameters on thermal comfort and energy use was investigated in the parameter study. The simulations were run with 100 % internal gains and an electrical heater in each zone. Domestic hot water is not included in the comparison of the energy use.

11.1.5.1 Effect of night cooling

The effect of night cooling was investigated by running simulations with schedules for window opening only during occupancy hours (07:00-17:00). Figure 74 shows the yearly number of hours above 26 and 27°C with and without night cooling. The straight line in the figure represents the upper limit of 50 h per year recommended in TEK.

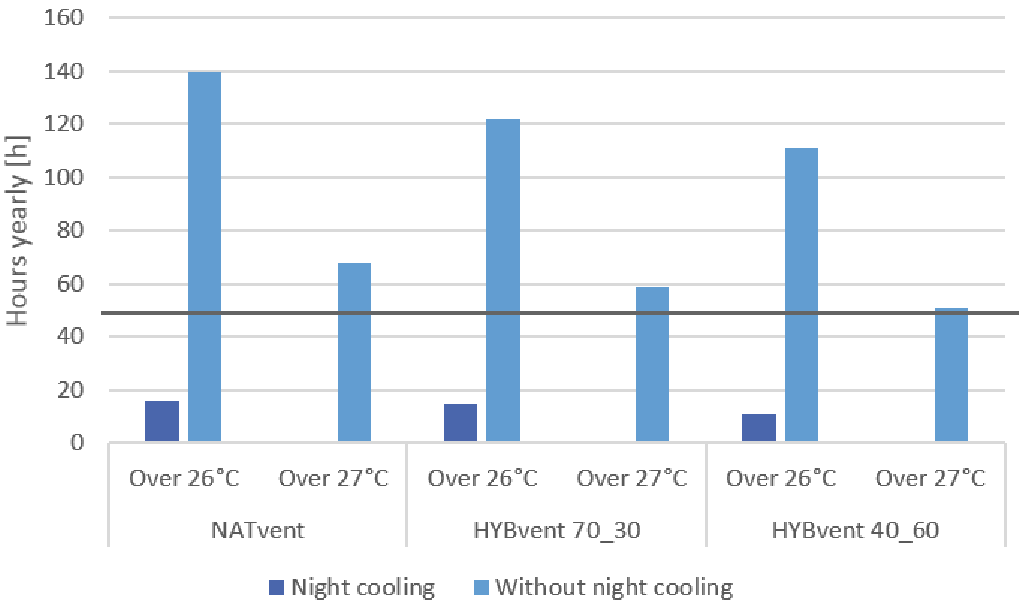


Figure 74 Yearly hours above 26 and 27°C with and without night cooling

The use of night cooling is necessary to avoid overheating and achieve the requirement in TEK of maximum 50 h over 26°C during a year. As seen in Figure 74, all the scenarios without night cooling greatly exceed 50 h above 26°C and additionally have a high number of hours above 27°C. The night cooling ensures a slower increase in temperature during the day, as the building construction has been cooled down and can buffer the temperature increase by absorbing heat. Thus, the night cooling also affects the maximum temperature in the building, as seen in Figure 75.

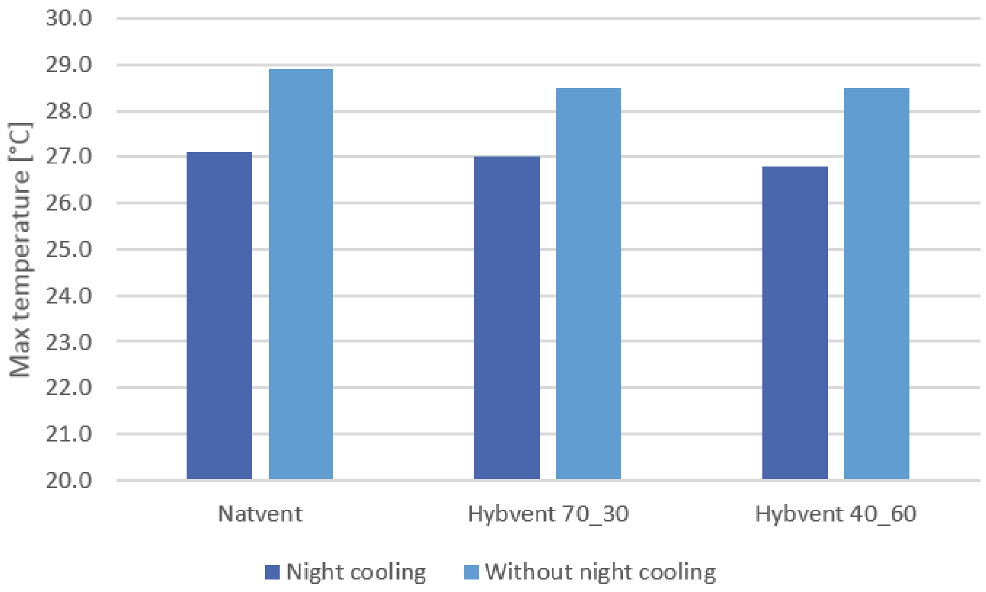


Figure 75 Maximum temperature with and without night cooling

The indoor temperature increases with a certain number of degrees during the day due to heat from internal loads and solar gains. The use of night cooling ensures low indoor temperature in the morning and decreases the maximum temperatures on warm days by 1.5 - 2°C. Further, the energy use of the scenarios with and without night cooling is seen in Figure 76.

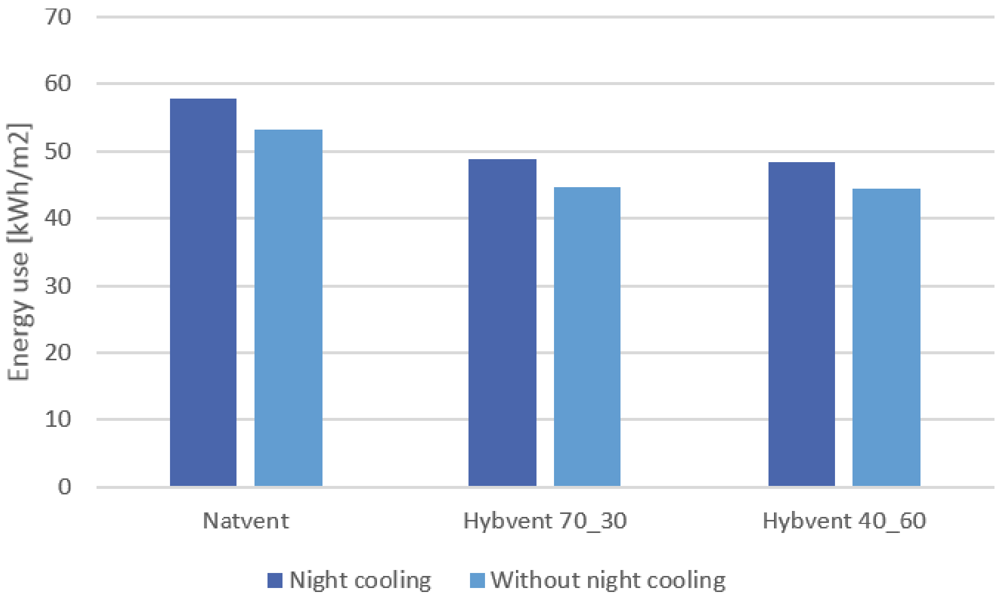


Figure 76 The effect of night cooling on energy use

According to Figure 76, the use of night cooling actually increases the energy use with about 8 % in all scenarios. The reason for the increase could be the lack of optimization of the control system for night cooling, causing an additional need of heating. However, the significant improvement of the thermal conditions is more important than the slight increase in energy use, and passive night cooling is the most efficient way to remove excess heat from the building.

11.1.5.2 Effect of heat capacity

The effect of the construction's heat capacity was investigated by simulating the scenarios with a suspended ceiling in each zone. The suspended ceiling was created by adding a layer of light insulation to cover the exposed thermal mass in the ceiling. Figure 77 show the number of hours yearly with more than 26 and 27°C for a construction with high and low heat capacity.

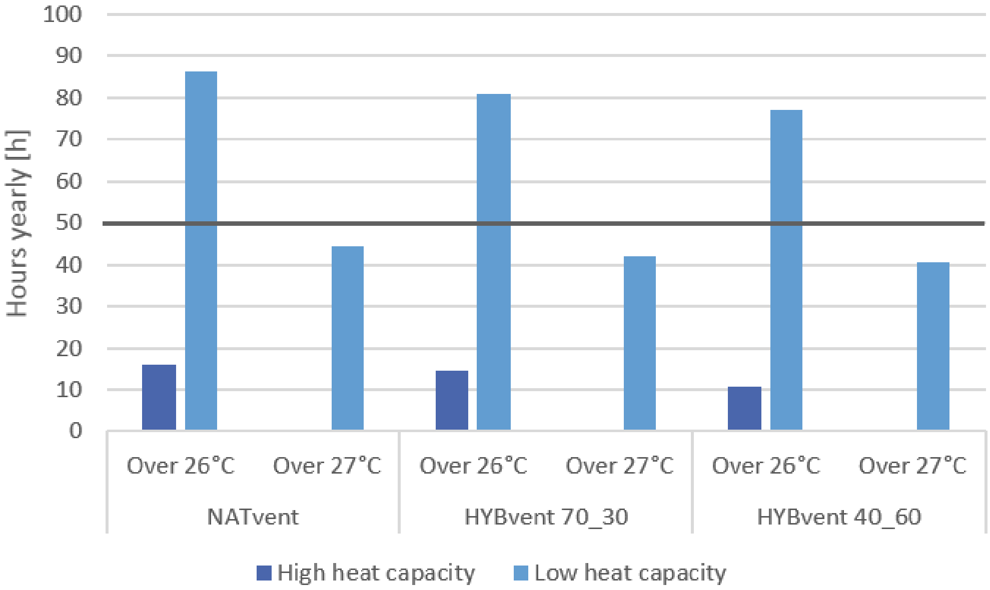


Figure 77 Yearly hours above 26 and 27°C with high and low heat capacity

As seen in Figure 77, none of the scenarios with suspended ceiling achieves under 50 h below 26°C. The lack of heat capacity limits the effect of the night cooling, as thermal mass is needed to create a heat sink that can slow down and buffer the temperature increase during the day. Radiation from surrounding surfaces affects the operative temperature. When the thermal mass is cooled down at night, the colder surfaces gives a lower perceived temperature than the air temperature in the room. The effect of the thermal mass on the maximum operative temperature is seen in Figure 78.

