Master's thesis

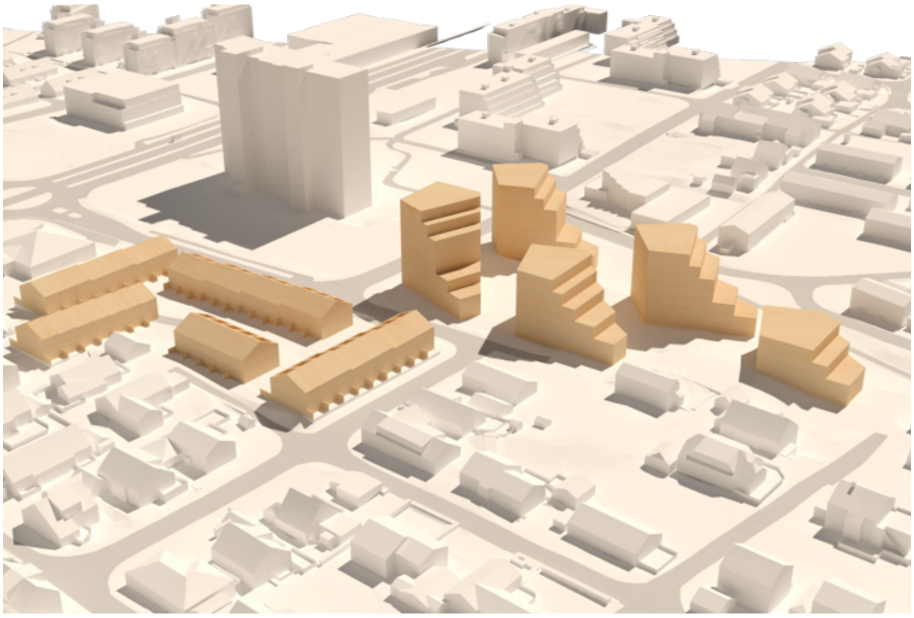
NTNU
Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Architecture and Technology

Vegard Skregelid Johansen

The impact of ventilative cooling technologies on heating energy and thermal comfort in residential buildings

In cold climate

Master's thesis in Master of Science in Sustainable Architecture
Supervisor: Mohamed Hamdy
June 2020



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First and foremost, I would like to express gratitude towards my academic supervisor Mohamed Hamdy (NTNU), for excellent guidance and sharing knowledge throughout the semester. His commitment and extensive experience were essential for this master thesis. I wish to thank research advisors Laurina C. Felius (NTNU) and Hans Martin Mathisen (NTNU), and also external supervisor Mika Vuolle (EQUA) for valuable help conducting the modeling in IDA ICE and giving exceptional feedback.

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Vegard Skregelid Johansen

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Abstract

In the recent decade, the requirements for energy and indoor climate in buildings have become increasingly stringent. At the same time, new technologies have been introduced, which can have the potential to solve existing problems related to the poor indoor climate and excessive energy use. Window and hatch-ventilation with integrated control systems and ventilated windows are some of the technologies that have been launched as a replacement for conventional solutions. In Norway, there are few multi-story residential buildings with sophisticated ventilative cooling control systems. However, there have been projects for schools and dwellings, where the outcome has been positive.

The building, which is analyzed, is a multi-story residential building located in Mariero, Stavanger, and is planned to be completed by 2023. The multi-story building is modeled with the use of the simulation software IDA ICE 4.8. In the initial phase, the building was evaluated as a whole in order to find the most critical apartment based on thermal comfort. Further, the most critical apartment was chosen and a more detailed model was developed to achieve more reliable results.

Thermal comfort has been studied for several years, where new standards have become more specific for the different building categories. Despite that, the new standard NS-EN 16798:2019 does not distinguish between thermal comfort adaption in different rooms in residential buildings. In this thesis, the thermal adaptivity and energy use for bedrooms and living rooms have been investigated for different building ambition levels, ventilation strategies, automation systems, and ventilative cooling technologies.

The results for occupant emulated window opening shows a significant increase in energy use compared to an automated control system. Energy savings up to 46% can be achieved when applying an automated control system with the ventilation hatch technology. In addition, there is a significant improvement in thermal comfort for the optimal solution.

Sammendrag

I løpet av de siste tiårene så har kravene for energiforbruk og termisk inneklima blitt stadig strengere. Samtidig har nye løsninger blitt introdusert som har potensiale til å løse problemer relatert til unødvendig energiforbruk samt dårlig inneklima. Vinduer og luker med integrerte kontrollsystem og ventilerte vindu er noen av løsningene som har blitt introdusert som en erstatning for konvensjonelle løsninger. I Norge er det få boligblokker som har kontrollsystem for naturlig ventilativ kjøling, men det er referansebygg der skoler og småboliger har benyttet løsninger der resultatet har vært positivt.

Bygningen som har blitt analysert er en boligblokk som er lokalisert på Mariero i Stavanger, og bygningen er planlagt ferdig løpet av 2023. Boligblokken har blitt modellert ved hjelp av simuleringsprogrammet IDA ICE 4.8. I startfasen så ble hele bygningen simulert for å finne ut hvilken leilighet som var mest kritisk for overoppheting. Da den mest kritiske leiligheten var funnet så ble leiligheten laget mer detaljert slik at resultatet ble mer presist.

Termisk komfort i bygninger har blitt studert i flere år, og nye standarder har blitt mer presise for forskjellige bygningskategorier. Til tross for dette så skiller ikke standarden NS-EN 16798:2019 mellom termisk adaptasjon mellom forskjellige rom i boligbygg. I denne masteroppgave så skal termisk adaptasjon bli analysert for soverom og oppholdsrom med forskjellige nivåer av bygning ambisjoner, ventilasjonsstrategier, bygnings-automasjon, og teknologier for ventilativ naturlig kjøling.

Fra resultatene er det gjort funn på at manuell åpning av vindu vil øke energiforbruket betydelig ved sammenligning til automatiserte vindus kontroll. Ved bruk av automatiserte luke kontroll er det mulig å gjøre energibesparelser på opp til 46%. I tillegg er det betydelig forbedring av inneklima ved å gå over til en slik løsning

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Chapter 1 Introduction

1.1 Motivation

Norway was one of 195 countries that signed the Paris agreement and committed, therefore, to reduce the $CO_{2\text{-eq}}$ emissions to 40 percent by 2030. The focus and development of new technologies to reduce emissions are more vital than ever. The building stock in Norway is responsible for 40 % of the final energy consumption, of the which residential sector represents 22%(Sartori, Jensen Wachenfeldt, & Hestnes, 2009).In order to ensure sustainable development, it is essential to design buildings that can adapt to the climate of the future. In Norway the annual mean temperature is projected to rise 3,3-6,4 °C by 2100 (Hanssen-Bauer et al., 2017), and in combination with highly insulated buildings this can potentially cause unforeseen problems.

For the purpose of cooling residential buildings, mechanical cooling is not suitable due to high energy consumption. Cooling with natural ventilation can be a solution to reduce overheating and thus contribute to a pleasant indoor environment. It is essential to develop a plan in the early stages when developing for ventilative cooling. Improper planning can cause thermal discomfort and excessive energy use.

The expansion of low-energy buildings can cause a chain reaction in the development of new technologies and thus drive sustainable development. The motivation of the master thesis is to assess the potential of using natural ventilation in a apartment building blocks and to address the effects of energy-use and thermal comfort. An objective of this master thesis is to find a compelling reason for the choice of using automation systems for ventilative cooling.

This master thesis is part of a larger residential developing project called “Fjelltun,” where the plan is to exploit the potential of zero-emission solutions in a neighborhood. The project is located in Mariero, Stavanger, and it consists of several stakeholders where the real estate company “Base Bolig” is the project owner. The project will establish solutions that include mobility, reuse of materials, local energy production and energy storage, and ambitions to develop energy-efficient and sustainable buildings.

1.2 Scope

The main focus of this thesis will be to evaluate the energy consumption and thermal comfort when utilizing ventilative cooling for several design conditions. Besides, different building ambitions levels and ventilation systems will be evaluated. The window opening behavior for occupants will be emulated in a realistic window macro to assess the effects of energy demand and thermal comfort. In addition, automation control systems for the opening control of windows will be tested, where non-automation systems will be compared to automation systems. Due to the timeframe, a computational fluid dynamics(CFD) analysis was not conducted on the building. Also, due to the limitation of the capacity of the simulation program it was decided to first conduct analysis in a less detailed model. Further, to have reliable results only the most critical zone for overheating was analyzed in a more detailed model.

1.3 Research questions

Following research questions will be answered in this master thesis:

- What is the impact of letting people control the windows themselves?
    - Research method: Applying an adaptive thermal comfort model in IDA ICE. Where people open windows when it is the upper limit of thermal comfort

- What is the optimal realistic solution for ventilative cooling?
    - Research method: Assess the potential for ventilative cooling by using different automation systems and ventilative cooling technologies.

1.4 Methodology

The methodology in this thesis contains elements that involve a collection of data, literature study, and use of the simulation tool IDA ICE. A literature study was used to find relevant academic articles and form a theoretical basis for indoor climate, automation systems, and ventilative cooling. Also, it was decided early on that the simulation program IDA Indoor Climate and Energy (IDA ICE) would be an essential part of the thesis.

1.4.1 Literature study

The literature study in the thesis covers everything from journal articles, textbook literature, previous master theses to conference proceedings, and technical documentation. Research referred to in this thesis has mainly been accessed through ScienceDirect, Oria, and ResearchGate. The literature validation has been assessed based on the amount of research citations as well as state of the art research. The search for the study has been performed in both English and Norwegian to maximize the outcome. Meetings with experts in the field of research and stakeholders have been a significant contribution to gather relevant literature and data. Besides, valuable feedback and information regarding the thesis were obtained by peer-reviews organized by the course coordinator.

The first main focus in this thesis covers mainly ventilative cooling, building automation systems and indoor climate. Reference projects and relevant technology will also be a part of the literature. According to the thesis objective, knowledge within the topics mentioned earlier will help to interpret and analyze the simulation results in a competent manner.

1.4.2 Programs

In this thesis, the program IDA ICE will be utilized for thermal comfort and energy analysis. To generate the model in IDA ICE, several steps had to be followed, as shown in ***Figure 1***. Firstly, the author received volumes and floor plans from the architect involved in the Fjelltun project. Secondly, the files received from the architect had to be put together into one 3D file. The building design software REVIT was used to construct the 3D-model and develop the thermal spaces to further export the Revit file into an IFC format. Thirdly, the IFC model was validated and prepared for use in IDA ICE by utilizing the program SimpleBIM. In SimpleBIM, the thermal zones were verified, and unnecessary objects were removed from the model to decrease complexity and thus minimize the risk of errors. Finally, the model was imported to IDA ICE, and several simulations had to be conducted to validate the energy model. The process of importing the model to IDA ICE was performed several times with different modifications and simplifications to minimize the errors.

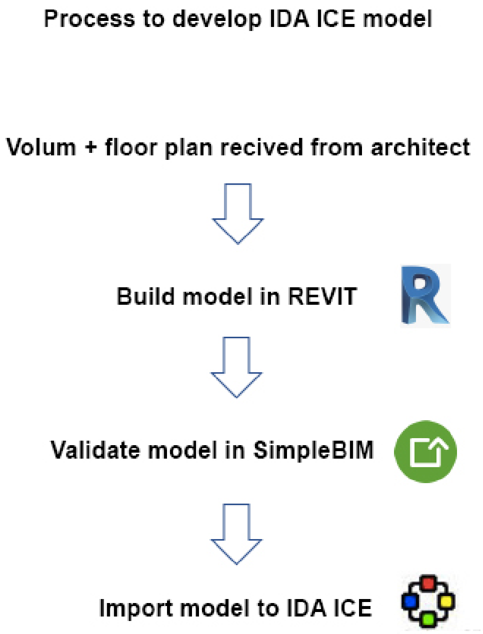

Figure 1 Process to develop the IDA ICE model

Chapter 2 Theory

This chapter contains information on topics considered necessary to develop an understanding to answer the problem statements, and further form a foundation to discuss the results of the study.

2.1 Building automation and control system

In Norway, the building requirements for energy efficiency have become more stringent the recent years. Therefore, it is essential to investigate new smart solutions, which can help to comply with the requirements. Building automation and control systems (BACS) is a promising contributor to improving indoor climate and reducing energy consumption. The BACS provides the functionality of "control, regulation, and monitoring." These are functions in a building that can control, regulate, and monitor all technical installations e.g., HVAC-systems, solar-shading, electrical systems, lighting systems, audiovisual (AV) systems and protection systems. The standard (NS-EN 15232, 2017)targets building automation control(BAC) and technical building management (TBM). The standard gives an overview on how to reduce the energy consumption with different automation criteria and technical solutions. Two methods, detailed and simplified, have promoted the technological solutions that underlie the improvement of energy performance. The simplified method is based on a factor method, where results from reference cases are collected into one database. The factor method defines efficiency factors for thermal energy (heating, domestic hot water, and cooling) and electricity (auxiliary and lighting).

In Table 1, four efficiency factors corresponding to thermal energy and electrical energy for different automation classifications. In comparison to classification D-No-automation, the highest-ranking "A" could have an improved thermal energy performance of 29% and enhanced electrical energy performance of 16 %. In a retrofitting project in Norway for a single-family house, it was found that the BACS alone could reduce the energy consumption by up to 21% and 60% in combination with retrofitting of the building envelope(Felius, Hamdy, Hrynyszyn, & Dessen, 2020).

Table 1 The factor method for residential buildings(Felius, Hamdy, Hrynyszyn, & Dessen, 2020).

Classification	Thermal energy	Electrical energy
D: No-automation	1.10	1.08
C: Standard BAC for new building	1	1
B: Advanced BAC with some TBM functions	0.88	0.93
A: High performance BAC and TBM functions	0.81	0.92

2.2 Natural ventilation concept

There are three main aspects to natural ventilation that define and describe various concepts. The first aspect is a natural force used to drive the ventilation. The driving force for natural ventilation can be driven by wind, buoyancy, or a combination of both. The second aspect is the ventilation principle, which is utilized to exploit the natural driving force in a space. To use the natural driving force in a space, the three ventilation principles single-sided ventilation, cross-ventilation, and stack ventilation, are commonly referred to. The third and final aspect is the characteristic element used to realize natural ventilation. The typical characteristic elements are wind scoops, openings in façade, wind towers, chimneys, double facades, atria, and embedded ducts (Kleiven, 2003).

2.2.1 Buoyancy driven flow

The first driving force for natural ventilation is pressure due to buoyancy. Natural ventilation from buoyancy is induced by the density difference between the indoor and outdoor air. When the internal air temperature is larger than the external air temperature, air will flow from the lower point due to external overpressure to a higher point due to internal overpressure. As a result, there will be a height witch the airflow direction is inverted. The pressure at this point is zero so-called neutral pressure level (***Figure 2***) (Liddament, 1996).The pressure difference between two vertically spaced openings H_1 and H_2 is given by:

$$\boldsymbol{P_S} = p_0 g 273(H_2 - H_1)\left[\frac{1}{T_{ext}} - \frac{1}{T_{int}}\right] \ [Pa] \tag{1}$$

Where:

$\boldsymbol{po} = air\ density\ at\ 273K(1.29\frac{kg}{m^3})$

$\boldsymbol{g} = gravitational\ acceleration\ (9.81\frac{m}{s^2})$

$\boldsymbol{T_{ext}} = Outdoor\ air\ temperature\ (K)$

$\boldsymbol{T_{int}} = Indoor\ air\ temperature\ (K)$

$\boldsymbol{H_1} = Height\ of\ opening\ 1\ (m)$

$\boldsymbol{H_2} = Height\ of\ opening\ 2\ (m)$

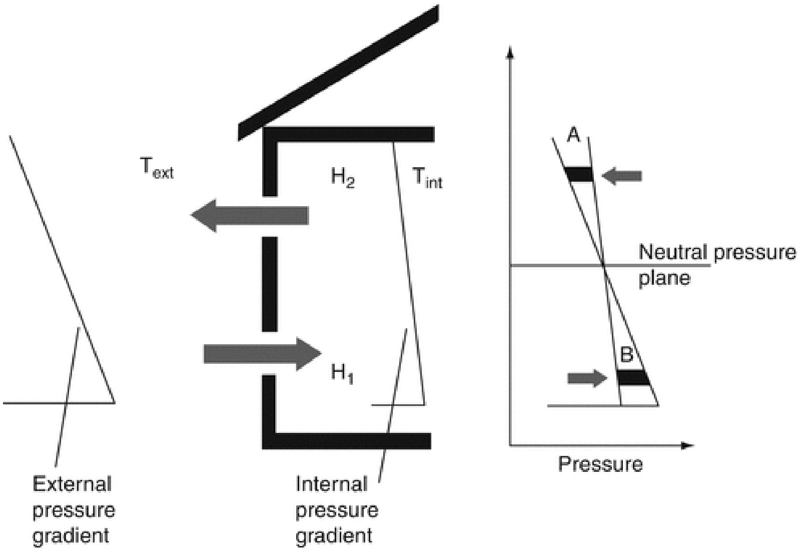

Figure 2 Pressure distribution due to buoyancy between to vertically placed openings (Liddament, 1996).