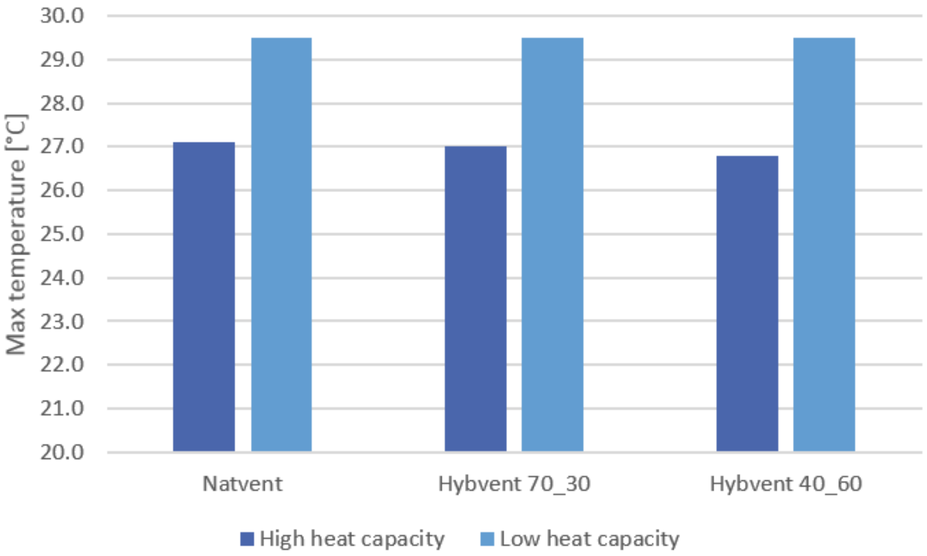


Figure 78 Maximum temperature with high and low heat capacity

The reduction of heat capacity increases the maximum operative temperature with about 2.5°C in all cases. The maximum temperature is generally around 27°C with exposed thermal mass in the ceiling, but increases to 29.4°C when the mass is covered by a suspended ceiling. As discussed in 11.1.5.1, the night-cooled thermal mass will limit the temperature increase during the day. The energy use of the different solutions show no particular change between high and low heat capacity, as seen in Figure 79.

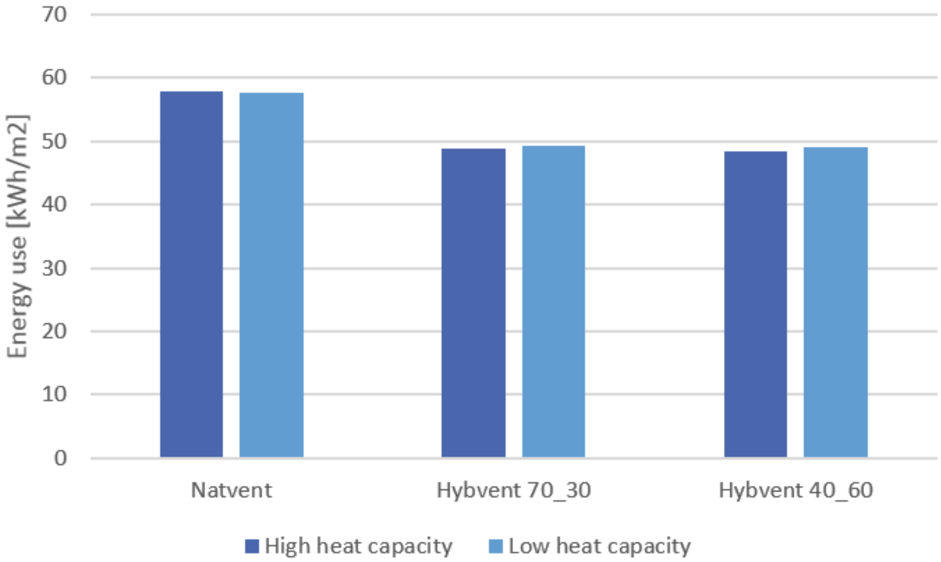


Figure 79 The effect of heat capacity on energy use

According to literature, a construction with high heat capacity should have a somewhat lower energy use than a construction with suspended ceiling, because the thermal mass can buffer changes in temperature and reduce the necessary heat rates. This is the case in the hybrid scenarios, where Figure 79 shows a slight increase in energy use of 1 % with suspended ceiling. The naturally ventilated scenario on the other hand, shows a minor decrease in energy use.

11.1.5.3 Effect of internal loads

The effect of changes in internal loads was investigated by simulating occupant densities of one occupant per 20 m^2, 10 m^2 and 8 m^2. Each occupant in the office was assumed to have a computer and a lamp on the desk, and hence the values for equipment were scaled correspondingly. Figure 80 show the number of hours above 26 and 27°C for the different internal loads in the three scenarios.

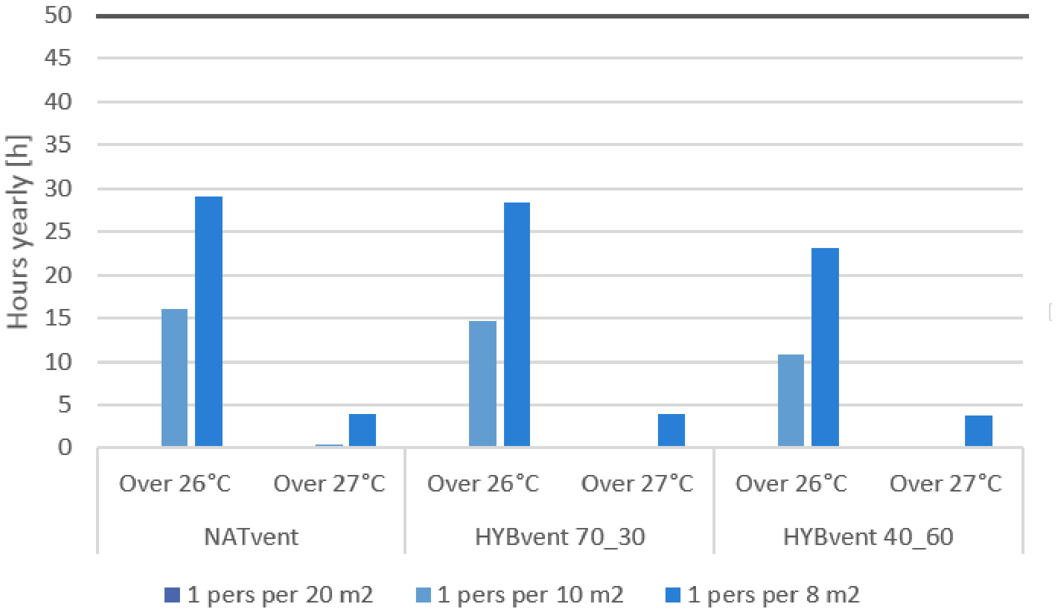


Figure 80 Yearly hours above 26 and 27°C with different internal loads

As seen in Figure 80, all sizes of internal loads fulfill the TEK-requirement of maximum 50 h with good margin. Low occupant density gives no overheating during the year, while the increase in internal loads by higher occupant density increases the number of hours above 26 and 27°C during the year. The maximum temperature of the scenarios are seen in Figure 81.

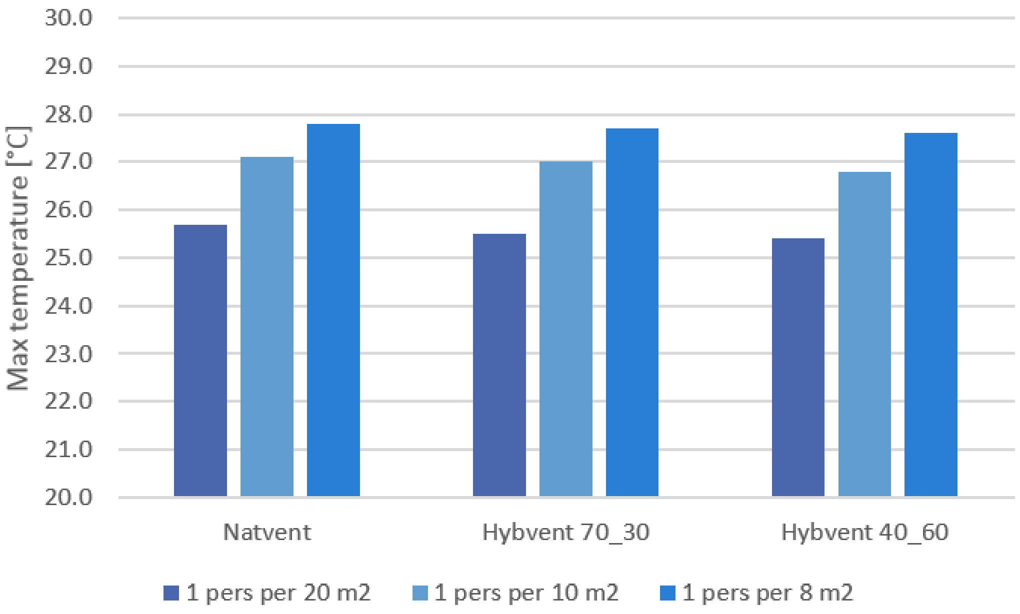


Figure 81 Maximum temperature with different internal loads

Higher occupancy density adds larger internal gains and thus increases the maximum temperatures in the building. The scenarios with low occupant density never exceed 26°C, while the intermediate and high levels have a maximum of about 27-28°C. Increasing degree of hybrid ventilation gives a slight decrease in the maximum temperature. High maximum temperatures are mainly a problem during warm days when the outdoor temperature exceeds the indoor temperature and the vents remain closed to avoid additional heating from the outside air. This happens occasionally in summer, but according to Figure 80, overheating is generally not a problem in any of the cases.

The effect of the occupant density on the total energy use is seen per person in Figure 82 and per area in Figure 83.

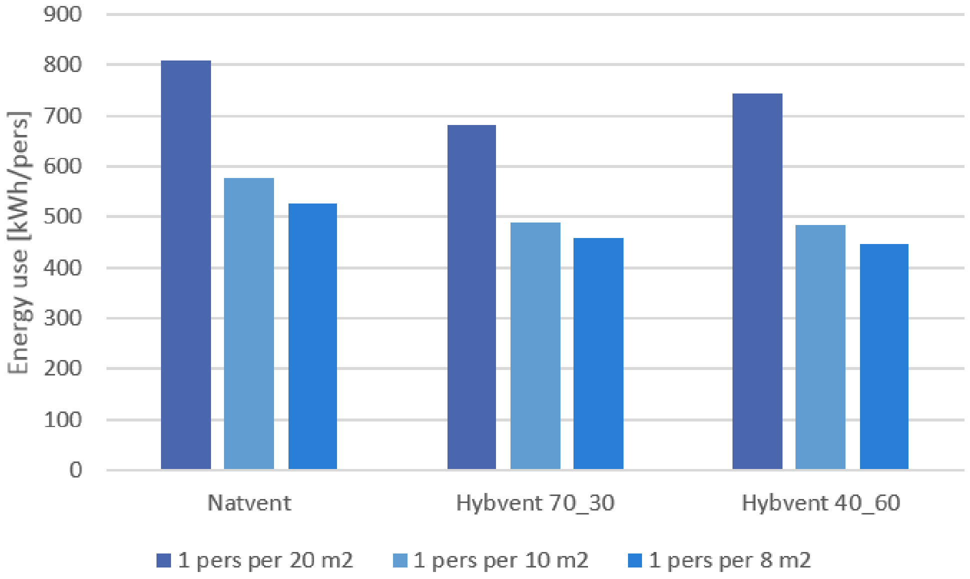


Figure 82 The effect of internal loads on energy use per person

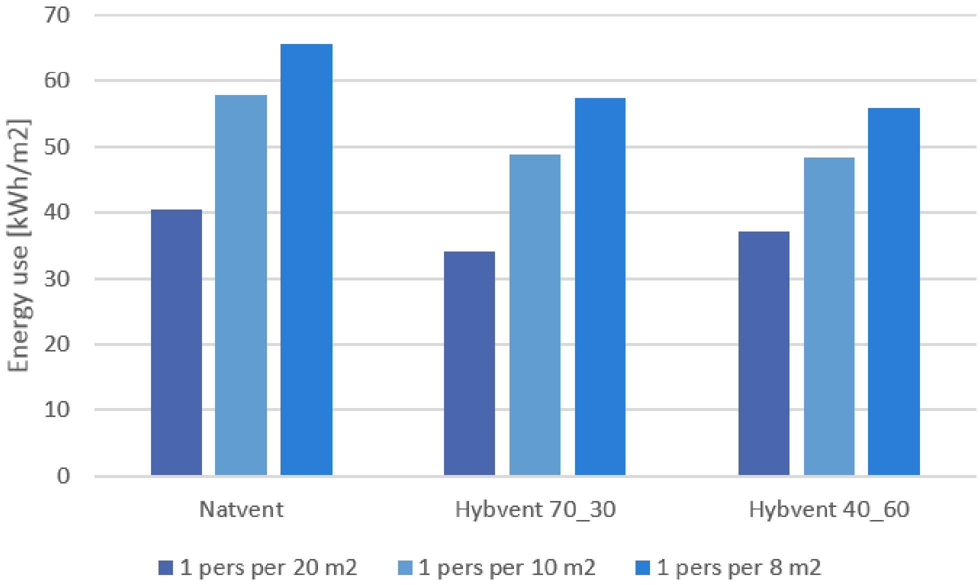


Figure 83 The effect of internal loads on energy use per floor area

In all scenarios, the energy use per person decreases with increasing occupant densities. However, higher occupant densities leads to an increase in the total energy use per floor area. The increase is largely related to the demand control of the indoor air quality. Since the CO_2-level is related to the number of people present, an increase in occupant density requires higher air flow rates to maintain 1000 ppm in the building. Consequently, higher occupant densities increases the number of window openings on cold days and heating is activated to regain comfort temperature. Table 10 show the number of airings needed during a cold day (in addition to the morning airing) to maintain a CO_2-level of 1000 ppm with different occupant densities.

Table 10 Number of airings during cold winter day (in addition to morning airing)

	Natvent	Hybvent 70_30	Hybvent 40_60
1 pers per 20 m^2	12	0	0
1 pers per 10 m^2	23	9	0
1 pers per 8 m^2	28	15	0

For the naturally ventilated scenario and the hybrid scenario with low air quantities, there is a clear relation between the occupant density and the number of window openings on cold days. The hybrid scenario with higher air quantities does however manage to avoid window openings on the coldest days, since the base ventilation in this case is sufficient to cover up to one person per 8 m^2.

In real life, the presence in office buildings will vary due to meetings, travels, home office etc. The simulations in the parameter study were run with 100 % presence, and thus the results can be seen as a worst case scenario of the different occupant densities.

Floor area efficiency is important for tenants, as the utilization of area affects the cost of rent. The parameter study show that it is favorable to limit the occupant density in natural and hybrid ventilated buildings, since it limits incidents with overheating in summer and the number of window airings in winter. If high occupant densities are required, a solution could be to increase the degree of mechanical supply a hybrid ventilated building.

11.2 User controlled window ventilation and stochastic modelling

To model manual window openings of users being stimulated by an app, a new window controller was developed in IDA ICE. The controller was created by using accessible modules in IDA ICE and including files with random numbers. An overview of the set up in IDA ICE is seen in Figure 84.

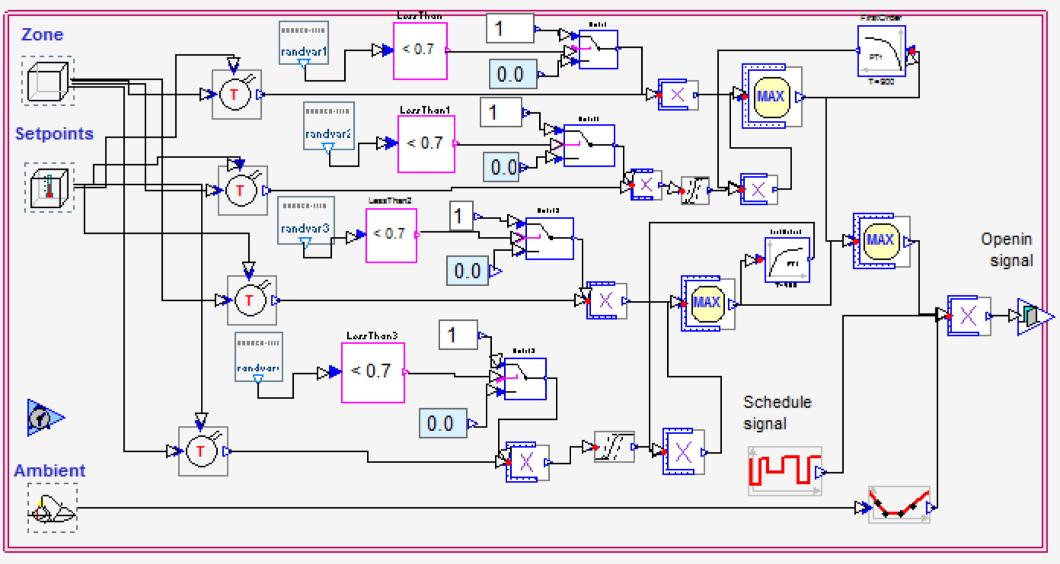


Figure 84 Manual window controller, set up in IDA ICE

The controller was created with two main branches, one related to opening signals due to temperature and another related to air quality (CO_2-level). The maximum value of the two signals determines the final opening signal together with the occupancy schedule and outdoor temperature. Each of the two main branches consists of two sub-branches representing opening and closing, having different random values. The temperature and CO_2-levels are measured in the zone and an opening signal is sent to the user by the app. The random number decides if the user chose to react and the window is to be held open by the time delay until a closing signal is generated and the user chose to manually close the window.

Creating a well-functioning window controller to models manual window opening and stochastic behavior in a simulation program is however a challenging task. The controller shown in Figure 84 was the result of many attempts with different approaches. The simulation results seemed logical, but when looking deeper into the signals in the controller, it was found that the window control does not operate as intended. An example of the course during window opening on a cold day is seen in Figure 85. The two straight lines indicates the upper and lower set-point values for CO_2.