2.2.2 Wind driven flow

The wind-driven force is the other driving force for natural ventilation in a building. Wind-driven ventilation is a result of pressure difference on a building envelope. ***Figure 3*** illustrates the effect, wind-exposed to the façade generates a positive pressure region on the windward side and negative pressure on the downward side. Openings will cause air to pass through the building from the positive pressure region to the negative pressure region. The pressure created by the wind depends on different factors, for instance, the terrain, localized obstructions, wind speed, and the direction relative to the building and the shape of the building (Cibse, 2016). The wind pressure on any point of a building façade can be approximated by the following equation:

$$\boldsymbol{P_w} = \frac{pC_p * v^2}{2} \quad [Pa] \tag{2}$$

Where:

$\boldsymbol{C_p} = Wind\ pressure\ coefficient$

$\boldsymbol{v} = Local\ wind\ velocity\ at\ a\ specified\ reference\ height\ (\frac{m}{s})$

$\boldsymbol{p} = air\ density\ (\frac{kg}{m^3})$

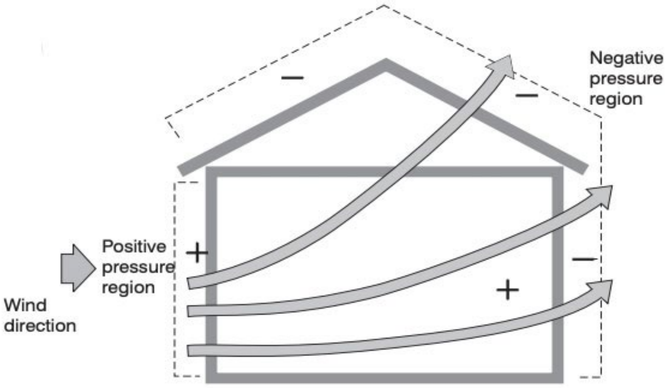

Figure 3 Wind driven ventilation (Liddament, 1996).

2.2.3 Natural ventilation principles

Single-sided ventilation is a principle where an opening is located on a single side of a space. The effect of the wind-driven ventilation can be affected by only allowing supply and extract air through the same opening. To allow full ventilation in the entire space a rule of thumb is that the depth of a single-sided ventilated room should not exceed 2.5 times the ceiling height (***Figure 4***) (Liddament, 1996).

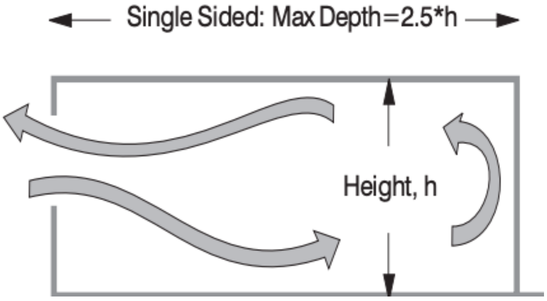

Figure 4 Single sided ventilation principle (Liddament, 1996).

Figure 5 illustrates the different concepts of outcomes for the design of single-sided ventilation. The most common one is show in ***Figure 5*** a) with one opening and sealed enclosure, where the main driver for air exchange is by turbulence fluctuation around the window. For the second design, ***Figure 5*** b), the air takes place through buoyancy forces and/or differences in the wind pressure. This design relies upon sufficient spacing between the openings to generate predictable air exchange. In some cases, when designing for single-sided ventilation, the outcome can be unwanted cross-ventilation. The reason is unsealed enclosure in a space which can lead to air leakage from e.g., leakage paths or internal doors ***Figure 5*** c) (Liddament, 1996).

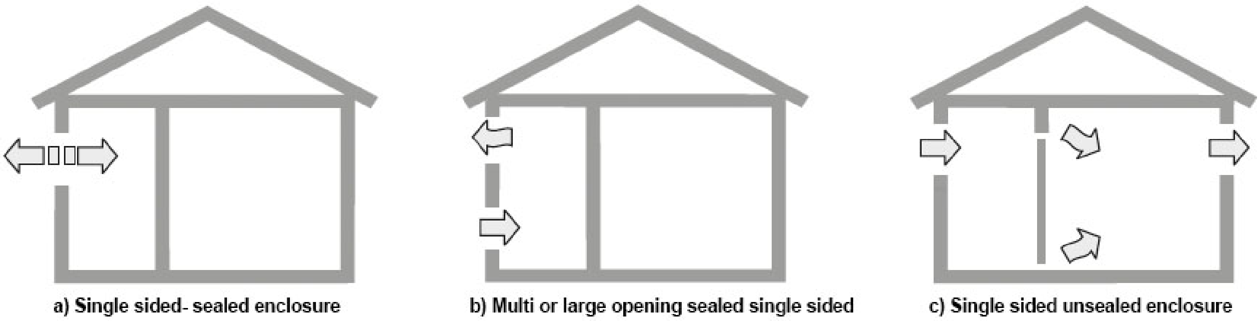

Figure 5 Different single sided ventilation concepts (Liddament, 1996).

Cross ventilation is possible when the inlet and outlet are appointed in two or more building facades, shown in ***Figure 6***. Architectural elements like corridors or hallways can enhance the effects of cross ventilation and supply air to the required building zones(Tahir, 2008). When the air is transported through the space, the temperature will increase, and pollution will be picked up by the air. As a result, the effect of cross ventilation will gradually be decreased when penetrating through the space. The rule of thumb for adequate cross ventilation is a room depth of maximum five times the floor to ceiling height (Cibse, 2005).

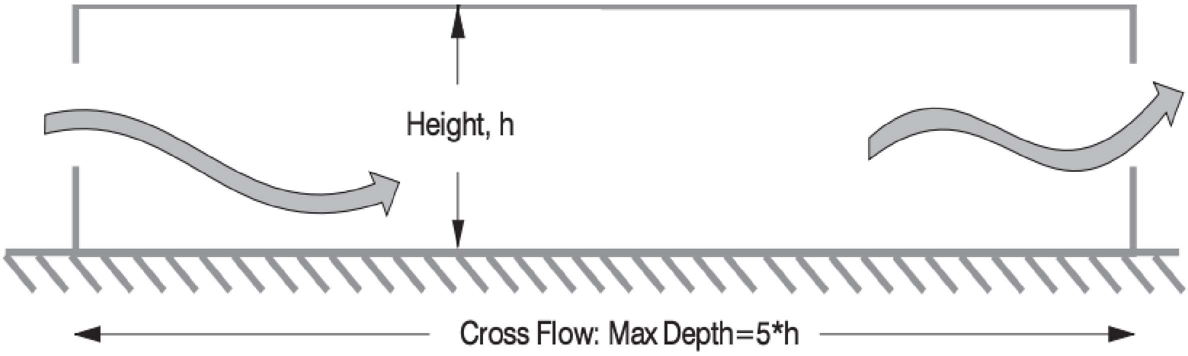

Figure 6 Cross ventilation principle (Liddament, 1996).

The stack ventilation is driven through a building by the effect of thermal buoyancy. Air draws across the ventilated space and exhaust through a vertical flow path (***Figure*** *7*). In order to achieve sufficient ventilation, the same rule of thumb as cross-ventilation applies for stack ventilation i.e., depth of five times the floor to ceiling height. Careful designing of the stack ventilation is vital in order to achieve adequate ventilation e.g., location and size of openings and sufficient building height (Cibse, 2005).

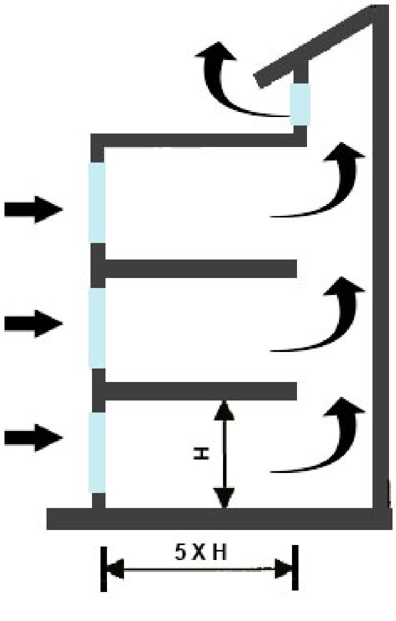

Figure 7 Stack ventilation (Bhatia, 2011)

2.3 Mechanical ventilation

The most common form of mechanical ventilation in existing residential buildings is mechanical extract ventilation, where fans are used mechanically to exhaust air from wet-rooms and kitchens. The suction effect from the mechanical system induces an under pressure which promotes air to penetrate from air inlets and through infiltration. The simplicity of the system reduces the installation cost. However, ventilation loss is significant if the system is dimensioned based on the current Norwegian requirements for volume flow rates. Besides, there can be a risk of draft due to uncontrolled cold air induced from infiltration or through the openings (Wigenstad, Schild, Klinski, & Simonsen, 2012). The operational efficiency can be optimized by keeping the mechanical pressure higher than the pressure from natural forces. Also, to ensure optimal control of the air, an airtight envelope is preferred where the air inlets are the main supplier of the air. An option to reduce the ventilation loss for mechanical extract ventilation is to recover the exhaust air, by an air to liquid heat pump. These heat pumps can be utilized to recover the energy from the extract air to pre-heat the domestic hot water (Liddament, 1996).

In recent years balanced mechanical ventilation has become increasingly popular, and it is the most common ventilation system in new residential buildings in Norway. In a system with balanced mechanical ventilation fans will ensure the same volume flow rate for both the supply and exhaust. In comparison to natural and mechanical extract ventilation, balanced ventilation has the advantages of filtrating the supply air, control of air volumes and air velocity to building zones, low ventilation loss, and a good total economy. Also, heat exchangers are commonly used in new buildings, which effectively will recover the heat from the air. However, some of the disadvantages can be an increase in maintenance cost or a possibility of increased energy consumption if the system is unbalanced e.g., through poor air-tightness (Wigenstad et al., 2012).

2.4 Hybrid ventilation

The hybrid ventilation system can be described as a system that utilizes the potential of both natural -and mechanical ventilation to provide a comfortable indoor climate. A difference from mechanical ventilation is that hybrid ventilation can have an intelligent control system that can switch from mechanical-and natural ventilation mode, thus reducing energy consumption. The energy reduction for hybrid ventilation is often due to a reduction in the use of fans, but also for cooling or heating. In addition, the lifetime cost of a hybrid system is usually lower than for mechanical ventilation. However, the initial cost for hybrid ventilation varies depending on the complexity of the system (Heiselberg, 2002).

Hybrid ventilation can be utilized in a building in three categories (Dokka, Mysen, Schild, & Tjelflaa, 2003).

- Fan assisted natural ventilation: This principle is mainly based on natural driving forces but is supplemented with supply or extract fans.
- Natural and mechanical ventilation (mixed-mode ventilation): This principle is based on two autonomous systems, one mechanical system, and natural system. In this principle, a control system switches between the two states, or where one system is used for one different purpose. This can be done when the natural ventilation system is in operation during summer, and the mechanical system is in operation during winter, autumn, and spring.
- Mechanical ventilation with natural assistance: This principle is a low- pressure mechanical system which should ideally utilize the potential of natural driving force e.g., wind or buoyancy drive force, as far as it is appropriate to do.

In this thesis, the main focus will be on the hybrid principle of mixed-mode ventilation. A mixed-mode ventilation system refers to a combination of a mechanical system which distributes the air and natural ventilation from e.g., manual/automatic windows or passive inlet vents. Mixed-mode ventilation allows the use of natural ventilation when feasible or desirable and are supplemented with mechanical ventilation if the conditions for natural ventilation is not sufficient. Mixed mode ventilation systems are classified in accordance to the type of operation strategies. The three classifications of operations are concurrent, change-over and zoned system(G. Brager, 2006).

2.4.1 Concurrent mixed-mode

This is the mixed-mode ventilation design strategy, which is commonly used. With this system, natural ventilation and mechanical ventilation are operating at the same time in the same space. The mechanical ventilation system can supply the zone with air if the required air from the natural ventilation is not sufficient or serve as background ventilation. An example of this mode can be variable air volume(VAV) ventilation with openable windows, where if a window is opened a sensor will turn the VAV to minimum airflow rates (***Figure 8***) (CBE, 2013).

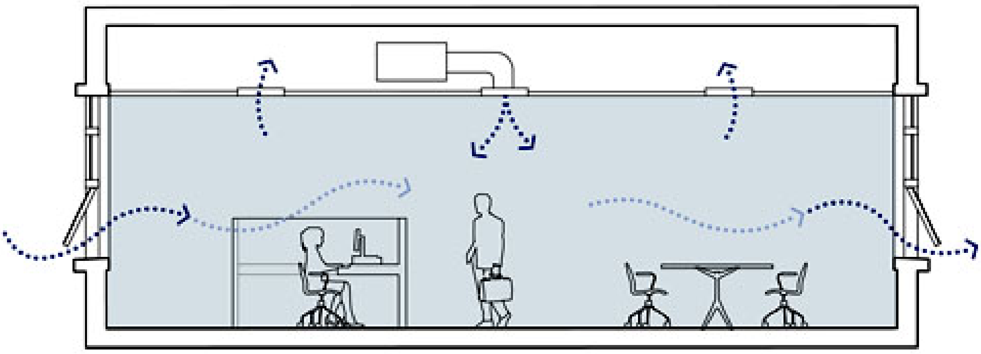

Figure 8 Concurrent mixed-mode operation (CBE, 2013)

2.4.2 Change over-design

With a change over-design, the mechanical-and natural ventilation will switch the operating system on a seasonal or daily basis. A building automation and control system (BACS) can determine the operation mode based on outdoor temperature, occupancy sensors, window sensor for opening and closing or controlled by individual instructions. A typical example of a change over-design is when a window is closed a sensor will notify the mechanical system to shut it down (***Figure 9***) (CBE, 2013).

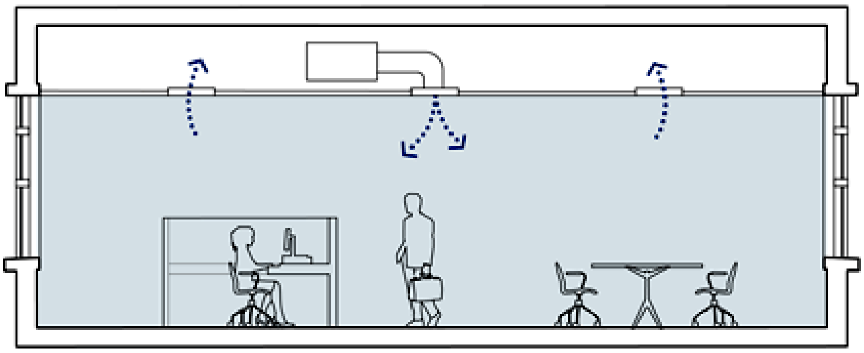

Figure 9 Change over-design (CBE, 2013)

2.4.3 Zoned system

In a building with a zoned system, the zones in a building will have different ventilation strategies. An example is when an office zone in a building is ventilated naturally, at the same time another zone in the same building with conference rooms can be ventilated mechanically(***Figure 10***) (CBE, 2013).