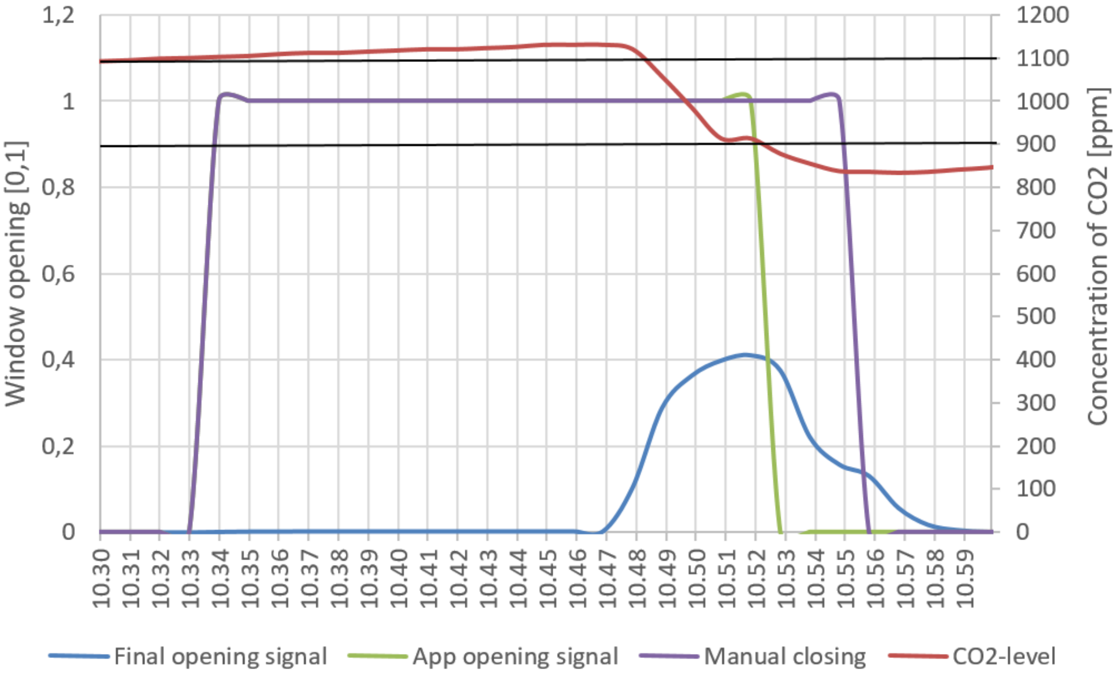


Figure 85 Manual window controller in IDA, Signals

When the CO_2-level exceed the upper set point value of 1100 ppm at around 10:30, the app sends an opening signal to the user. The user does not react at first, but after 15 minutes, the user chose to open the window around 10:47. The problem in the controller arise when the CO_2-level drops below the lower set point value. The opening signal in the app is switched to zero and forces the final opening signal to close the windows. The closing of the windows was not supposed to happen before the signal from the manual closing set the final value to zero, and thus the control acts too efficiently and does not properly model human behavior. The same problem occurs when the windows are opened due to high temperatures.

Since the manual window control was found to not work as intended, further results from the stochastic analysis are not presented in this thesis. The introduction of stochastic variables in building simulation can generally be a good procedure to model the different outcomes of human behavior, but further work is needed to develop a suitable simulation model for manual window control stimulated by an app in IDA ICE.

11.3 General remarks

The building 2226 in Austria is an example of a construction with a minimum of technical installations. The concept has been made possible through clever optimization of the building geometry, floor plans, choice of materials, use of internal gains and control of natural ventilation. Such solution requires a holistic approach by a highly skilled multidisciplinary design team with good knowledge of local climatic conditions, building physical properties and software development. Most building projects will not have the frames to create a fully optimized solution as in 2226. However, the philosophy of the building is important to bring forward. It can be possible to limit the use of advanced technical installations though the use of architectural solutions and integration of heating and ventilation strategies in the building construction. A focus on high quality solutions and flexibility is important to achieve sustainable buildings with a long lifetime.

In Norwegian conditions, a building solution based on the principles in 2226 can maintain a low energy consumption, but will not achieve the current energy requirements in TEK due to the required calculation method. Optimal control of the natural ventilation system is crucial to ensure a good indoor environment. It is challenging to provide good thermal conditions in winter, when cold outdoor air is taken directly into the occupant zone. The risk of draft could be reduced by choosing a multi-element window with an upper bottom hung element combined with cross ventilation in winter or by pre-heating the air. A hybrid solution can solve many of the challenges with natural ventilation. Hybrid strategies combines the advantages of natural and mechanical ventilation by utilizing passive cooling and heat recovery. The hybrid solutions assessed in this thesis improves the indoor environment by lowering the CO_2-levels and decreasing the number of window openings needed on cold days.

The optimal ventilation solution in each project depends on the building’s site, context, function, users and project pre-requisites. In some cases, an advanced mechanical system will be the most appropriate solution. However, in cases where it is feasible, it is favorable to limit the complexity and size of the technical systems. Many building owners experience faults and problems with the operation of advanced technical installations. Systems of lower complexity are more comprehensible, and thus easier to operate and maintain. Integrated ventilation solutions by automatic window openings can be more cost and resource efficient than an advanced mechanical installation over the lifetime of a building, since fewer adjustments are needed when new tenants are moving in. Ventilation by manual window control could further lower the system’s cost and complexity. Perceived personal control of natural ventilation has been proven to increase user satisfaction. However, manually controlled natural ventilation can be challenging as it requires motivated and cooperative users who act according to instructions given to ensure good indoor climate and low energy use.

12 Conclusion

In this thesis, integrated ventilation strategies inspired by the building 2226 in Austria were investigated by the use of the dynamic simulation tool IDA Indoor Climate Energy. The strategies consisted of natural and hybrid ventilation and were simulated with automatic and manual windows in combination with a heavyweight construction. The aim of this thesis has been to analyze the indoor environment and energy use of the strategies in Norwegian conditions.

The results show that all three scenarios with automatic windows can provide satisfactory thermal conditions during spring, summer and autumn. The combination of night cooling and exposed thermal mass limits problems with overheating in summer. The main challenge, particularly in the naturally ventilated scenario, is to provide good thermal comfort during window airing in winter. Even though the mean temperature remains above 20°C, the temperature drops below the comfort limits for short periods at every window opening. A hybrid strategy can provide a better indoor climate and lower energy use by limiting the number of pulse ventilations needed on cold days and thus increase the thermal comfort in winter. The optimum degree of natural and mechanical ventilation will have to be developed based on project prerequisites, user requirements and cost analysis.

Due to the general lack of guidance in building standards on evaluation of thermal comfort in hybrid ventilated buildings, thermal comfort was evaluated using the heat balance method, adaptive comfort analysis and exceedance calculations. The analysis show it is favorable to apply adaptive comfort to promote thermal comfort in naturally and hybrid ventilated buildings. However, as natural or hybrid ventilation with automatic openable windows and open offices limits the perceived personal control of natural ventilation, the heat balance method can be seen as a conservative estimate. The naturally ventilated scenario exceed below 20°C for more than the recommended 3 % of occupied hours in NS-EN 15251. Otherwise, all scenarios remain within recommended levels of exceedance. Regarding indoor air quality, the scenarios provide satisfactory air quality based on recommended CO_2-levels, but do not fulfill requirements to minimum air quantities in TEK10. The necessity of the large air quantities in TEK can be discussed, since the systems ensure sufficiently low CO_2-levels.

Do a building based on the 2226-concept have a need for heating in Norwegian conditions? The naturally ventilated scenario was found to have a dimensioning heating rate of about 2000 W in each open office. There is the need of a heating system that can react quickly to regain a satisfactory temperature after pulse ventilation in winter. For the hybrid scenarios, the need for heating is lower and depends on the degree of natural ventilation and internal loads. With sufficiently high mechanical supply and minimum airing on cold days, internal gains could cover large parts of the heating demand. Hence, the choice and optimal control of heating systems can be discussed. Due to the required calculation method in NS 3031, buildings with only natural ventilation cannot fulfill the energy requirements in TEK. However, simulations show a low energy use of 63 kWh/m^2 for the naturally ventilated scenario and 54 kWh/m^2 for the two hybrid scenarios.

Night cooling and exposed thermal mass was found to be crucial to achieve satisfactory thermal conditions in summer, and under 50 h with temperatures above 26°C. The effect of internal loads is more complex. Since the system is demand-controlled, higher internal loads increase the amount of natural ventilation, and thus low occupant densities are generally favorable for both indoor climate and energy use in winter.

A solution with manual window control and stimuli from a user app could further decrease the complexity of the technical systems. A possible method to model human behavior in buildings is to introduce a probabilistic approach in simulation program. Manually controlled natural ventilation can however be challenging because of the complex and stochastic nature of human behavior. The design of a manual window control based on stochastic variables was not successful in this thesis. Hence, further work is needed to develop a suitable simulation model in IDA ICE of occupant behavior with stimuli from an app.

The results in this thesis show that passive design strategies and the use of hybrid ventilation are promising tools to obtain a more sustainable building design with low life cycle cost, low energy use and good indoor climate. However, the use of hybrid ventilation systems requires a different approach than conventional mechanical systems. It is crucial that conditions for natural ventilation and passive cooling are present and that the system is well controlled and integrated in the building design. The building’s context, function, geometry, users, components and floor plans determines the feasibility of the solutions and should be thoroughly assessed in every case.

13 Future Work

According to the simulation results, the control strategy of the automatic windows and the heating and cooling set points could be further optimized. The passive night cooling is controlled according to season and gives somewhat low temperatures in summer. The indoor temperature in the hybrid solution with a higher degree of mechanical ventilation could be adjusted to ensure a maximum temperature of 24°C during the heating season. Furthermore, the choice a suitable of heating system for the natural and hybrid solutions should be further assessed. Dimensioning and optimum control the systems needs to be evaluated in the light of cost and comfort.

IDA ICE can simulate the temperature stratification in a building, but can not model the stratification of CO_2. The stratification of CO_2 is often approached with a two-zone model, where the room is divided in an occupant zone and a polluted zone. However, the formation of vertical air layers is dependent on a constant air supply, and uncertainty is related to how the stratification will be affected in a building with a varying air supply due to demand-controlled natural ventilation. Further research is needed to investigate the influence of pulse ventilation on the stratification of CO_2, through laboratory experiments or CFD-simulations.

Detailed studies of the air flow distribution and air velocities in the occupant zone are necessary to evaluate the local thermal comfort and risk of draft.

The building concept 2226 depends on internal gains for heating. In this thesis, simulations were run with 100 % occupancy. In reality, the presence of occupants in an office building will vary during the day due to meetings etc. and thus a more realistic approach would be to evaluate the indoor environment and energy use based on varying occupancy schedules.