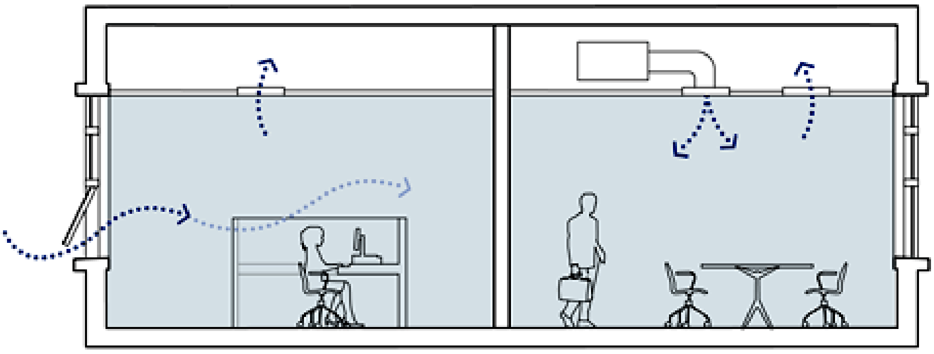

Figure 10 Zoned system (CBE, 2013)

2.5 Thermal environment

Humans spend around 90% of their time indoors, and people's health and welfare are strongly dependent on the indoor environment. Indoor was defined by the world health organization (WHO) as a combination of the five main elements thermal, atmospheric, acoustic, actinic, and mechanical environment. For this master thesis, the focus will be on the indoor elements' thermal -and atmospheric environment.

Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment” (Standard, 2006). The thermal comfort is affected by the environmental factors: dry bulb temperature, air-velocity and turbulence, radiant temperature, and relative humidity. Besides, thermal comfort is also affected by personal factors: clothing level, metabolic heat, wellbeing, and sicknesses. Due to human biological variations, it is not possible to satisfy everyone at the same time. It is therefore essential to implement a condition where the highest possible percentage of the number of people are thermally comfortable(Bjarne W Olesen, 1995). It is not required to document the thermal comfort the same way as for the building's energy performance. However, there are several standards that provide guidance on how to provide a good thermal indoor environment. Examples of the standards are NS-EN ISO 7730 (2006) and NS-EN 15251 (2007)

2.5.1 The heat balance method

In order to assess the thermal environment, Povl Ole Fanger developed an index that established a relationship between metabolic activity, clothing, and the physical parameters of the environment. The two indexes he introduced was predicted mean vote (PMV) and predicted people dissatisfied (PPD)(Fabbri, 2013). The predicted mean vote index indicates the mean response of a larger group of people on a seven-point comfort scale (***Table 2***). A value of 0 in the PMV index indicates neutrality, (-1 and +1) indicates slightly cold and warm discomfort, and (+3,+2,-2,-3) represent discomfort with too warm or cold surroundings. There are three ways to determine the PMV, either using digital computation, directly from the tables in Annex E or by direct measurements(Standard, 2006).

Table 2 The basis of Predicted Mean Vote (PMV) 7 Scale index.

+3 hot
+2 warm
+1 slightly warm
0 neutral
-1 slightly cold
-2 cool
-3 cold

Predicted people dissatisfied (PPD) is based on the percentage of the number of a group of people which are dissatisfied with the thermal environment based on clothing and activity. If the PMV value is determined, the PPD value can be found from following equation:

$$\boldsymbol{PPD} = 100 - 95^{(-0.03353*PMV^4 - 0.2179*PMV^2)} \qquad (3)$$

By using the PMV and PPD index the effects of increased air velocity and dynamic clothing insulation can be taken into account (Standard, 2019). In ***Figure 11***, the connection between PPD and PMV are expressed by equation (3). It can be seen that even if the PMV=0, at least 5% of the people in a group will be dissatisfied with the thermal climate. The recommended requirement for thermal indoor environment in a room is given from the standard NS-EN ISO 7730, and consist of requirements of PPD to be below 10% and PMV to be between -0.5 and +0.5. For the PPD and PMV values in this interval the indoor climate is acceptable

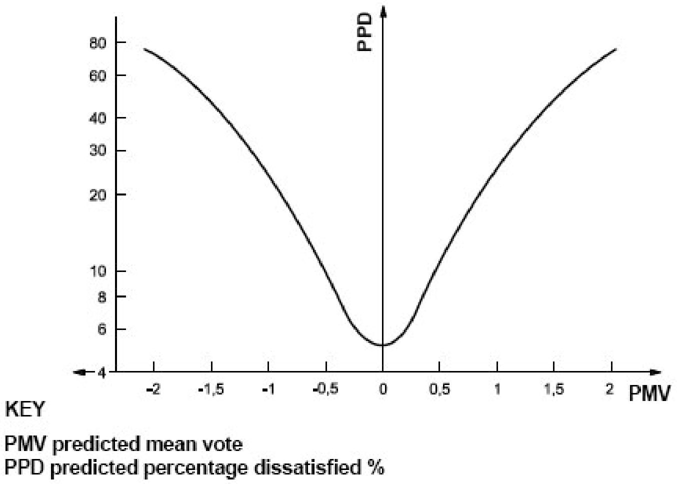

Figure 11 PPD as a function of PMV (Standard, 2006).

2.5.2 Adaptive thermal comfort method

The concept of PMV and PPD were conducted based on steady-state laboratory experiments, where the occupants in most cases were doing sedentary activities and wearing standardized clothes. Several publications((Humphreys & Fergus Nicol, 2002),(Stoops, 2004) and (Kabele & Jokl, 2007) indicates that the PMV and PPD disregard the effect of adaptation and therefore address the steady-state approach as poor in evaluating thermal comfort. Field measurements of perceived thermal comfort conducted in a wide range of buildings (ASHRAE RP-884 project) indicated that occupants are satisfied with temperatures above what predicted by P.O Fanger. This is primarily the case in situations with high outdoor temperatures and where the occupant has the opportunity to open the windows. Therefore, in 1998, an "adaptive comfort"- method was developed for use in buildings without mechanical cooling.(G. S. Brager & De Dear, 1998) did a literature review of thermal adoption in built environment. Their principal findings indicate that occupants had a higher tolerance for temperature changes and had more relaxed expectations of naturally ventilated buildings in comparison to air-controlled buildings. This was explained by a combination of both behavioral adjustment and physical adjustment. In air-controlled buildings, occupants typically have a higher expectation of the thermal comfort, and a slight deviation from the control setpoints can lead to dissatisfaction.

In the standard NS-EN 16798:2019, a method for adaptive comfort for buildings without mechanical cooling is described. The method is primarily applicable for conditions where the occupant performs sedentary activities, access to openable windows, and where the occupant can adapt clothing according to indoor/outdoor thermal conditions. The adaptive method in NS-EN 16798:2019 only applies for office buildings and other buildings of similar type (residential buildings). ***Figure 12*** displays how the operative temperature is influenced by the outdoor temperature for the different categories listed in **Table *3***.

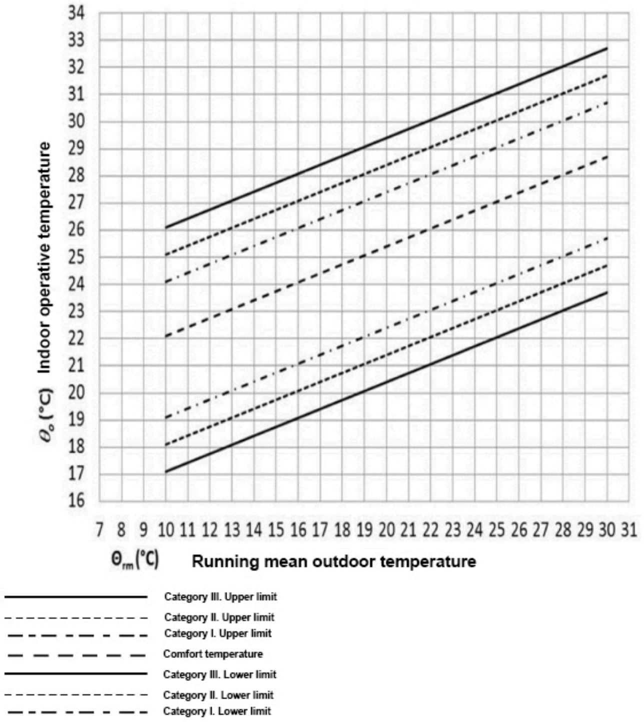

Figure 12 Default design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperature(Standard, 2019).

Table 3 Categories for indoor environment ambition level (Standard Norge, 2016)

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly people.
II	Normal level of expectation and should be used for new buildings and renovation.
III	An acceptable, moderate level of expectation and may be used for existing buildings.
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

2.5.3 Thermal adaptation in residential buildings

The adaptive thermal comfort method from NS-EN 16798:2019 does not distinguish between the occupant's adaptation for different rooms. Therefore,(Peeters, Dear, Hensen, & D'haeseleer, 2009) developed adaptive comfort models for the bathroom, living rooms, and bedrooms. The models were created in an algorithmic manner, which facilitates implementation in any Building Energy Simulation (BES) program. The thermal comfort in residential buildings has a strong dependency on recent outdoor temperatures (Morgan & De Dear, 2003) demonstrated that the weather of the past days influenced the clothing level and perception of the comfort temperature.

In this thesis ,(Peeters et al., 2009) adaptive comfort models for living rooms and bedrooms will be used to emulate the realistic opening of windows. In order to use the adaptive comfort model of (Peeters et al., 2009), several steps of calculations have to be conducted . To take into account the recent day's external temperatures, the influence on today's external temperatures $T_{e,ref}$ have to be calculated, where $T_{e,ref}$ represents the reference external temperature. The following equations is used to calculate $T_{e,ref}$:

$$\boldsymbol{T_{e,ref}} = \frac{(T_{today}+0.8T_{today-1}+0.4T_{today-2}+0.2T_{today-3})}{2.4}\,[°\mathrm{C}] \tag{4}$$

Where:

$\boldsymbol{T_{today}} = Arithmetic\ average\ of\ todays\ max\ and \min external\ temperature[°\mathrm{C}]$

$\boldsymbol{T_{today-1}} = Arithmetic\ average\ of\ yesterdays\ max\ and \min external\ temperature[°\mathrm{C}]$

$\boldsymbol{T_{today-2}} = Arithmetic\ average\ of\ \ max\ and \min external\ temperature\ of\ 2\ days\ ago[°\mathrm{C}]$

$\boldsymbol{T_{today-3}} = Arithmetic\ average\ of\ \ max\ and \min external\ temperature\ of\ 3\ days\ ago[°\mathrm{C}]$

2.5.4 Thermal adaption in bedrooms

In bedrooms, occupants usually accept lower temperatures, and good sleeping quality is observed as low as 12 °C (Humphreys, 1979).(Bjorvatn et al., 2017) conducted a survey in Norway for bedroom habits and bedroom preferences for adults. In the survey 39,2 % of the participants preferred to always have the bedroom windows open at night regardless of the season. During the winter, it was also found that one-third of the participants reported temperatures in the bedroom of 12°C or lower, and about 70% reported temperatures below 18 °C.

For the minimum neutral temperature T_n in bedrooms (Peeters et al., 2009) used a temperature recommended by the World health organization(WHO) of minimum of 16 °C and a maximum neutral temperature of 26°C. The values for the neutral temperature are obtained by finding the reference external temperature $T_{e,ref}$ on an hourly basis and use one of the equations listed below.

$$\boldsymbol{T_n} = 16\text{ °C} \quad \text{for} \quad T_{e,ref} < 0\text{ °C} \tag{5}$$

$$\boldsymbol{T_n} = 0.23T_{e,ref} + 16 \quad \text{for} \quad 0\text{ °C} \le T_{e,ref} < 12.6\text{°C} \tag{6}$$

$$\boldsymbol{T_n} = 0.77T_{e,ref} + 9.18 \quad \text{for} \quad 12.6\text{ °C} \le T_{e,ref} < 21.8\text{°C} \tag{7}$$

$$\boldsymbol{T_n} = 26\text{°C} \quad \text{for} \quad T_{e,ref} \ge 21.8\text{°C} \tag{8}$$

In order to find the upper and lower value of thermal comfort, a 90% acceptability was chosen, corresponding to 10% PPD. In (Peeters et al., 2009) research, a temperature change of 5°C correlated to a 10%PPD, assuming that the occupants in a residential building had a low sensitivity to indoor temperatures changes. In this thesis, a width of the comfort zone (w) of 5°C will be used for the calculations of the upper(T_{upper}) and lower(T_{lower}.) limit of comfort band. The occupant's preference for non-thermal sensation is also common, and it varies asymmetrically around the neutral temperature $T_n \pm a$, where a is a constant (≤1). For the case of a 10%PPD, a is equal to 0.7.

The upper and lower temperature of the comfort band for the bedroom is calculated by the use following equations (9) and (10). It must, however, be noted that equation 10 is modified; if the equation for lower limit is used according to (Peeters et al., 2009), the lower limit will be higher than the comfort temperature. Therefore, the same equation as for lower comfort temperature in livingrooms equation 14 was used, but with 16°C as a lower limit.

$$\boldsymbol{T_{upper}} = \min\,(26\text{°C}, T_n + w * a) \tag{9}$$

$$\boldsymbol{T_{lower}} = \max\,(16\text{°C}, T_n - w(1 - a)) \tag{10}$$

2.5.5 Thermal adaption in living rooms

In a study on room temperatures in Norwegian residential buildings, it was evident that many occupants kept the temperature setpoint lower than the comfort temperature to save energy costs (Halvorsen & Dalen, 2013). Also, the comfort temperature in living rooms was measured approximately 23°C on average for buildings with passive house requirements and a comfort temperature of approximately 22°C for conventional residential buildings. (Peeters et al., 2009) defined the neutral temperature for living rooms as listed in equations 11 and 12.

$$\boldsymbol{T_n} = 20.4\text{ °C} + 0.06 * T_{e,ref} \quad \text{for} \quad T_{e,ref} < 12.5\text{ °C} \tag{11}$$

$$\boldsymbol{T_n} = 16.63\text{ °C} + 0.36 * T_{e,ref} \quad \text{for} \quad T_{e,ref} \ge 12.5\text{ °C} \tag{12}$$

The width of the comfort zone (w=5°C) and constant (a=0.7) was used for the input for the upper and lower temperature of comfort. The following equations for lower and upper limit are used to determine the comfort temperatures:

$$\boldsymbol{T_{upper}} = T_n + w * a \qquad (13)$$

$$\boldsymbol{T_{lower}} = \max\,(18°\mathrm{C}, T_n - w(1-a)) \qquad (14)$$

2.5.6 Temperature, relative humidity and air velocity

The air temperature is the most common factor used to describe the thermal environment. However, if there are no specific radiation sources in the room, the dry bulb temperature can be used. When there is a significant radiation source in the room, operative temperature is more appropriate to use as a measure(Novakovic, 2007). In the Norwegian technical regulations for buildings "Direktoratet for byggvalitet" (DIB), the recommended operative temperature is listed in ***Table 4***. Although the recommended temperature ranges have a maximum value of 26 °C, it is recommended that the temperature is kept below 22 °C when there is a heating-demand. Besides, it is recommended that the operative temperature don't exceed 26 °C for more than 50 hours during a common year(Helge Dokka, Klinski, & Haase Mads Mysen, 2009) . Both too high and too low temperatures can cause comfort and health problems. If there is a too high temperature, the air can often feel dry and can cause the growth of microorganisms and the occurrence of house dust mites, as well as emissions from surfacing materials. Some of the passive strategies which can reduce overheating are reduced window area in the sun exposed facades, exposed thermal mass, exterior shading, and openable windows for natural ventilation. In addition to the operative temperature, the vertical temperature difference should be kept to a minimum. According to TEK17, a vertical temperature difference above 3-4 °C between feet and head can cause discomfort('§ 13-4. Termisk inneklima - Direktoratet for byggkvalitet', n.d.).

Table 4 Recommended values for operative temperatures('§ 13-4. Termisk inneklima - Direktoratet for byggkvalitet', n.d.).

Activity group	**Light physical work**	**Moderate physical work**	**Hard physical work**
Temperature °C	19-26	16-26	10-26

The moisture content in the air influences the building materials properties and lifetime, as well as the thermal environment. In the context of the thermal environment, the term relative humidity (% RH[1]) is often used. The relative humidity indoors is strongly influenced by the

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[1] Relative humidity is the ratio of the ambient vapor pressure of water to the saturation water vapor pressure('Water Vapor Saturation Pressure - an overview | ScienceDirect Topics', n.d.)

relative humidity outdoors. The moisture content g/m^3 in the outdoor air is most extensive during the summer, and this can lead to high indoor relative humidity. In contrast, during winter with low outdoor temperatures, the air will contain significantly less moisture. This will result in a low indoor relative humidity, especially where the indoor temperature is high or with steady ventilation rates and high air change per hour. In Norway, the recommended relative humidity in residential building is in the range from 20-70% during summer, and 20-40% during winter(Asphaug,Silje Kathrin. Time, Berit. Vincent Thue,Jan. Geving,Stig .Gustavsen,Arild. Mathisen,Hans Martin . Uvsløkk, 2015).

Epidemical studies indicate that the incidence of respiratory infections and absenteeism is lower in the "optimum zone" of relative humidity, which is from 40-60 % (***Figure 13***). Besides, mite and fungi production is directly related upon the relative humidity. Where optimal conditions for house mites is from 60-70% and fungi is 75-80% (Arundel, Sterling, Biggin, & Sterling, 1986).

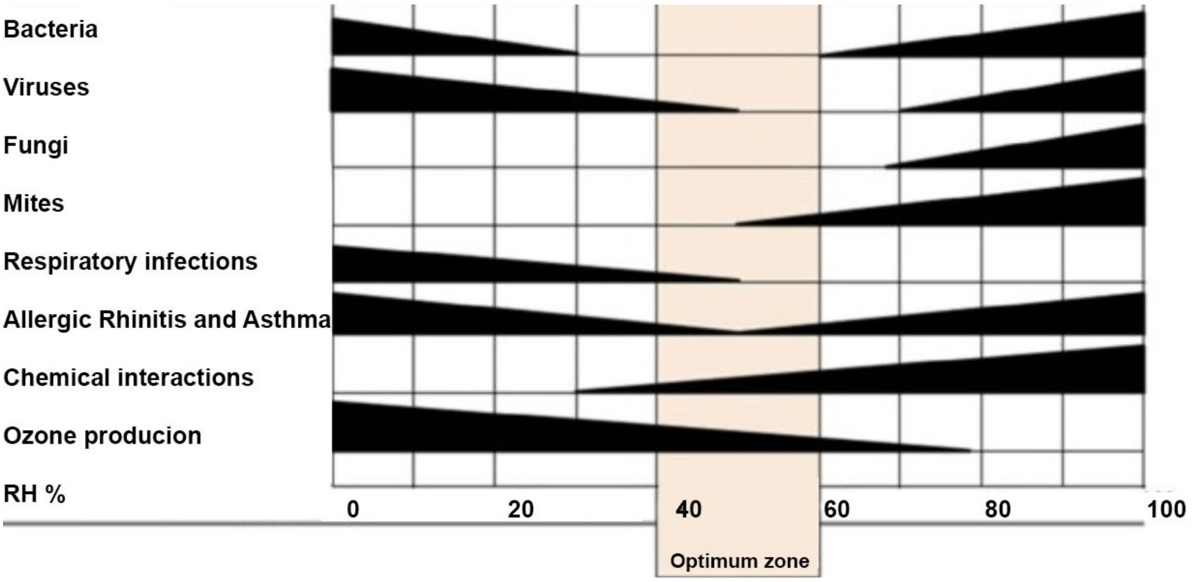


Figure 13 Optimum relative humidity range for minimizing health effects (Arundel et al., 1986)

The air motion in a room can have a significant impact on thermal comfort. Predicted mean vote (PMV) and predicted people dissatisfied (PPD) express the cold and warm comfort for a body as a whole. However, thermal dissatisfaction can also occur from unwanted cooling or heating on one specific part of the body, often referred to as local discomfort(B. W. Olesen & Parsons, 2002). Local discomfort may be caused by air velocity and turbulence within a space and lead to draught, but in warm conditions, air motion can also improve thermal comfort.

Problems related to draught are usually concentrated on the face, neck, hands, and lower part of the legs. The general recommendation for air velocity during periods with heating demand should not exceed 0.15 m/s. Similar, for periods with cooling demand, the respective value is 0.25 m/s(Novakovic, 2007). The turbulence intensity in a room with mixed-mode mechanical ventilation is generally in the range from 30-60%. With the use of natural ventilation both the turbulence intensity and air velocity can be lower(Blom, 1999).

2.6 Atmospheric environment

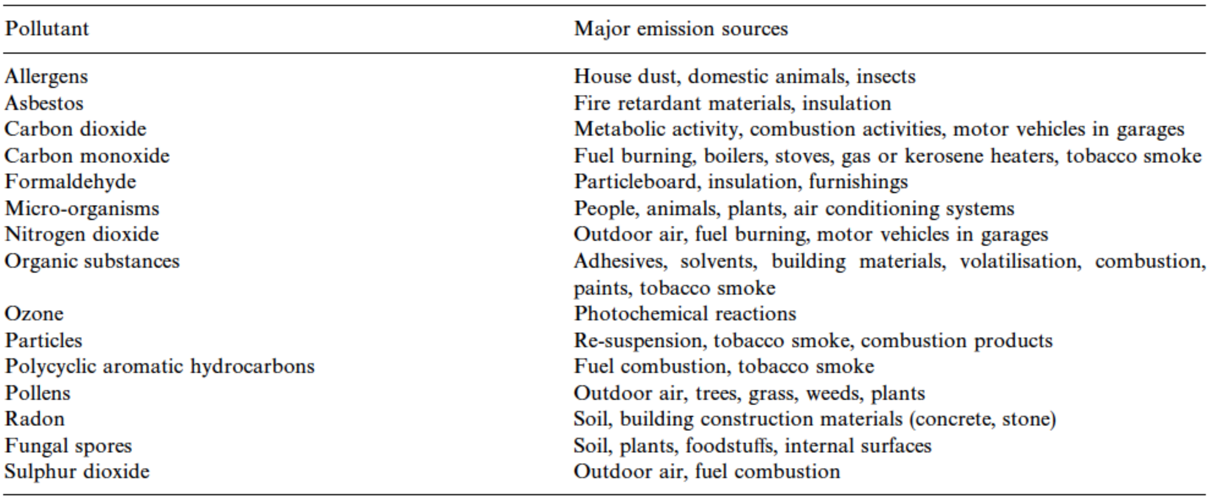
Problems related to air quality are well-known factors that can affect human health, productivity, and performance. Indoor air quality is a result of interactions involving indoor/outdoor ventilation, toxicological, microbiological and physical systems(Jones, 1999). The four main factors which determine the atmospheric indoor environment is pollutant sources, the design of the room, the ventilation system and cleaning (Novakovic, 2007).

2.6.1 Indoor pollution

The indoor quality is affected by pollution with airborne contaminations like gaseous compounds, fine particles, and bioaerosols(Makonin, 2016). The air pollutants in the indoor environment are caused by a range of different emission sources (***Table 5***). In residential buildings, the design of a ventilation system is crucial in order to remove pollutants. Factors that can determine the dimension and the type of ventilation system are pollutants from cooking, building materials, and body odor(Novakovic, 2007).

(C. Wang et al., 2020) conducted a study of the air-surface interactions of 19 common indoor air contaminants for a residential building with ventilation through windows. The chemicals which were measured were all volatile, meaning that they would evaporate into the air. The building was vented by the windows for 15 and 30 minutes, and after closing the windows, it was evident that the chemicals reached the same levels as before opening the windows. The reason for the unchanged levels before and after opening windows was found to be because of chemicals sticking to building surfaces and furbishing rather than being removed and mixed with outdoor air.

Table 5 Major indoor pollutants and emission sources(Jones, 1999).

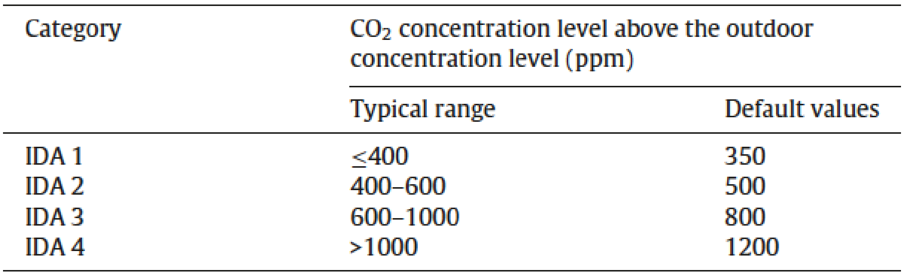


Pollutant	Major emission sources
Allergens	House dust, domestic animals, insects
Asbestos	Fire retardant materials, insulation
Carbon dioxide	Metabolic activity, combustion activities, motor vehicles in garages
Carbon monoxide	Fuel burning, boilers, stoves, gas or kerosene heaters, tobacco smoke
Formaldehyde	Particleboard, insulation, furnishings
Micro-organisms	People, animals, plants, air conditioning systems
Nitrogen dioxide	Outdoor air, fuel burning, motor vehicles in garages
Organic substances	Adhesives, solvents, building materials, volatilisation, combustion, paints, tobacco smoke
Ozone	Photochemical reactions
Particles	Re-suspension, tobacco smoke, combustion products
Polycyclic aromatic hydrocarbons	Fuel combustion, tobacco smoke
Pollens	Outdoor air, trees, grass, weeds, plants
Radon	Soil, building construction materials (concrete, stone)
Fungal spores	Soil, plants, foodstuffs, internal surfaces
Sulphur dioxide	Outdoor air, fuel combustion

2.6.2 CO_2-level

Traditionally the CO_2-level in a room has been an indirect indicator to determine the indoor air quality when humans are the dominant pollutant source. The amount of carbon dioxide (CO_2) a person produces per hour due to exhaling is approximately 15-20 liters. The concentration of CO_2 is often measured in parts per million(ppm), and the concentration in a room depends on the ventilation operation and the size of the room(Novakovic, 2007). Generally, the CO_2 concentration recommendation can be listed in four categories. The Indoor Air Quality (IDA) classification is sorted in descending order, where IDA 4 is low indoor air quality, and IDA 1 is high indoor air quality (***Table 6***)(Fucci et al., 2016). People that are regarded as healthy can tolerate CO_2- concentrations up 10000 ppm without any risk(Kumar, 2012). However, a laboratory test done by (Kajtár, 2012) indicates that human well-being and level of concentration decrease when levels of CO_2 increase up 3000 ppm. In Norway, the mean value of outdoor CO_2 of 400 is commonly used as a reference, and the recommended levels for indoor CO_2 concentration should be <1000 ppm(Novakovic, 2007).

Table 6 Indoor air quality classification as a function of CO2 concentration(Fucci et al., 2016).



Category	CO_2 concentration level above the outdoor concentration level (ppm)	
	Typical range	Default values
IDA 1	≤ 400	350
IDA 2	400–600	500
IDA 3	600–1000	800
IDA 4	>1000	1200

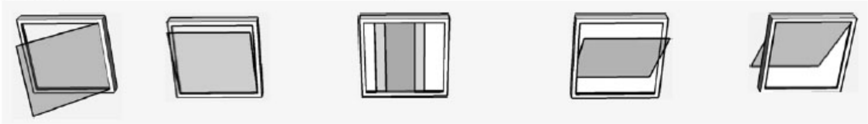
2.6.3 Consequences of a poor indoor climate

"Sick building syndrome" (SBS) is a term of various symptoms where occupants experience health and comfort effects associated with the time spent indoors. The symptoms are reported in residential buildings, where the reason can be tight envelops and the use of mechanical ventilation. Factors that can cause SBS are inadequate ventilation, chemical contamination from outdoor and indoor sources, and biological contaminations. Indicators for SBS can include headache, eye and nose irritation, dry skin, and difficulty in concentration (Epa & Environments Division, 1991). In a cross-sectional study, it was found that temperature levels above 22 °C and relative humidity levels below 25% have been associated with an excess of SBS(Jaakkola, 1994). (Seppanen & Fisk, 2002) found that relative to natural ventilation, air conditioning with or without humidification had a statistically increase in one or more SBS symptoms. Even though if a poor indoor climate does not lead to a direct illness, it can have severe consequences for concentration, well-being, and general conditions.

2.7 Characteristic element for natural ventilation

Window openings are a characteristic element that is commonly used in naturally ventilated buildings. The design and size of the window play a significant function in directing the air to the required spaces. According to (Roetzel, Tsangrassoulis, Dietrich, & Busching, 2010), the choice of window is mainly a result of the architectural decision, which is strongly influenced by the climate. There are two main aspects that influence ventilation efficiency based on the façade design. Firstly, the choice of the window opening type and secondly the placement and size of the window on the façade. In moderate climates, window design, which protects from wind and precipitation, is preferable e.g., bottom hung opening to inside. However, in warm climates, the size, adjustability, and ventilation rate of the window can be of higher interest e.g., horizontal pivoted window. A comparison of window types and the performance of the design was conducted by(Roetzel et al., 2010), shown in ***Figure 14***.

(Heiselberg, 2000) did a laboratory investigation in Denmark of three different window types: horizontal pivot window, side-hung window, and tilting top vent. From the investigation, it was clear that during summer due to low-temperature differences, the horizontal pivot and side hung window was an optimal solution to provide sufficient airflow. However, during winter due to high-temperature difference (the tilting top vent was the ideal solution.(J. Wang, Wang, Zhang, & Battaglia, 2017) conducted a Computational Fluid Dynamics (CFD) study of the ventilation rate and indoor temperature for six window configurations. Among the six windows, the vertical slide window performed best hence achieving the highest ventilation rate and lowest indoor temperature. On the other side of the scale, the bottom-hung opening to inside, followed by top-hung opening to outside performed the worst.



	Side hung opening to inside	Bottom hung opening to inside	Sliding, opened pane always covers part of window	Horizontal pivoted, lower part opening to outside	Top hung, opening to outside
Weather protection	Poor	Good	Poor	Medium	Medium
Max acheivable ventilation rate	Good	Poor	Medium	Good	Medium
Adjustability of opening size	Good	Poor	Good	Good	Good
Flexibility for placement of furniture	Poor	Good	Good	Medium	Good

Figure 14 Evaluation of different window opening designs (Roetzel et al., 2010)

2.7.1 Elements influencing ventilative cooling

Studies on building geometry and natural ventilation have indicated the internal airflow, and the volume flow rate has a significant dependency on the roof geometry. (Peren, van Hooff, Ramponi, Blocken, & Leite, 2015) compared five different roof geometries A) straight roof, B) concave roof, C) hybrid convex-concave D), and E) convex roofs. The volume flow rate and average pressure coefficient of the outlet for the different geometries were simulated and compared the CFD program ANSYS fluent. From the study, it was found that A) straight roof, D) and E) convex roof had approximately 12-13 % higher volume flow rate than for the case with B) concave roof (***Figure 15***a). The design of the roof and the effectiveness of natural ventilation is strongly dependent on the magnitude of under-pressure in the leeward side of the roof. Where higher under-pressure will generate higher volume airflow through the building (***Figure 15***b). (Peren et al., 2015) also conducted a study on multiple eaves inclination cases and how it affected the volume flow rate in a building. Eaves on the leeward and windward façade was tested separately, and the optimal design was combined to maximize the volume flow rate. The combined solution for the eaves was found to increase the flow rate by 24% in comparison to the reference building without any eaves.