Finally, more research on window opening behavior and occupant reaction to stimuli in open offices is of interest. The introduction of stochastic variables in building simulation is interesting to improve modelling of energy-related human behavior and different outcomes of indoor environment and energy use. Further work is needed to develop a suitable simulation model for manual window control in IDA ICE, and the control strategy developed would need to be verified through monitoring of a similar solution with a user app in a Norwegian office building.

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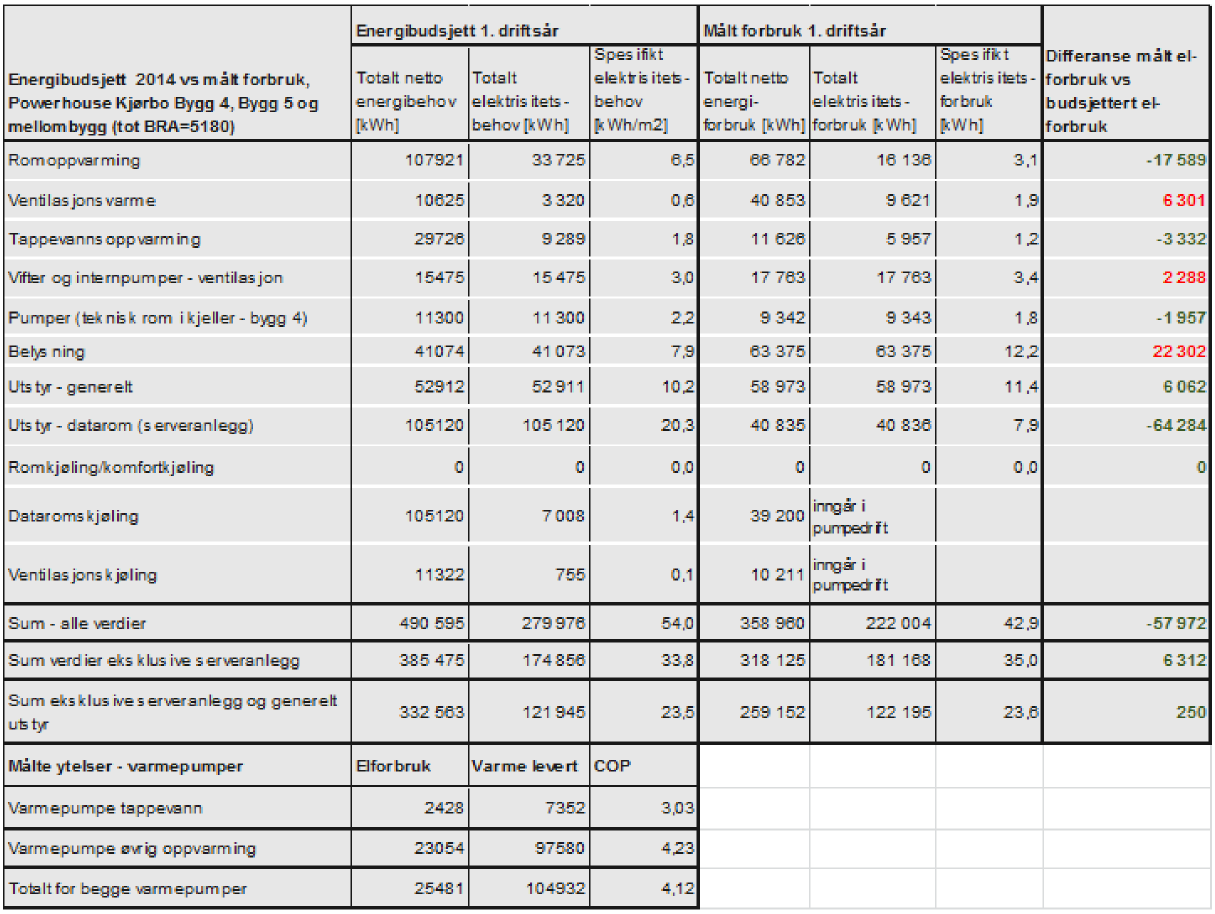
Appendix A - Energy use Powerhouse Kjørbo

Energy budget and measured energy consumption for Powerhouse Kjørbo after the first year of operation. Provided by Peter Bernhard from Asplan Viak [32].



Energibudsjett 2014 vs målt forbruk, Powerhouse Kjørbo Bygg 4, Bygg 5 og mellombygg (tot BRA=5180)	**Energibudsjett 1. driftsår**			**Målt forbruk 1. driftsår**			**Differanse målt el-forbruk vs budsjettert el-forbruk**
	Totalt netto energibehov [kWh]	Totalt elektrisitets-behov [kWh]	Spesifikt elektrisitets-behov [kWh/m2]	Totalt netto energi-forbruk [kWh]	Totalt elektrisitets-forbruk [kWh]	Spesifikt elektrisitets-forbruk [kWh]	
Romoppvarming	107921	33 725	6,5	66 782	16 136	3,1	-17 589
Ventilasjonsvarme	10625	3 320	0,6	40 853	9 621	1,9	6 301
Tappevannsoppvarming	29726	9 289	1,8	11 626	5 957	1,2	-3 332
Vifter og internpumper - ventilasjon	15475	15 475	3,0	17 763	17 763	3,4	2 288
Pumper (teknisk rom i kjeller - bygg 4)	11300	11 300	2,2	9 342	9 343	1,8	-1 957
Belysning	41074	41 073	7,9	63 375	63 375	12,2	22 302
Utstyr - generelt	52912	52 911	10,2	58 973	58 973	11,4	6 062
Utstyr - datarom (serveranlegg)	105120	105 120	20,3	40 835	40 836	7,9	-64 284
Romkjøling/komfortkjøling	0	0	0,0	0	0	0,0	0
Dataromskjøling	105120	7 008	1,4	39 200	inngår i pumpedrift		
Ventilasjonskjøling	11322	755	0,1	10 211	inngår i pumpedrift		
Sum - alle verdier	490 595	279 976	54,0	358 960	222 004	42,9	-57 972
Sum verdier eksklusive serveranlegg	385 475	174 856	33,8	318 125	181 168	35,0	6 312
Sum eksklusive serveranlegg og generelt utstyr	332 563	121 945	23,5	259 152	122 195	23,6	250
Målte ytelser - varmepumper	Elforbruk	Varme levert	COP				
Varmepumpe tappevann	2428	7352	3,03				
Varmepumpe øvrig oppvarming	23054	97580	4,23				
Totalt for begge varmepumper	25481	104932	4,12				

Figure A- 1 Energy budget and measured energy consumption Powerhouse Kjørbo

Appendix B – Choice of frequency of results in simulations

When running the simulations, it is important to choose an appropriate frequency of the results. In most cases, the temperature in an office building will vary throughout the day and with a mechanically regulated system, the temperature variations will be quite soft and steady. However, with the use of natural ventilation there is a greater chance of rapid temperature changes due to untreated supply air. These fluctuating temperatures can have a great impact on the indoor environment and must be detected in the analysis. To find the appropriate data frequency, three simulations with different time steps were analyzed for the natural and the hybrid solutions. The chosen time intervals were results per minute, per ten minutes and per hour. The frequency of the values are presented by adding the number of incidents into hours per year.

Regarding the indoor environment, it is mainly of importance to evaluate the temperature- and CO_2-levels during the working hours. The values may drop outside of the comfort zone when there are no occupants present. The programming tool Matlab was used for post processing to obtain the results for the indoor environment during occupancy hours. The results of the indoor temperature for the naturally ventilated scenario with the three different time step are presented in Figure B- 1, Figure B- 2 and Figure B- 3.

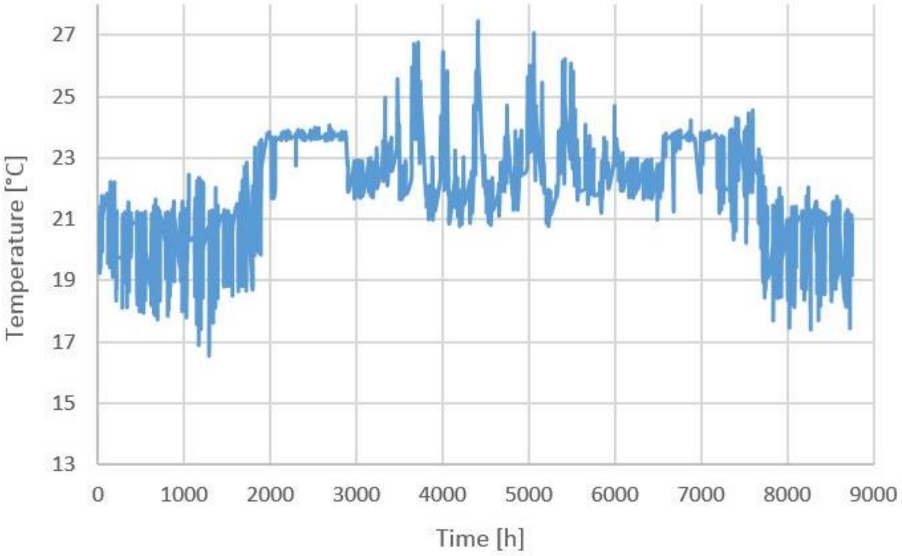


Figure B- 1 Indoor temperatures during occupancy hours, time step for results 1h

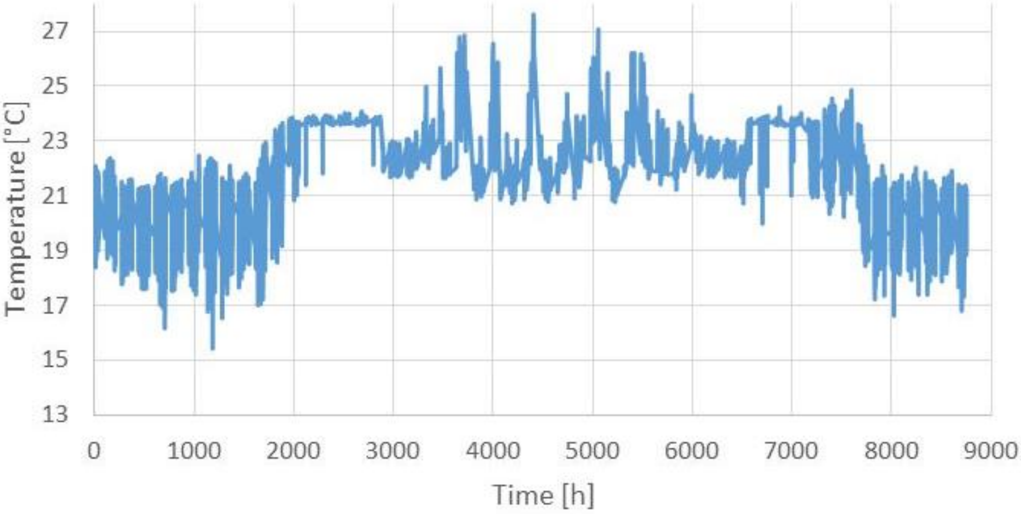


Figure B- 2 Indoor temperatures during occupancy hours, time step for results 10 min