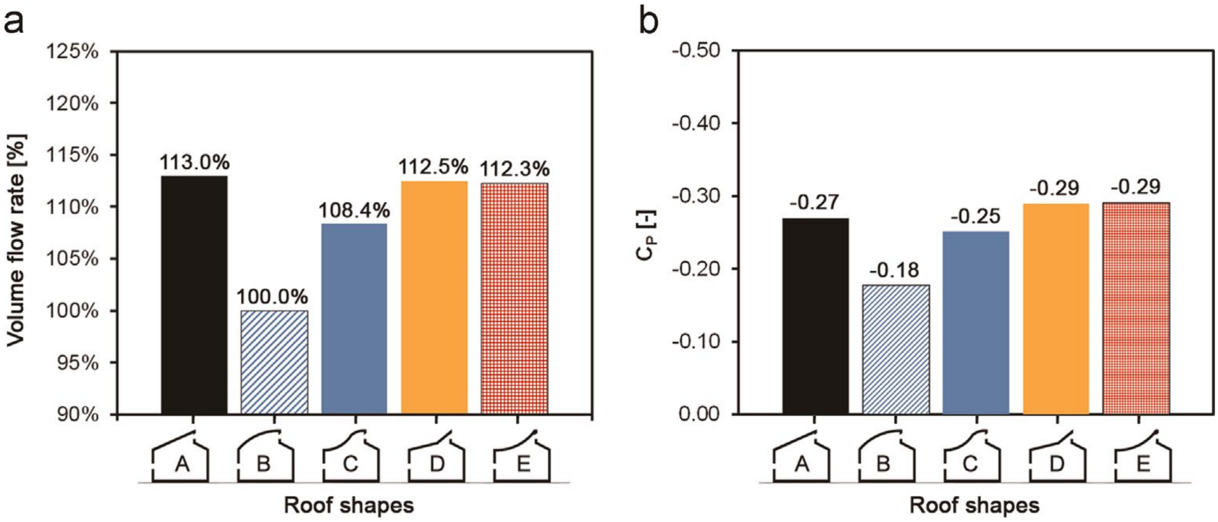


Figure 15 Impact of roof geometry as a function of a) volume flow rate and b) average pressure coefficient in the outlet opening (Peren et al., 2015).

Roof inclination and the position of the window are parameters that can affect the potential of natural ventilation. (Perén, van Hooff, Leite, & Blocken, 2015) carried out a CFD study of ventilation flow for five different roof inclinations and various vertical placement of openings (***Figure 16***). It was found that an inclination of 45° could improve the volume flow rate by more than 22% in comparison to the reference building with a flat roof. For the studied building, it could be seen that the 9° tilt performed even worse than for the flat reference roof. In the context of achieving higher volume flow rates, the inclination angle must be larger than 18°. However, the vertical placement of the outlet opening was shown to have minimal impact on the volume flow rate compared to the roof inclination angle. (Kosutova, van Hooff, Vanderwel, Blocken, & Hensen, 2019) did a CFD investigation on the volume flow rate and air exchange efficiency of four different opening locations in a generic isolated building. The largest and lowest dimensionless flowrates were observed to be respectively the openings in the upper part of the façade and openings located in the lower part of the façade. However, the highest air exchange efficiency (42%) is for the configuration with center placed openings, and the lowest air exchange efficiency (20%) is for the upper placed openings. The upper placed openings resulted in low mixing of air, mainly due to short circuiting flow.

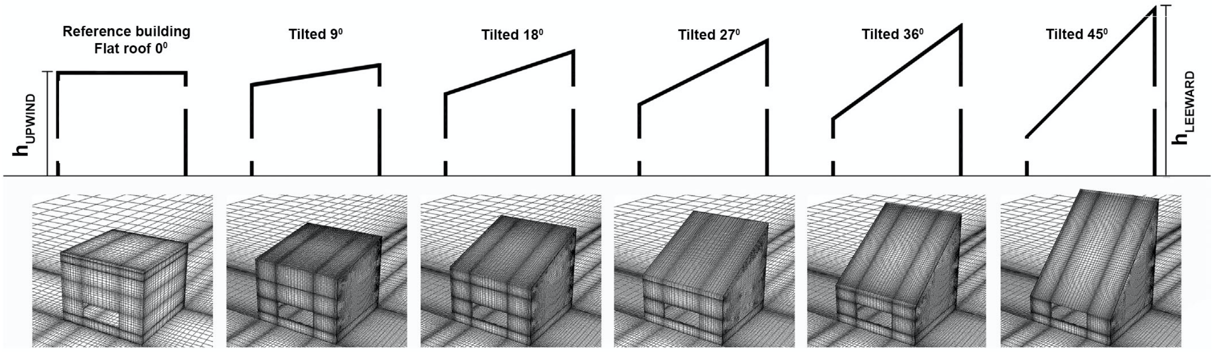


Figure 16 Vertical cross-section and computational grid of different roof inclinations and building geometries (Perén et al., 2015)

The ratio between the inlet area A_{inlet} and outlet area A_{outlet} is another factor that has an effect on the potential for natural ventilation. When the windows are placed adjacent to each other and $A_{inlet}= A_{outlet}$, maximum air change is achieved. Furthermore, symmetrical opening configurations of $\frac{A_{inlet}}{A_{outlet}} < 1$ can result in high indoor air speeds, and should be limited if the indoor air velocity has to be kept within comfort limits. Whereas, for symmetrical opening configurations of $\frac{A_{inlet}}{A_{outlet}} > 1$, the indoor air velocity is reduced. When there is configurations of non-symmetrical inlet and outlet the mixing of indoor air will increase, besides improving the indoor air quality(Karava, 2008).

The orientation of the opening concerning the incident wind is also shown to influence the performance of natural ventilation.(Sacht & Lukiantchuki, 2017) investigated the consequences of various angles of incidence of the wind on openings through a cross-ventilated room. The difference of the average pressure coefficient (C_p) for the inlet and outlet was investigated as a function of incidence angles of the winds. From the investigation, it was evident that the most significant difference of (C_p) and thus best performance for natural ventilation was in the range from 0^o and 45^o . The maximum air change per hour was achieved when the wind moved obliquely at the building (45^o), and the worst performance and hence the minimum air exchange occurs when the wind moved parallel to the opening (90^o).

2.8 Reference cases and technologies

In this chapter, a review of reference cases and relevant technologies for ventilative cooling will be investigated.

2.8.1 Nydalen Vy

The 18 stories multipurpose building "Nydalen Vy" is located in Oslo, Norway, and consists of residential, office, and industry units (***Figure 17***). The building is a showcase project which has ambitions of achieving nearly zero emission building (nZEB) and is expected to be completed by 2020. For the office part, the ventilation concept is only to utilize natural ventilation, and for the residential and commercial part, the ventilation concept is mixed-mode ventilation. The relative narrow building volume and the building's triangular shape ensures pressure differences across the facades, thus resulting in sufficient ventilation airflows.

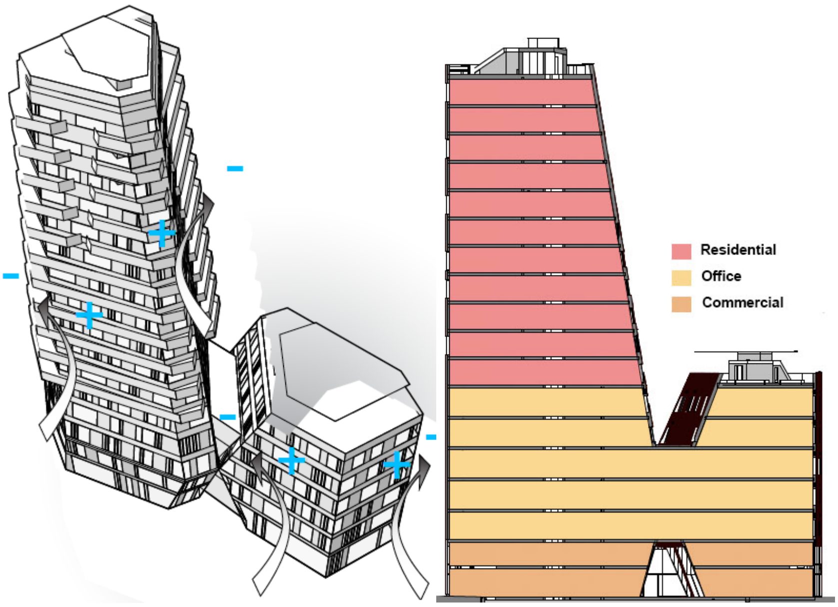


Figure 17 The pressure distribution due to wind (left) and the building zoning (right) (Hegli, Dokka, & Myrup, 2015) .

There are 42 apartments that are going to be placed on the top 12 floors of the building, and the apartments are organized around a compact core. The control system for the ventilation hatches is developed to ensure good indoor air quality and fresh air. Window master, which is a company that supplies various sustainable indoor climate solutions developed the control system for Nydalen Vy. The control system in the office part will operate on automatic motorized ventilation hatches placed horizontally above the window and is complemented with vertical, manually openable windows or hatches. Besides, the hatches are equipped with acoustic dampers on the exterior part (***Figure 18***). The automatic hatches are controlled by indoor CO_2 concentrations and temperature, as well as a weather station that will measure wind direction, wind speed, outdoor temperature, and precipitation. In the initial phase of the project, a CFD analysis was conducted in order to determine the opening area of the hatches and typology of the building. The real-time measurements complemented with CFD calculations form the basis of Windowmasters control system "NV Advance." In the residential part, there will be non-automatic trickle vents located above the windows and manual openable hatches vertically beside the windows(Hegli et al., 2015) .

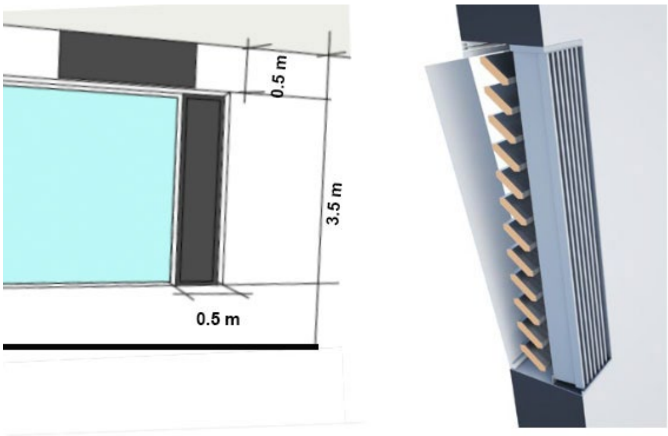


Figure 18 The placement and design for the ventilation hatches(Hegli et al., 2015) .

The concept of mixed-mode ventilation is chosen instead of only natural ventilation in the residential part due to the need for exhaust in the kitchens and bathrooms. For the ventilation concept in the residential part, wind-driven flow is utilized, with the natural ventilation principles single-sided ventilation and cross-ventilation. During summer, the ventilation drives through the manual openable vertical hatches. On the other hand, during winter or to activate night cooling, the ventilation air drives through the vertical trickle vents. Locating the vents high in the façade reduces draft during winter, and locating the hatches besides the windows increases the airflow during summer. The airflow rate during winter is for the residential part reduced to a level which is lower than the requirements for TEK 10, and therefore a dispensation for lower airflow rates was applied for. As can be seen from ***Figure 19***, the apartments have several facades with different angles. This will create a pressure difference on the facades and increase the effect of cross-ventilation through the apartments. The delivered energy for the residential part is 45 kWh/m^{2,} and the net energy demand is 103 kWh/m^{2}.

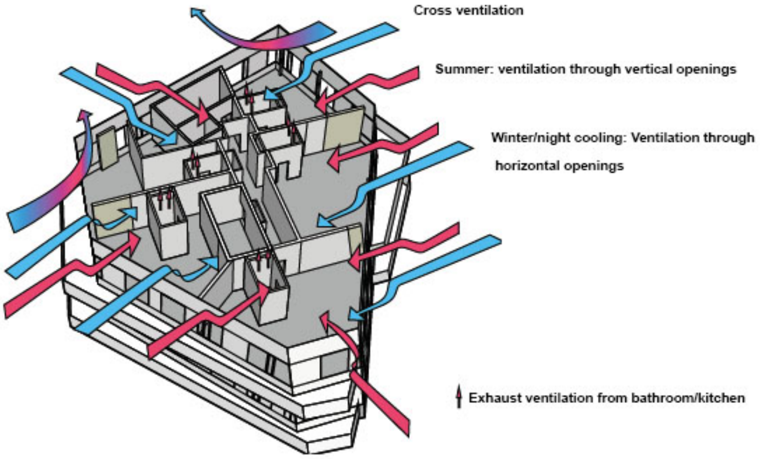


Figure 19 Ventilation strategy for the residential part (Myrup, 2018).

2.8.2 Ventilation hatches

Several products enhance the potential for ventilative cooling, where the main object is to prevent overheating and reduce energy consumption. In this section, different solutions for hybrid and natural ventilation will be reviewed.

Venting hatches is a venting aperture which consists of louvers/grilles and can generally replace windows for ventilation. DucoVentilation and sun control are a manufacturer of different ventilation products, for instance, "DucoGrille NightVent," which is a motorized/manual controlled ventilation hatch. The hatch consists of characteristic performance elements such as louvers, which will allow air exchange and simultaneously protect from precipitation penetration (***Figure 20***). The control system of the automatic version is based on CO_2 and temperature levels indoor, which is controlled by either a wired or wireless control. Anti-burglary louvers, insect screens, and acoustic louvers are other possibilities that can be equipped to the hatch. The hatch can be a part of a hybrid ventilation concept, where the hatch can be openable during summer and completely enclosed during winter. The u-value of the hatch (1.5 W/m^2K) can be a limitation in cold climates. However, with hatches, there will be no need for openable windows. Fixed frame windows have a lower window frame fraction percentage compared to openable windows; this can potentially lead to reduced energy use.

Figure 20 DucoGrille Nightvent (‘DucoGrille NightVent: glass-replacing ventilation hatch’, n.d.).

2.8.3 Ventilation window

The Danish company “Horn-Group” has developed a ventilation window and is, according to the company, an “energy solution providing fresh pre-heated air, a superb indoor climate, and considerable cost savings.” The ventilation window is a double window with a ventilation cavity between the glazing panes. Air circulates from the bottom of the window through the cavity and enters the building from a bio-wax temperature-controlled valve. The valve opens gradually when the window is exposed to the sun or by heat loss through the inside window. The window can operate in three different conditions minimal, normal, and self-cooling position depending on the indoor or outdoor temperature (***Figure 21***). In cold conditions, the valve will close to the minimum position where the window will deliver moderate but constant pre-heated air, mainly from room heat loss. Whereas for the normal position, the window will deliver an optimal stream of pre-heated air from room heat loss but also solar radiation. When cavity air temperature exceeds 26°C, the air outdoor air will ventilate the cavity, and the outdoor air will enter the building directly through the top located valve (Horn group, 2019).