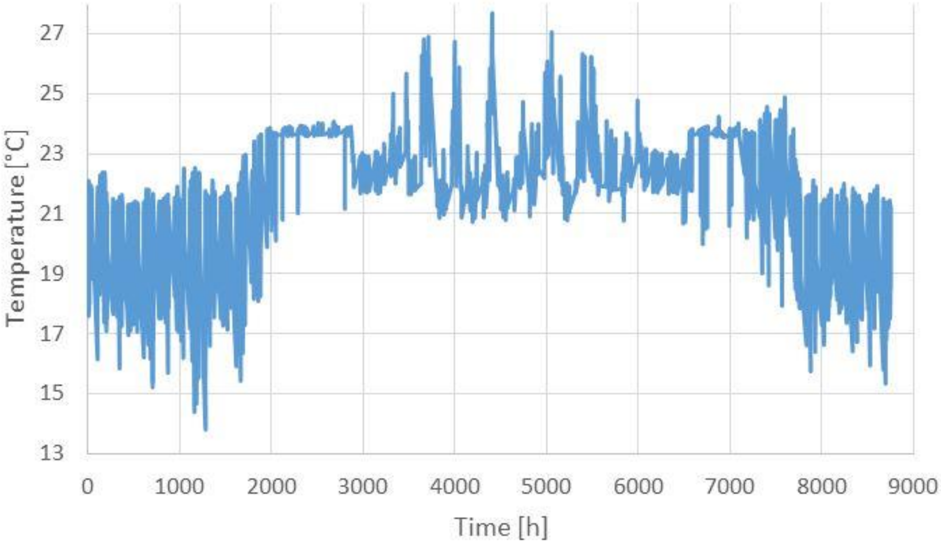


Figure B- 3 Indoor temperatures during occupancy hours, time step for results 1min

The results presented in Figure B- 1, Figure B- 2 and Figure B- 3 shows that the simulations must be run with a high frequency of results to detect the extreme temperature values. The larger time step, the less variation in temperature will be detected. A frequency analysis performed shows that in all cases the temperature remains mainly between 20 and 24°C, as seen in Figure B- 4, Figure B- 5 and Figure B- 6. However, the frequency of the extreme values differ according to the chosen time step, and are they are better detected when running with a higher frequency of results. The yearly frequency was found by adding all incidents over the year into a total number of hours.

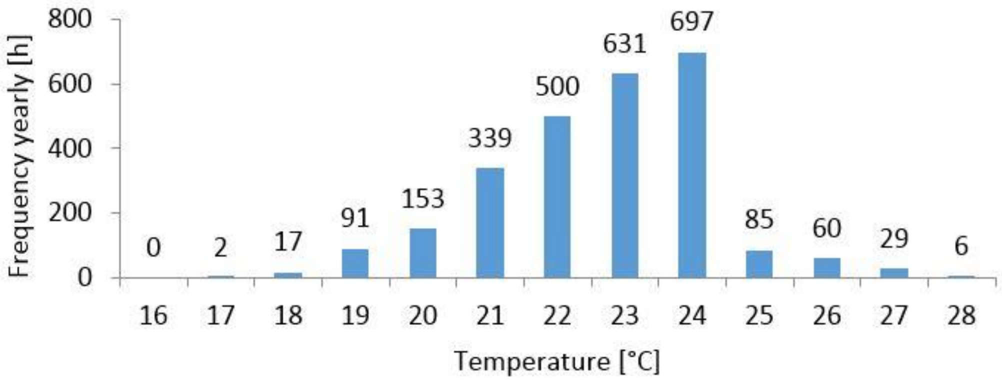


Figure B- 4 Frequency of temperatures, time step for results 1 hour

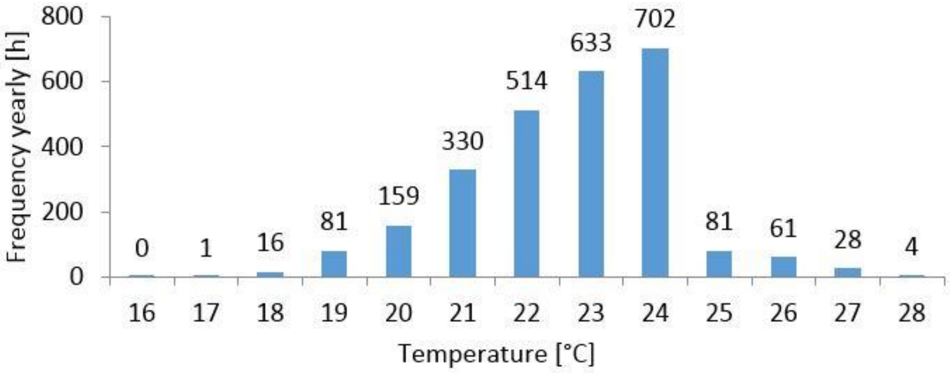


Figure B- 5 Frequency of temperatures, time step for results 10 min

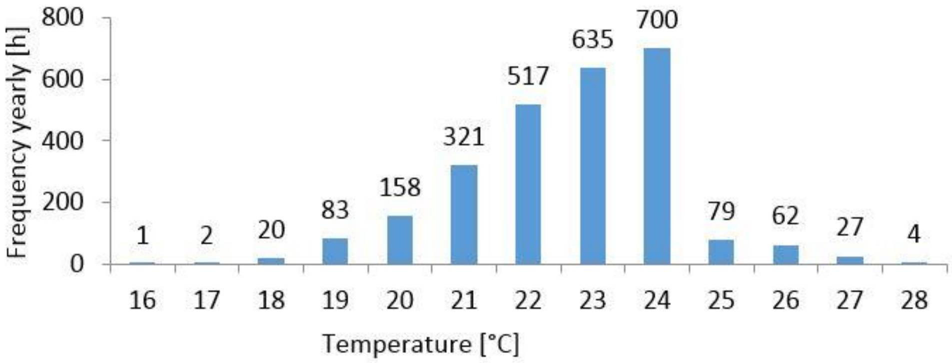


Figure B- 6 Frequency of temperatures, time step for results 1min

Furthermore, an evaluation of the frequency of the heating demand for the naturally ventilated model was performed. The results for the different time steps for the results are presented in Figure B- 7, Figure B- 8 and Figure B- 9.

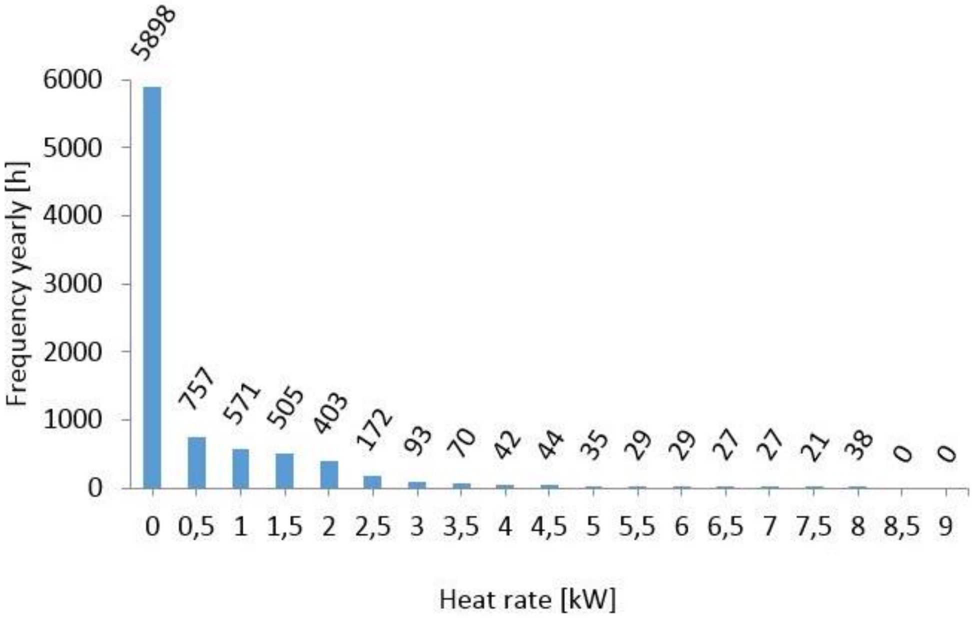


Figure B- 7 Frequency of heat rates, time step for results 1 hour

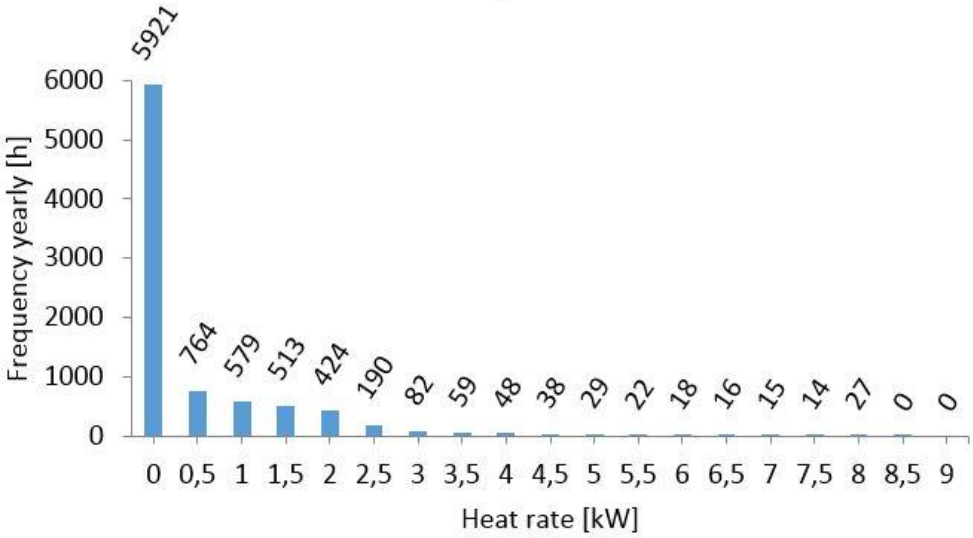


Figure B- 8 Frequency of heat rates, time step for results 10 min

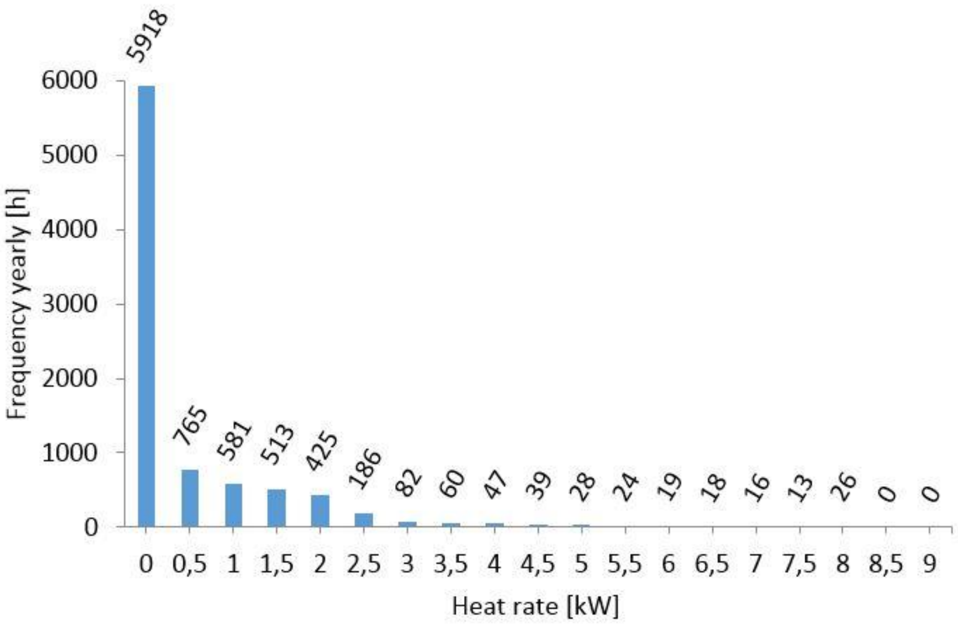


Figure B- 9 Frequency of heat rates, time step for results 1 min

As seen in Figure B- 7, Figure B- 8 and Figure B- 9 the heat rates vary little when the time step was intensified. In all cases, the heating demand is non-existing for about 6000 h per year. According to the results of the dimensioning heating effect, an appropriate time step would thus be 1 h. However, as the main aim is to evaluate the indoor environment, further simulations were run with a time step for results of 1 minute to detect low temperatures occurring during winter. As the trend also is present for the hybrid solutions, all simulations were run with a time step for results of one minute.