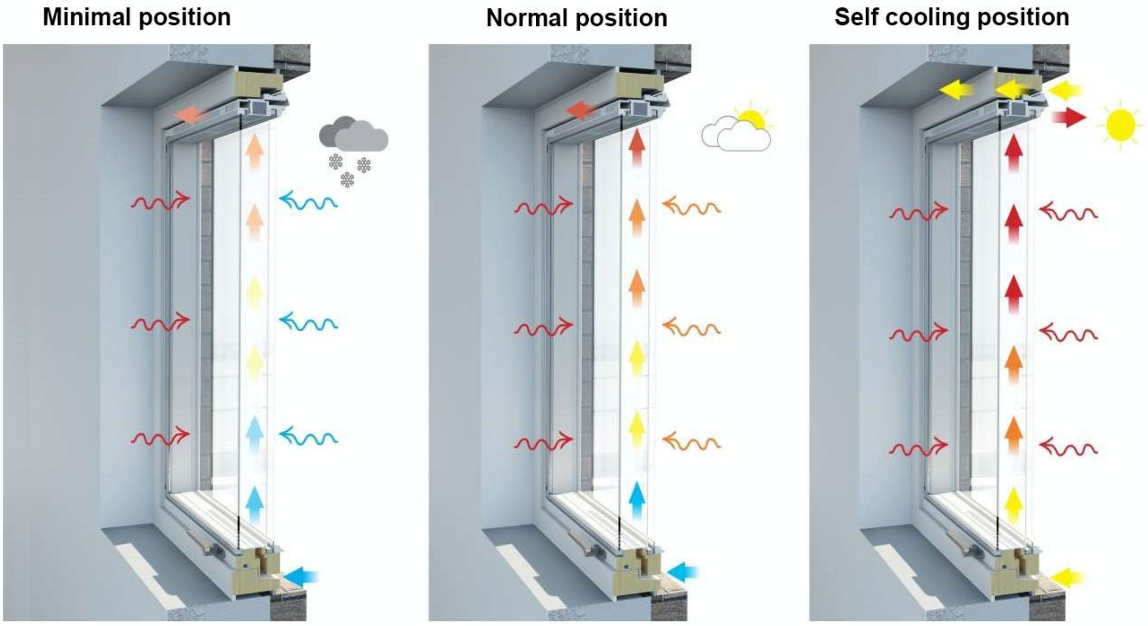


Figure 21 Three positions for the ventilation window (Horn group, 2019)

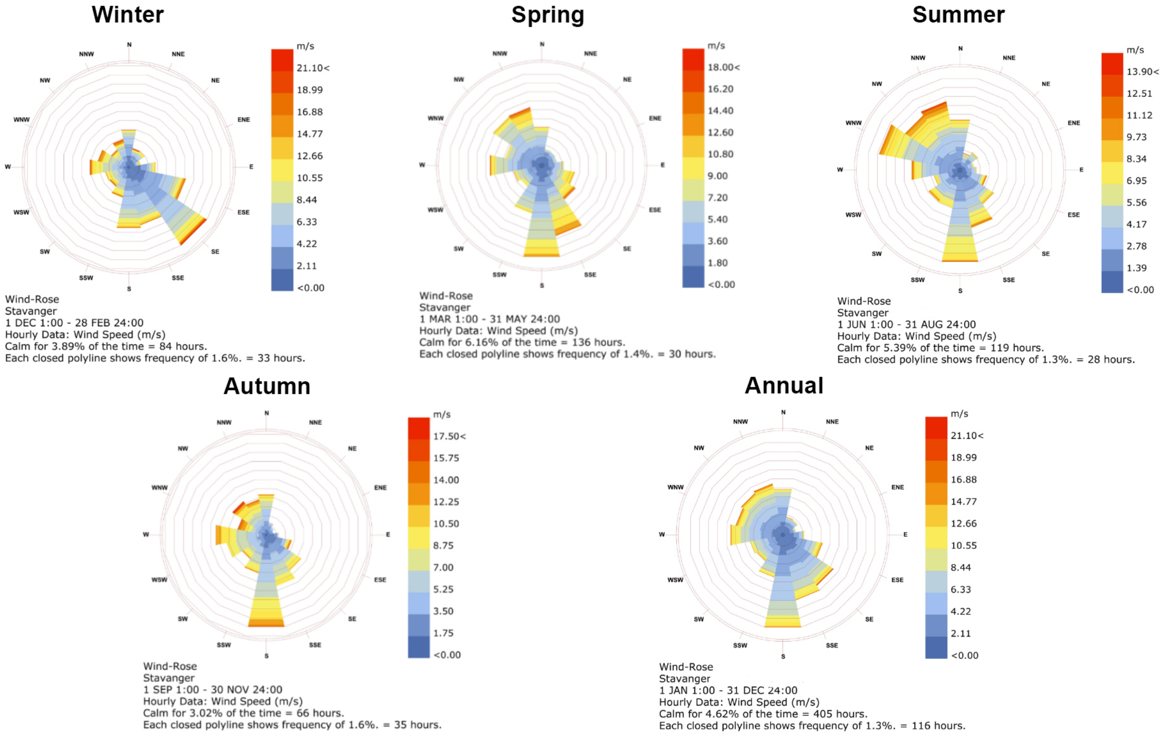
(Sandholm Madsen, Søvsø, & Draborg, 2016) conducted an indoor climate investigation of an apartment with the ventilated window from the Horn-group. Draft measurements from the ventilated window demonstrated no risk of draft with a temperature difference of 20 °C from outdoor to indoor. (Heiselberg & Larsen, 2013) did in-situ measurements with the first version of the ventilation window from the Horn-group. The measurements were conducted during a winter period in a residential building. From the results, it was clear that the ventilation window indicated enhanced energy performance in comparison to a normal window with the same U- and g-value. The ventilation window concept is effective when there is an under-pressure in the building, typically induced by exhaust ventilation. Also, the study revealed that the energy savings for a ventilated window could reach up to 11% to 20% in comparison to a conventional window. The energy savings is according to the study, dependent on the window typology and climate.

Chapter 3 Case Fjelltun

Fjelltun is a residential building project located in the suburban area of Mariero 4 km from Stavanger. The developer of the project Base Bolig has focused on holistic, environmentally friendly solutions, and especially zero-emission solutions. The area consists of two properties, one with detached row-houses and the other area with multi-story residential buildings (figure 17). In total, the plan is to have around 110 residential housing units partitioned on the plot of in total 7000 m^2. The project is currently (January.2020) in the early design phase, where the architects have proposed a feasibility study of the area (***Figure 22***). Besides, the construction start is planned to be in Q3 of 2021, and it is anticipated to be finished by 2023. The focus area in this thesis will, as earlier mentioned, be on the multi-story buildings, as this segment was of the most substantial interest for the project developer.

Figure 22 Proposed plot of Fjelltun, Mariero.

In order to develop an IDA ICE model and to conduct consistent analysis within the given time frame of the master thesis, it was decided to focus on one of the multi-story buildings. To determine which building to be considered and assessed further, the wind-speed and frequency were studied in the area. The weather station for the assessment of the wind conditions is located in Stavanger, Våland approx. 2 km from to Fjelltun, Mariero. From the assessment of the wind conditions on the plot, it was especially important to consider the wind direction and frequency during the periods with the highest potential of reducing overheating. In order to assess the wind conditions, wind roses for the different seasons were made based on wind measurements from 2003-2018 taken from the weather station at Våland, Stavanger (***Figure 23***). A trend for the wind direction for the seasons is either from south, north-west or south-east. The wind speed is generally considerable towards the wind direction with the highest frequency. For the raw wind data, a weather file in format "Energyplus weather form" (EPW) was exported from the webpage "climate.onebuilding.org." The EPW was further imported to Grasshopper for Rhino where wind roses were made on a seasonal basis



Winter

Wind-Rose
Stavanger
1 DEC 1:00 - 28 FEB 24:00
Hourly Data: Wind Speed (m/s)
Calm for 3.89% of the time = 84 hours.
Each closed polyline shows frequency of 1.6%. = 33 hours.

Spring

Wind-Rose
Stavanger
1 MAR 1:00 - 31 MAY 24:00
Hourly Data: Wind Speed (m/s)
Calm for 6.16% of the time = 136 hours.
Each closed polyline shows frequency of 1.4%. = 30 hours.

Summer

Wind-Rose
Stavanger
1 JUN 1:00 - 31 AUG 24:00
Hourly Data: Wind Speed (m/s)
Calm for 5.39% of the time = 119 hours.
Each closed polyline shows frequency of 1.3%. = 28 hours.

Autumn

Wind-Rose
Stavanger
1 SEP 1:00 - 30 NOV 24:00
Hourly Data: Wind Speed (m/s)
Calm for 3.02% of the time = 66 hours.
Each closed polyline shows frequency of 1.6%. = 35 hours.

Annual

Wind-Rose
Stavanger
1 JAN 1:00 - 31 DEC 24:00
Hourly Data: Wind Speed (m/s)
Calm for 4.62% of the time = 405 hours.
Each closed polyline shows frequency of 1.3%. = 116 hours.

Figure 23 Windroses for the wind frequency and-speed for Våland,Stavanger

In ***Figure 24***, the wind conditions during the summer and winter are visualized. During summer, the wind direction has the highest frequency and windspeed from north-west, followed by south direction. Regarding the wind exposure on a building scale, it can be assumed that building 1 and 2 will be on the leeward side during some parts during summer. Therefore, one of these buildings will be assessed further due to the least wind exposure; thus, most critical to receive sufficient internal air-flows. However, due to lack of an in detail computational fluid dynamic software to assess in-situ wind conditions, building 1 which is the tallest was decided to assess further.

Figure 24 Wind on the plot (based on wind roses figure 23)

3.1 Building description

In order to have a realistic scenario for the influence of solar radiation and especially wind conditions, the surrounding building was included in the IDA ICE file (***Figure 25***). The building, which is chosen for further assessments, is an 8-floor building with apartments of in total 2780 m^2 . The building consists of one elevator/stair shaft from level 1to level 8 in the core of the building and one staircase area from level 1 to level 2. For the assessment of energy use and thermal comfort of the building, the staircases and elevator shaft was assumed not ventilated or heated directly.

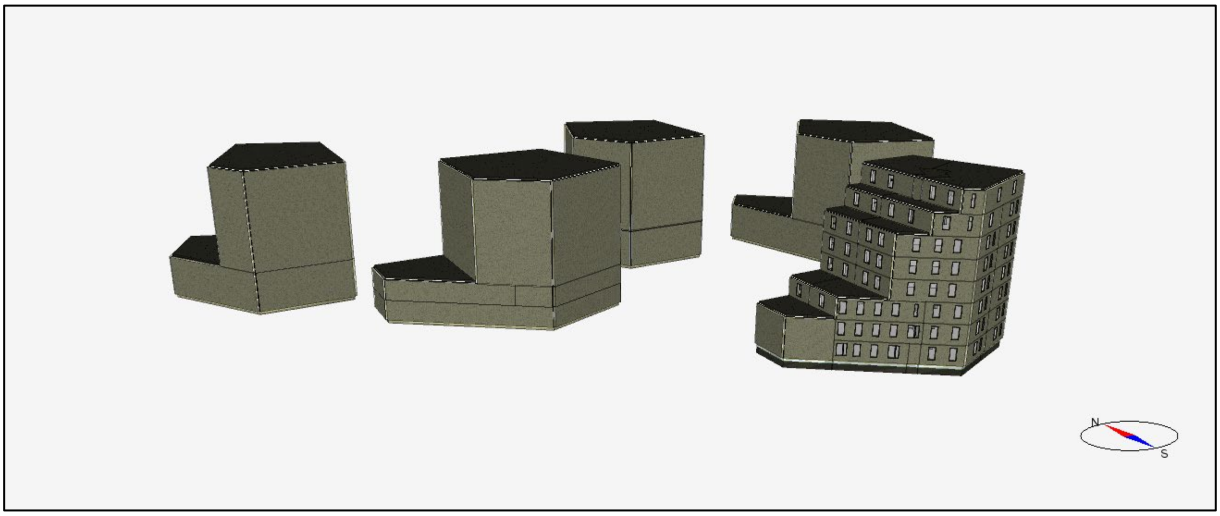


Figure 25 IDA ICE 3D view of the buildings.

In the initial assessment of the building, an investigation of energy consumption and overheating was conducted on all the 32 apartments. An overview of the floor plans for the different apartments is listed in **Appendix.1 Floor plan**. The apartments for the initial assessment are constructed without internal separation walls; this will significantly reduce the simulation time. For further analysis, the internal walls will be included for the most critical apartment based on overheating and energy consumption. The different floors vary in the heated gross internal area and apartment number per floor (***Table*** *7*).

Table 7 Overview of apartments and heated gross internal area

Floor	**Number of apartments**	**Heated gross internal area [m^2]**
Level 1	5	407
Level 2	5	416
Level 3	5	416
Level 4	4	342
Level 5	4	342
Level 6	4	343
Level 7	3	280
Level 8	2	235
Total	32	2780

3.1.1 Wind pressure coefficient

The pressure coefficients are used to calculate the wind pressure for the external surfaces in relation to the wind speed at roof height. In order to have good precision for the pressure coefficients, either CFD or wind tunnel measurements are required, however, to have an assumption for the wind effects on the façade handbook data can be used (Equa AB, 2002). The default values of the pressure coefficient for "semi-exposed building" were used in this thesis, where the data was retrieved from handbook data from (Air Infiltration and Ventilation Centre (AIVC), 1984). In ***Table 8***, the pressure coefficients are listed for level 1. The angles in the table represent the wind direction relative to the face/façade azimuth of the building where zero angles represent a wind directed towards the face. **Figure 26** illustrates the location and cardinal direction for the different building faces. The remaining pressure coefficient for other floor levels is listed in **Appendix 2. Pressure coefficients for the different levels and facades**.

Table 8 Pressure coefficient for level 1

Face/Angle	0°	45°	90°	135°	180°	225°	270°	315°	Face azimuth	Cardinal direction
Level 1									[°]	
Roof 1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	360	North
Facade 1	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	5	North
Facade 2	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	75	East-North-East
Facade 3	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	165	South-South-East
Facade 4	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	220	South-West
Facade 5	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	274	West

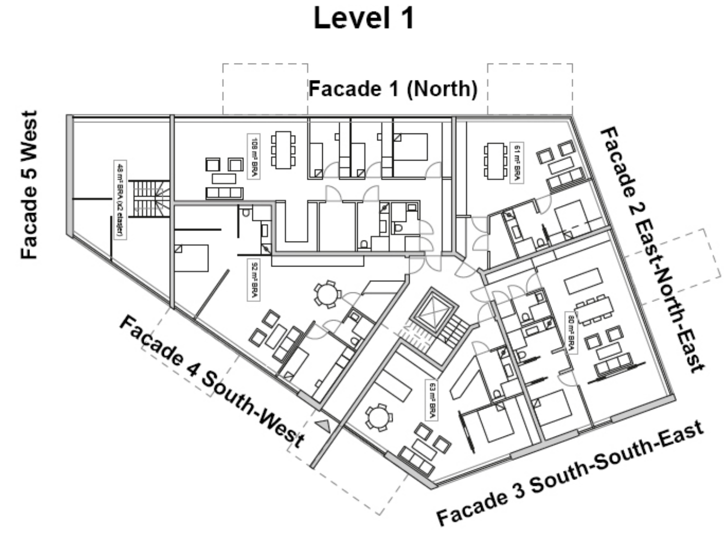


Figure 26 Floorplan of level 1 with corresponding facade numbers

3.1.2 Building envelope

For the building envelope, the IDA ICE model has been made with separate models for both the TEK 17 and passive house. The values used for minimum requirements and energy-saving measures for TEK 17 and the passive house standard for apartment blocks are listed in ***Table 9***.

Table 9 Minimum requirements and energy measures for TEK17 and passive house

Building envelope	TEK 17	Passive house
U-value outer walls [W/m^{2}K]	$\leq 0{,}18^{x}$	$\leq 0{,}10^{x}$
U-value roof [W/m^{2}K]	$\leq 0{,}13^{x}$	$\leq 0{,}08^{x}$
U-value floor [W/m^{2}K]	$\leq 0{,}10^{x}$	$\leq 0{,}08^{x}$
U-value windows and doors [W/m^{2}K]	$\leq 0{,}8^{x}$	$\leq 0{,}8^{y}$
Air leakage rate per hour at 50 Pa pressure difference	$\leq 0{,}6^{x}$	$\leq 0{,}6^{y}$

Normalized thermal bridge, where m^2 is stated as heated gross internal area [W/m^{2}K]	≤ 0,07^x	≤ 0,03^y
*	X: represent energy saving measures (TEK 17 and NS 3700:2013)	Y: represent minimum requirement for energy efficiency (TEK 17 and NS 3700:2013)

In order to have sufficient daylight in the apartments, the window area was calculated to meet the minimum requirement of an average daylight factor of 2% for the zones. According to TEK 17, the daylight factor can be approximated based on the following equation:

$$\boldsymbol{A_g} \geq 0{,}07 * A_{BRA}/LT \tag{15}$$

Where:

$\boldsymbol{A_g} = The\ glazed\ area\ of\ the\ window, located\ 0{,}8\ m\ above\ the\ floor.$

$\boldsymbol{A_{BRA}} = Heated\ gross\ internal\ area, including\ the\ area\ of\ balconies\ above\ the\ zone$

$\boldsymbol{LT} = Light\ transmittance$

For the light transmittance, a typical value of 0,65 was assigned to the windows. With the use of equation 3, the window to floor area was calculated to be 11% and uniform for all the apartments.

3.2 Internal loads

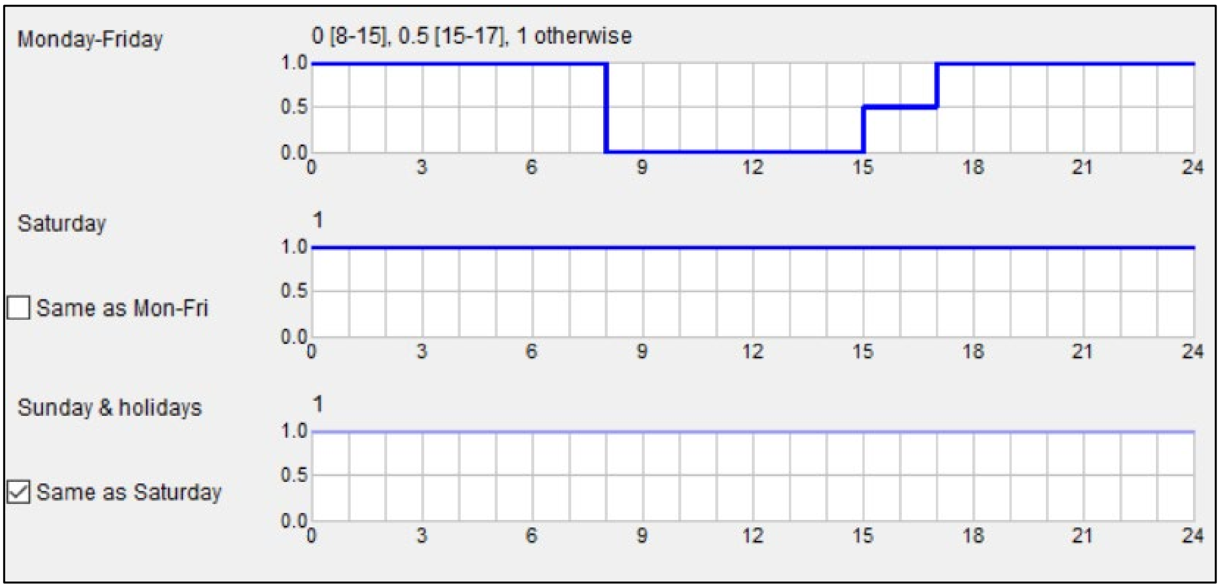
The inputs for the internal loads for the IDA ICE model are assigned based on the standardized values from the Norwegian standard NS:3031(2016) **Table 10**. The IDA ICE models will have a final energy consumption according to the NS:3031(2016) standard, where domestic hot water and equipment schedules will be based on the NS:3031. However, the occupant schedule in the standard is static, assuming that the occupants are always present. In addition, the lighting schedule in the standard has a uniform profile for all the seasons. Therefore, the occupancy and lighting schedule will have a more realistic profile.

Table 10 Standardized values for energy per year NS 3031(2016)

Energy per year for block of flats	**Domestic hot water**	**Equipment**	**Occupants**	**Lighting**
	[kWh/m^2/year]			
	25	17.5	13.1	11.4

3.2.1 Occupants

For the internal gains from occupants, IDA ICE requires input based on the number of occupants per square meter rather than watt per square meter. A calculation based on the activity level (MET) has to be performed. 1 MET corresponds to 58.2 W per m^2 body surface, and in IDA ICE, a body surface of 1.8 m^2 is used (Equa AB, 2013). Thus, 1 met emits 105 W of heat per occupant, and the number of occupants per square meter to achieve 1.5 W/m^2 can be calculated and assigned to IDA ICE. The occupancy schedule is dynamic during weekdays and static during weekends assuming always present (***Figure 27***).



Monday-Friday
0 [8-15], 0.5 [15-17], 1 otherwise

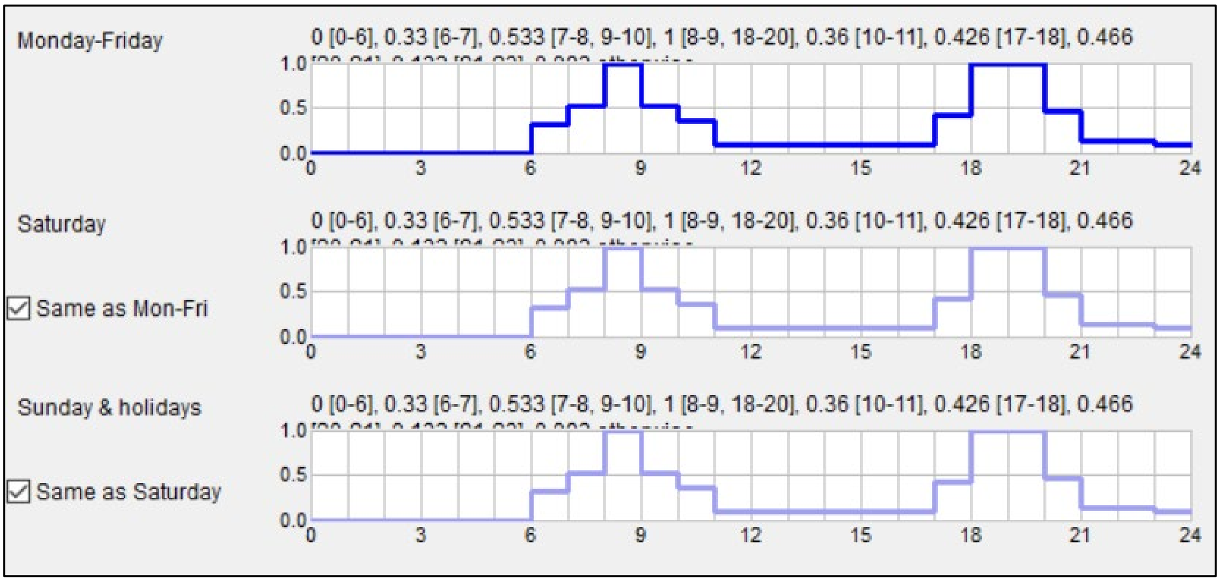
Saturday
1
☐ Same as Mon-Fri

Sunday & holidays
1
☑ Same as Saturday

Figure 27 Occupancy schedule IDA ICE

3.2.2 Domestic hot water

The domestic hot water is simulated in order to meet the standardized level of energy consumption per year. The standardized level 25 $kWh/m^2/year$ for domestic hot water use was met when the average hot water use was 26 liters per occupant per day. The schedule for the domestic hot water use is based on table A.2 in NS:3031(2016) (***Figure 28***). Also, the energy source for the domestic hot water is from district heating.



Monday-Friday

0 [0-6], 0.33 [6-7], 0.533 [7-8, 9-10], 1 [8-9, 18-20], 0.36 [10-11], 0.426 [17-18], 0.466

Saturday

☑ Same as Mon-Fri

0 [0-6], 0.33 [6-7], 0.533 [7-8, 9-10], 1 [8-9, 18-20], 0.36 [10-11], 0.426 [17-18], 0.466

Sunday & holidays

☑ Same as Saturday

0 [0-6], 0.33 [6-7], 0.533 [7-8, 9-10], 1 [8-9, 18-20], 0.36 [10-11], 0.426 [17-18], 0.466

Figure 28 Domestic hot water schedule NS:3031(2016)

3.2.3 Lighting

In Norway, the daylight conditions vary throughout the year; more artificial light is generally used during winter than during summer. (Karlsen, Hamdy, & Attia, 2020) developed a lighting distribution schedule based on the annual standardized values from NS:3031(2016) and a survey from households in Finland. The schedule is divided into four seasons with different lighting distribution depending on the time of the day and time of the year (***Figure 29***).

Monday-Friday

Multiple rules. Click "Advanced" for details

Saturday

☑ Same as Mon-Fri

Multiple rules. Click "Advanced" for details

Sunday & holidays

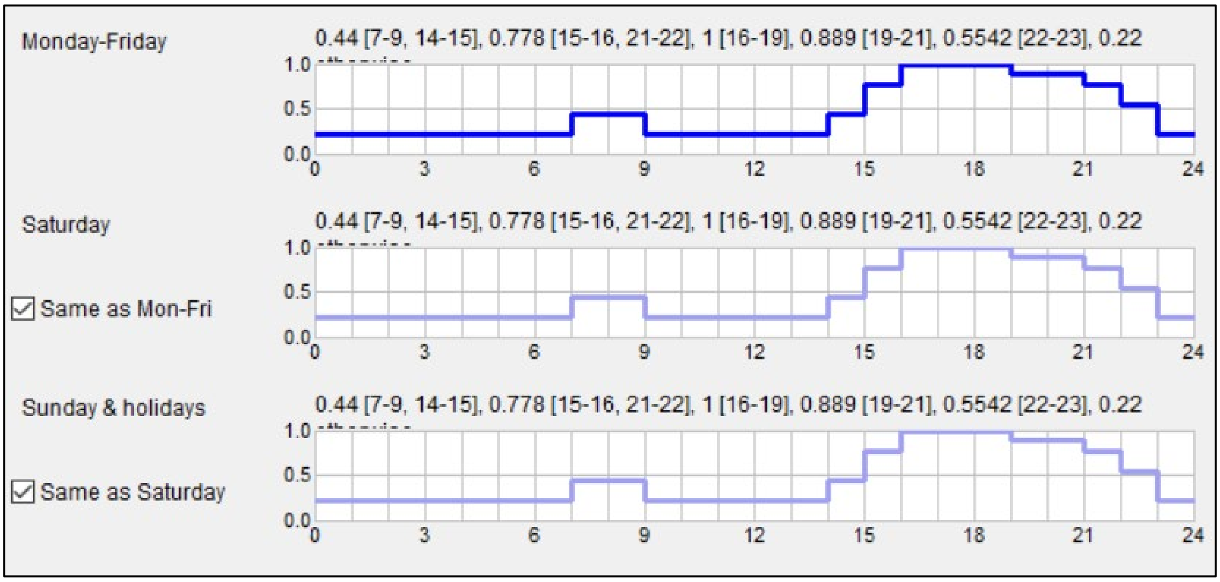
☑ Same as Saturday

Multiple rules. Click "Advanced" for details

Figure 29 Lighting distribution schedule based on NS:3031(2016) and finish survey (Karlsen et al., 2020).

3.2.4 Equipment

The technical equipment for the apartments is distributed according to table A.3 in NS:3031(2016) (***Figure 30***). The total annual energy consumption is set to 17,5 kWh/m^2 per year, where it is assumed that 60% of the energy are deposited as heat into the zones.



Monday-Friday

0.44 [7-9, 14-15], 0.778 [15-16, 21-22], 1 [16-19], 0.889 [19-21], 0.5542 [22-23], 0.22

Saturday

☑ Same as Mon-Fri

0.44 [7-9, 14-15], 0.778 [15-16, 21-22], 1 [16-19], 0.889 [19-21], 0.5542 [22-23], 0.22

Sunday & holidays

☑ Same as Saturday

0.44 [7-9, 14-15], 0.778 [15-16, 21-22], 1 [16-19], 0.889 [19-21], 0.5542 [22-23], 0.22

Figure 30 Equipment schedule NS:3031(2016)

3.3 Air handling unit

In the preliminary assessment of the building block, a study of two different ventilation strategies will be tested. One where the ventilation system is specified as a balanced ventilation system with constant air flow rates and another one with exhaust ventilation with constant air flow. The balanced system will have a specific fan power (SFP) of 1.5 kW/(m^3/s) for both the supply and return fan. The program will automatically calculate the pressure rise of the fan when the SFP value is inserted. Also, the cooling coil in the AHU is set to 0, which indicates that it is turned off. The exhaust ventilation system will have the same set up as the balanced system, except heat exchanger and supply air (***Table 11***). For the exhaust ventilation, disc valves were inserted to provide fresh air to the apartments. According to (Flexit, 2017), the distribution of disc valves to supply sufficient fresh air should be one disc per 25m^2 floor area (**Appendix 3. Supply disc valves for apartments**). The disc valves have a standard opening area of 0.005 m^2, which correspond to a diameter of 80mm.

Table 11 Input for the balanced ventilation AHU

Building Element	Value	Comments
Temperature Setpoints	Minimum: 21 ºC Maximum: 25 ºC	-
Heat exchanger	0.8	TEK17
Specific fan power (SFP)	Supply: 1.5 kW/(m^3/s) Return: 1.5 kW((m^3/s)	TEK17
Supply air temperature	Minimum. 16 ºC	-
Fan efficiency	0.6	Efficiency (electr. to air)
Air flows	Supply: 0.33 L/sm^2 Return: 0.33 L/sm^2	Balanced ventilation with CAV NS: 3031 (2016) table A.12
Schedule for AHU	Always on	NS: 3031 (2016) table A.8

3.4 Heating

The operation time and temperature setpoints are given based on the standard values in NS:3031(2016) for the building category block of flats (***Table 12***).

Table 12 Standard values for operation time and setpoint temperature NS:3031 (2016)

Building category	Operation time Hours/days/weeks	Setpoint for temperature [°C]	
	Heating	In operation-time	Outside operation time
Block of flats	16/7/52	21	19

The operation time for heating is chosen to be from 07.00-23.00, which corresponds to 16 hours during a day. The heating system is set to 19°C during the night from 23.00 to 05.00, and from 05.00 gradually increases the temperature to 21°C until 07.00 (***Figure 31***). By increasing the temperature from 05.00, the zones reach the operation time temperature by 07.00. The temperature setback is a measure to reduce energy consumption, besides occupants have a higher tolerance of lower temperatures when sleeping.

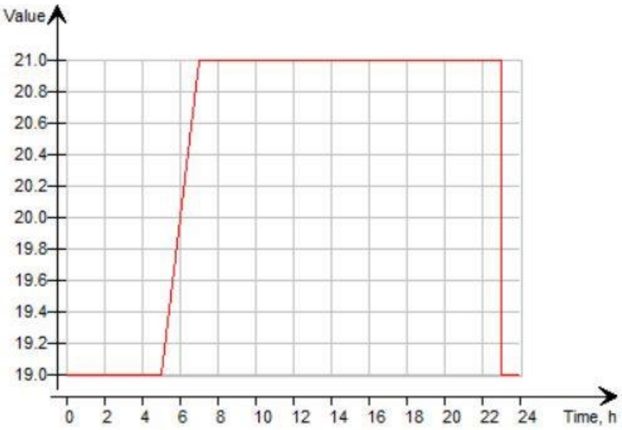


Figure 31 Temperature setpoint for heating

For the heating units, water radiators are used, where district heating is set to be the source of energy. The system efficiency for the zone heating from the district heating is set to 0.83 according to (Attachment B NS:3031:2014). In order to dimension the heating system for the apartments, a heating load calculation was performed in IDA ICE. The water radiators for the apartments was dimensions based on the external design temperature for Stavanger of -12℃ (Variant, 2013).

3.5 Ideal window opening control

The ideal window opening control is practically hard to achieve. It is, however, a measure to indicate the maximum potential of window airing. The ideal window opening is dependent on three variables, which sends an opening signal 1 or closing signal 0. The occupancy schedule is the first signal, sending an opening signal if there are occupants in the zone. Next, a cooling setpoint is defined to be 25 °C, and an opening signal is sent whenever the operative temperature exceeds the setpoint. The last opening signal is sent when the outdoor temperature is lower than the zone temperature. All the signals are sent through a “multiplier” block, which will multiply the incoming values. If the output signal from the multiplier is 1, the window will open. The ideal window opening macro is illustrated in ***Figure 32***.