Appendix C – Temperatures hybrid scenarios

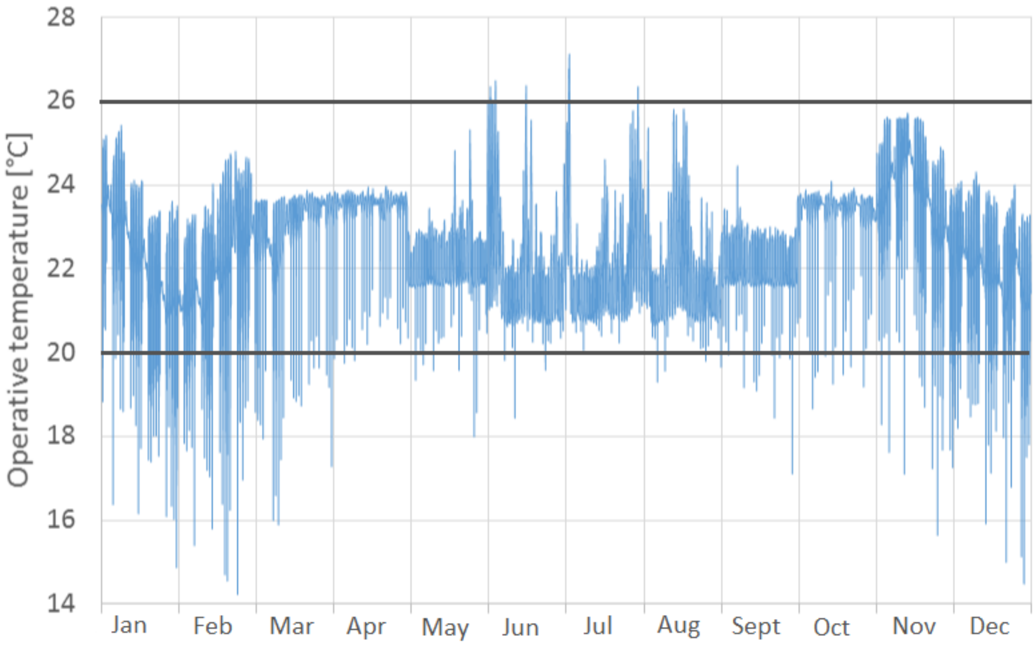


Figure C- 1 Indoor temperatures during a year, Hybvent 70_30, office South East

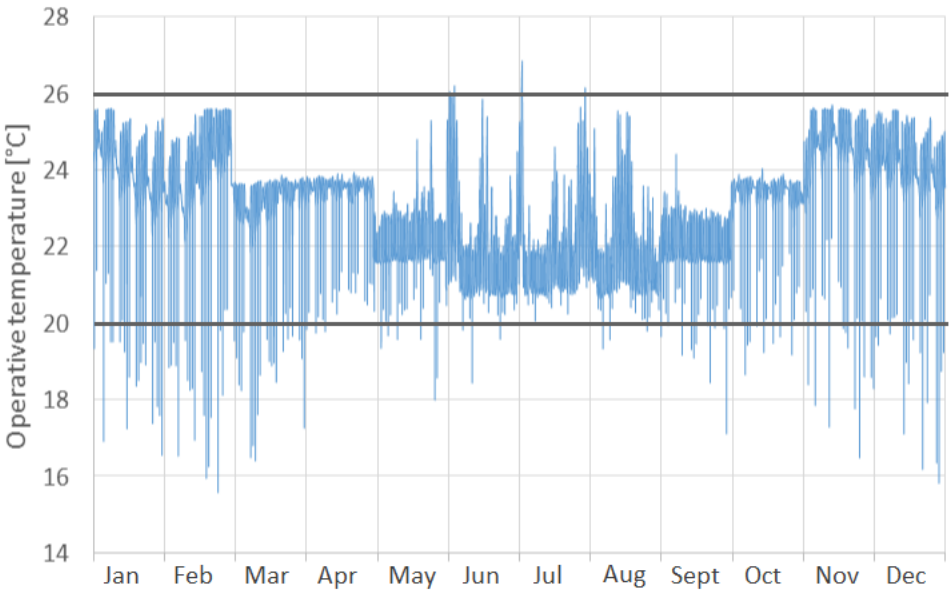


Figure C- 2 Indoor temperatures during a year, Hybvent 40_60, Office South East

Appendix D - Window controllers in IDA ICE

Automatic window controller

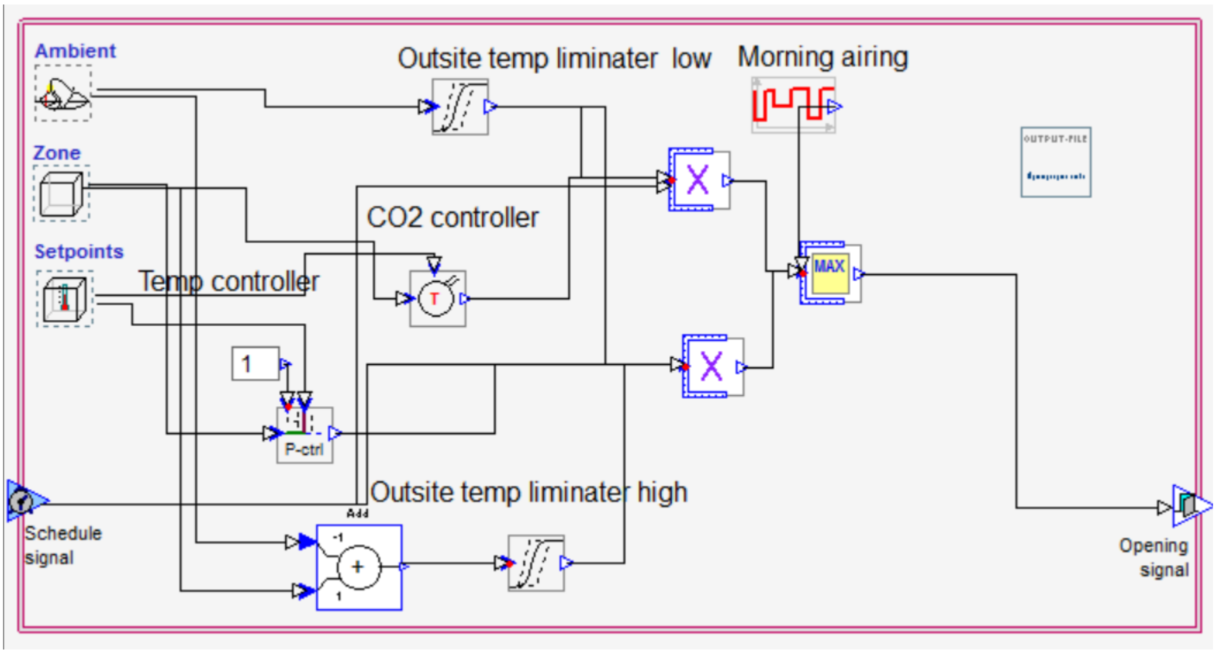


Figure D- 1 Automatic window controller, set up in IDA ICE

User controlled window openings

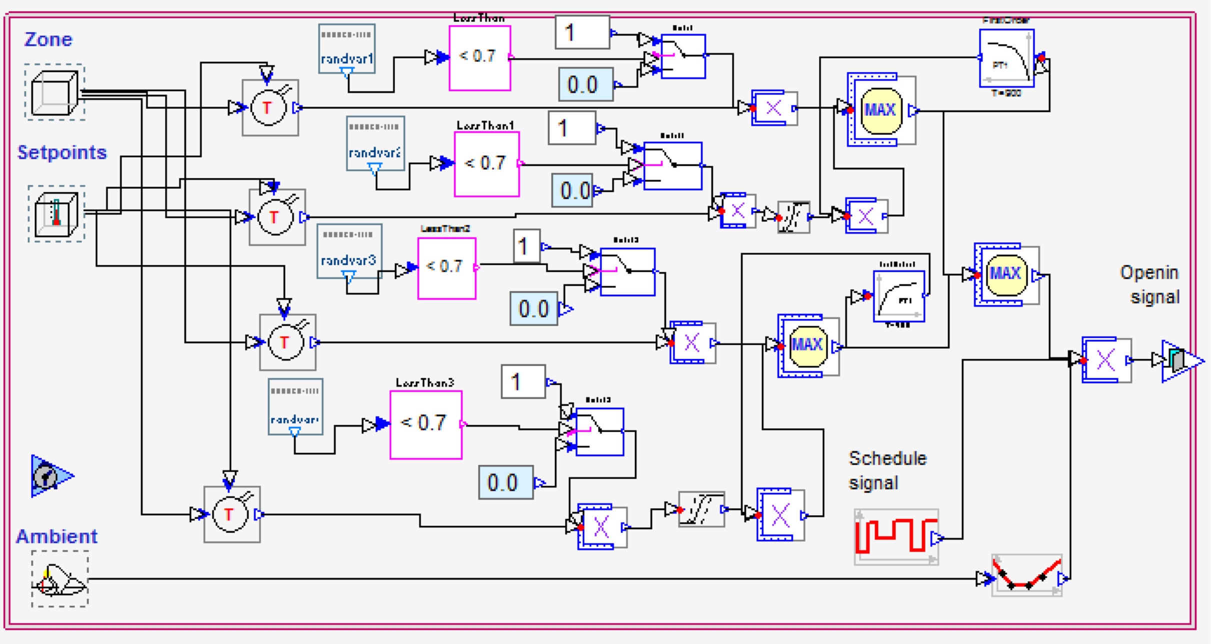


Figure D- 2 Manual window controller, set up in IDA ICE

Appendix E - Stochastic user profiles for occupancy

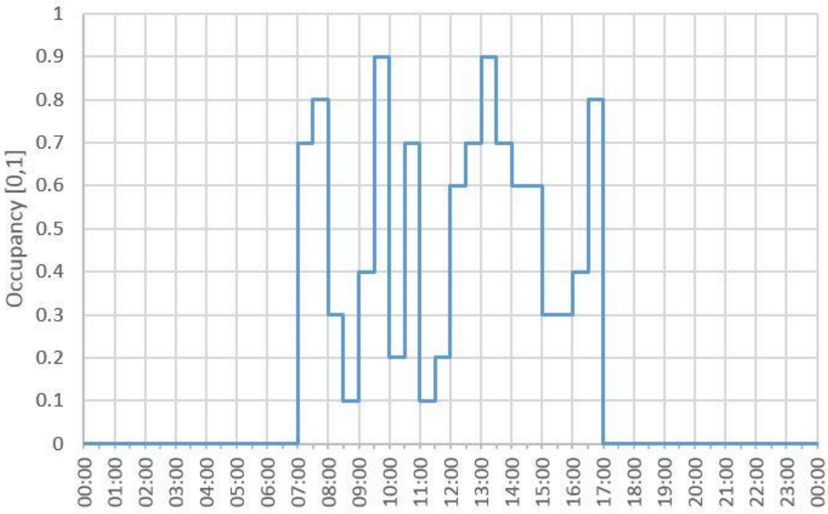


Figure E- 1 Stochastic user profile 1

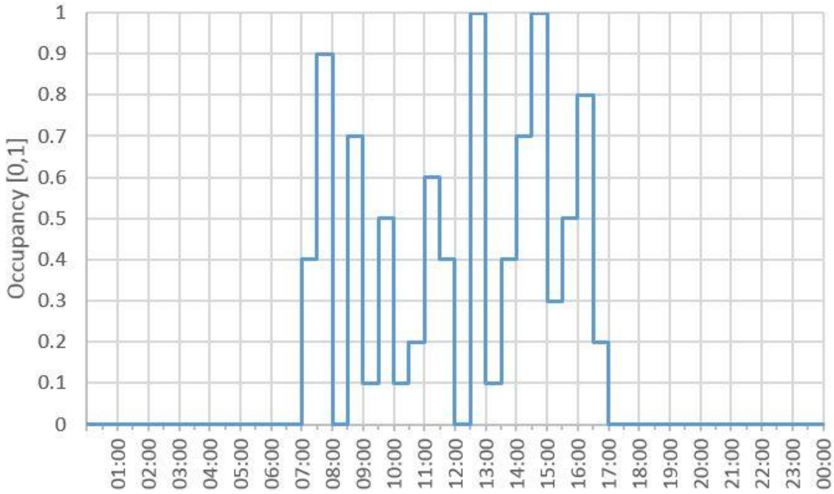


Figure E- 2 Stochastic user profile 2

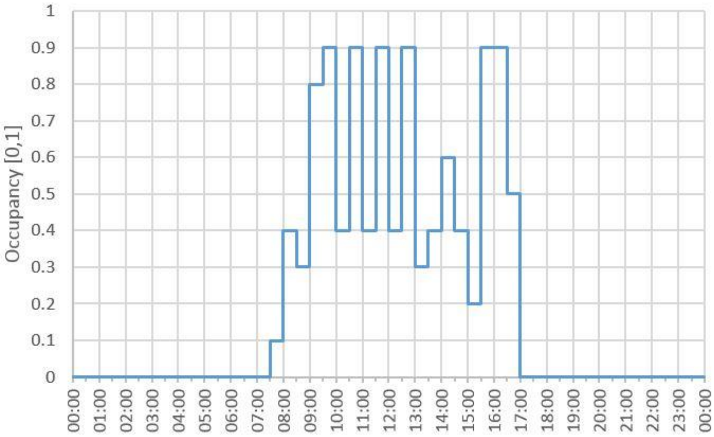


Figure E- 3 Stochastic user profile 3

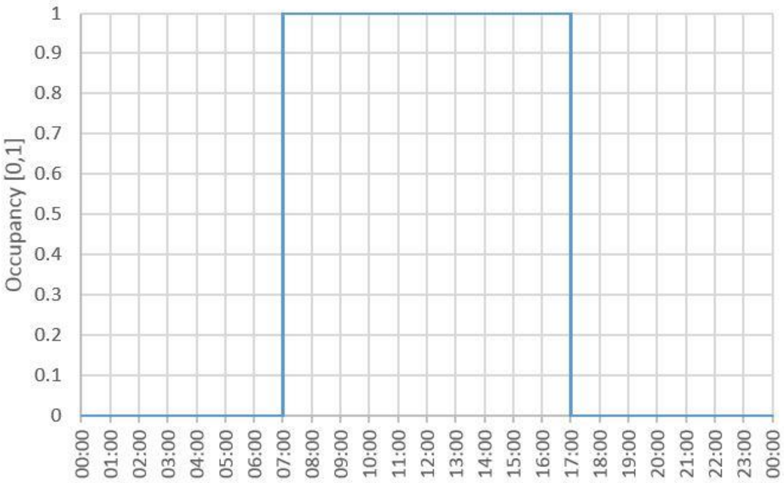


Figure E- 4 User profile 4, 100 % occupancy

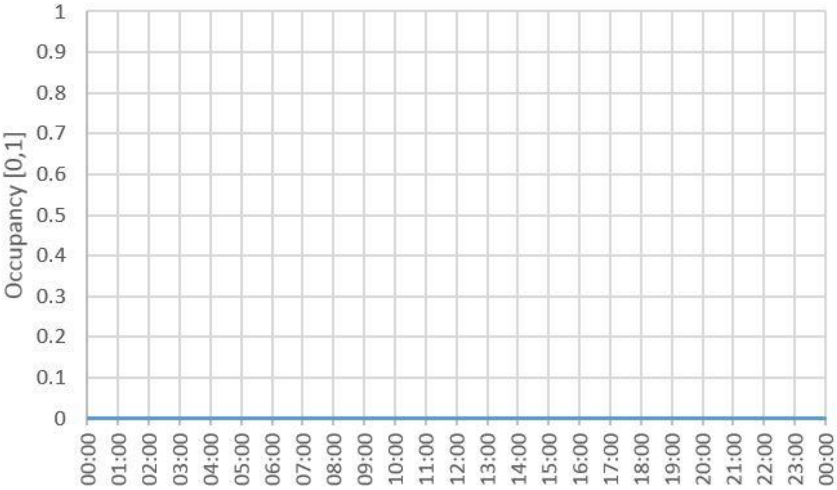


Figure E- 5 User profile 5, 0 % occupancy