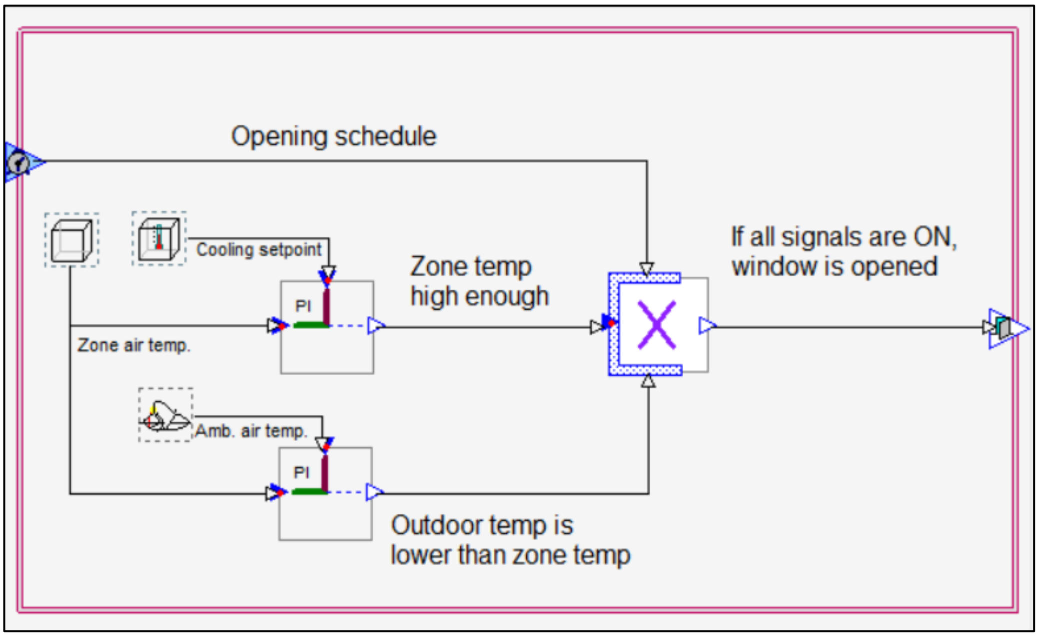


Figure 32 Macro for the ideal control of windows

Chapter 4 Results and discussion

4.1 Simulation 1, determine the most critical apartment

The first simulation was carried out to determine which apartment that had the most significant overheating, thus the one which is going to be assessed further. This was done by using an ideal window opening control for all the apartments, with a window opening area of 100%. The simulation was conducted for four designs with different building envelopes (passive house or TEK 17) and ventilation strategy (either balanced or exhaust ventilation), show in ***Table 13***.

Table 13 Design options simulation 1

Design	Building envelope	Ventilation type	Window opening area
1	**TEK 17**	**Exhaust**	100 %
2	**Passive house**	**Exhaust**	100 %
3	**Passive house**	**Balanced**	100 %
4	**TEK 17**	**Balanced**	100 %

To determine the apartment with the most overheating hours it was decided to assess the apartment which had the most overheating hours above 26 ℃. The apartment with the most overheating hours was found to be apartment 1.5, and the results were consistent for all the designs (***Figure 33***). Apartment 1.5 is located on the ground floor with an azimuth of 220°, south-west direction, shown in ***Figure 34***.

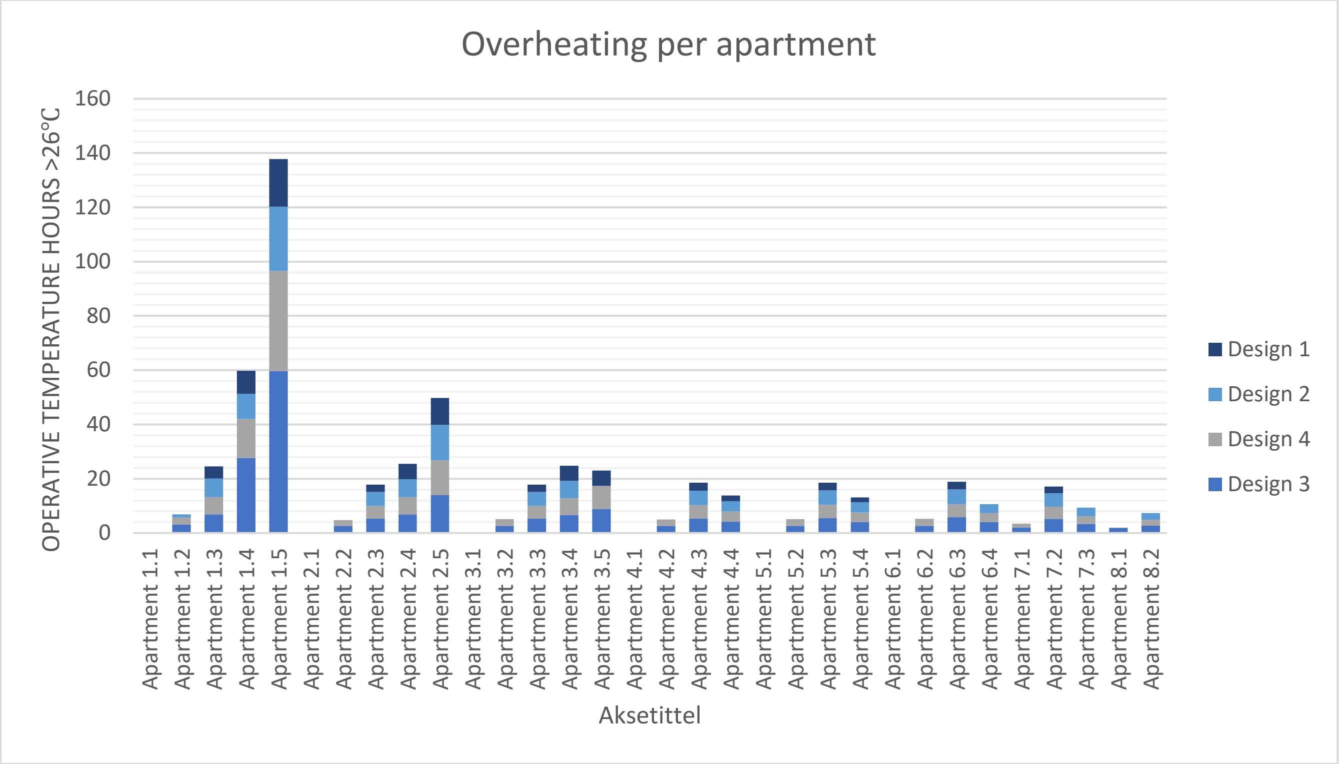


Figure 33 Overheating for the different designs per apartment

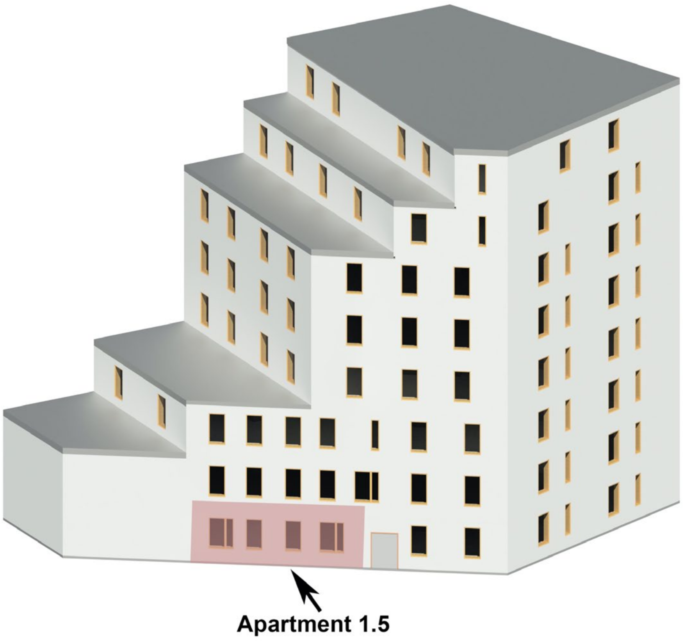


Figure 34 Location of apartment 1.5

In ***Figure 35***, the four designs are shown, where the different apartments are illustrated as a function of the window to wall ratio and operative temperature above 26 °C. The window to gross internal floor ratio is kept constant at 11% as described in chapter **3.1.2 Building envelope**; however, the window to wall ratio varies for the different apartments. The overheating is especially severe in the apartments where the window to wall ratio is large.

This overheating is also strongly dependent on the orientation, and the south-west oriented buildings are the ones with the highest overheating.

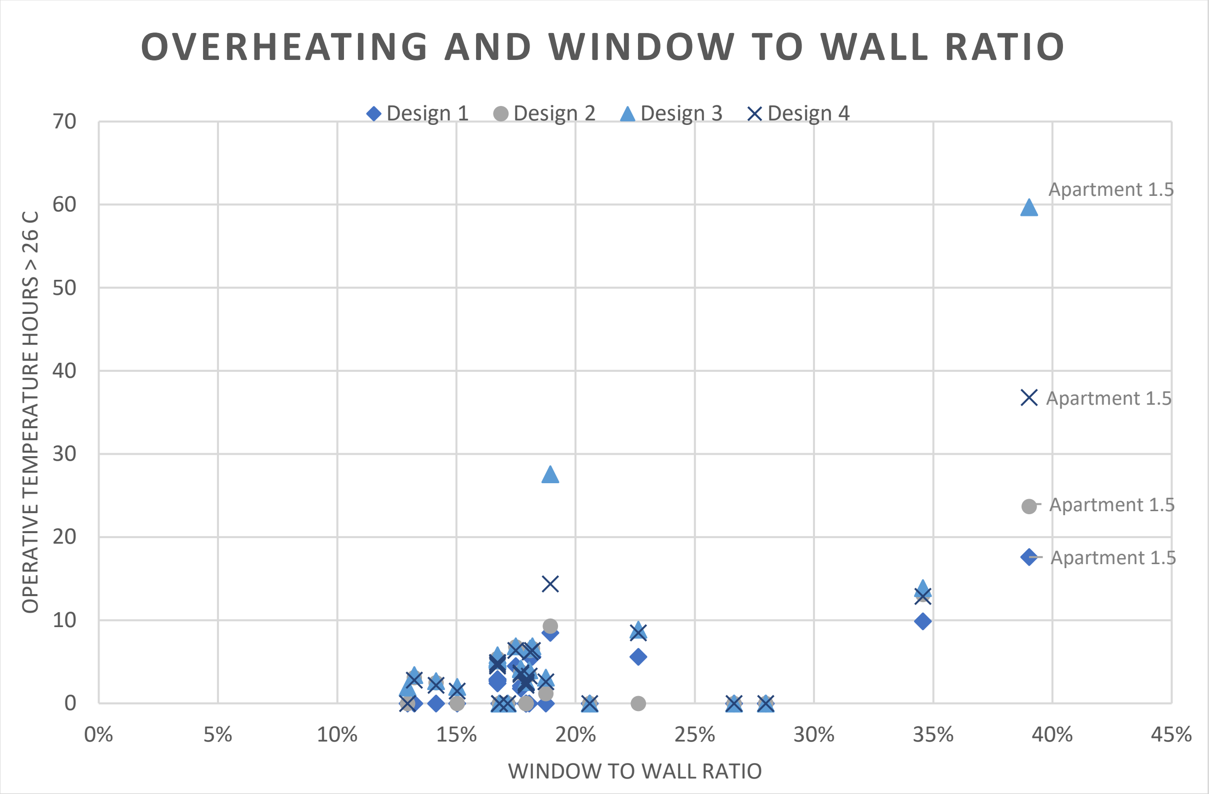


Figure 35 Overheating and window to wall ratio

4.2 Indata and validation for simulation 2

In the next simulation, the focus will be to emulate the realistic window opening behavior, assess automation systems and new technologies such as hatches, and ventilated windows. In simulation 1, the IDA ICE model was made without detailed apartments, only with separation walls between the flats. Now the critical apartment 1.5 has been made more detailed, with rooms and interior walls, as can be seen in ***Figure 36***. In addition, all the zones except from apartment 1.5 have been removed, and the energy consumption evaluated as a total for the apartment. Apartment 1.5 is made with six rooms; however, the assessment of overheating and thermal comfort will only be evaluated for bedroom 1 and 2 and the living room/kitchen.

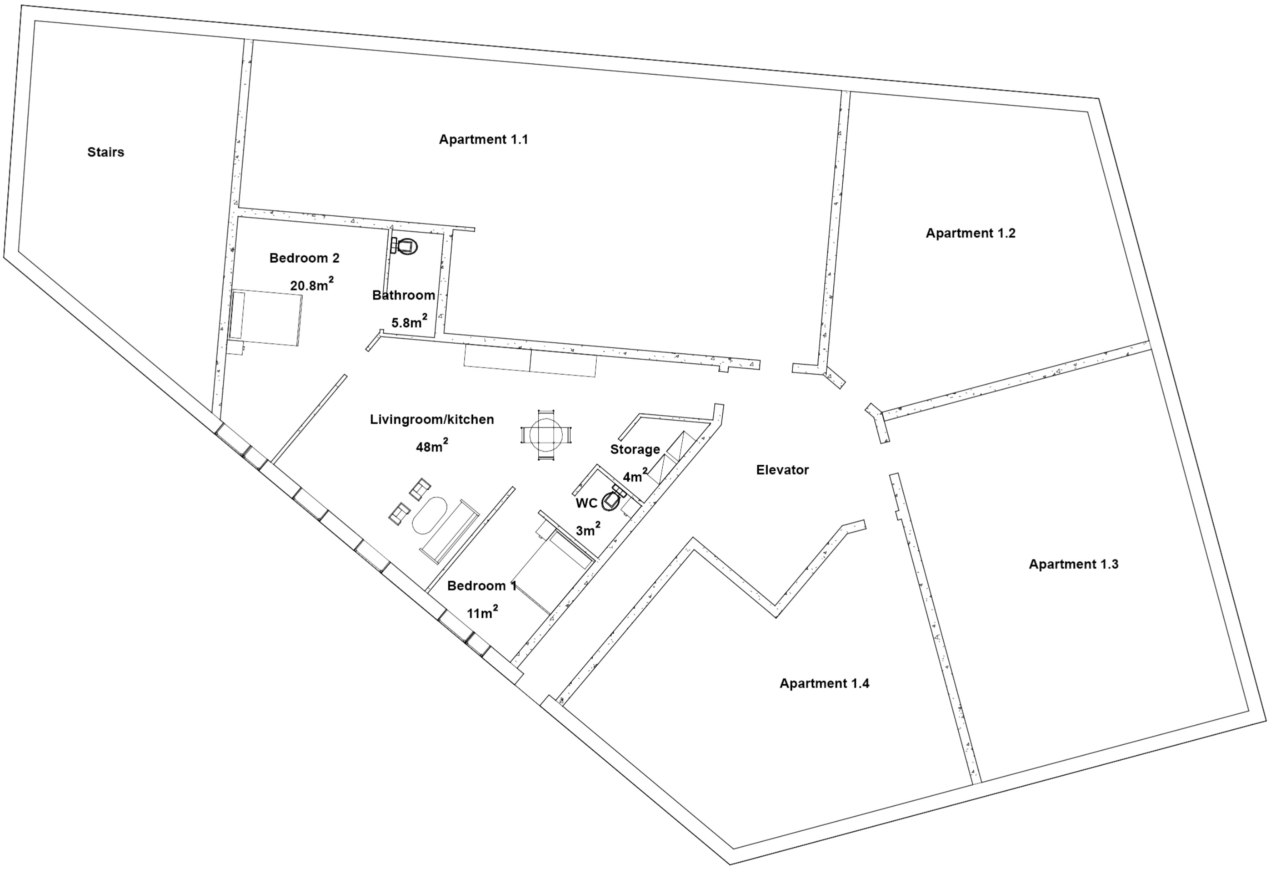


Figure 36 Floor plan of first floor

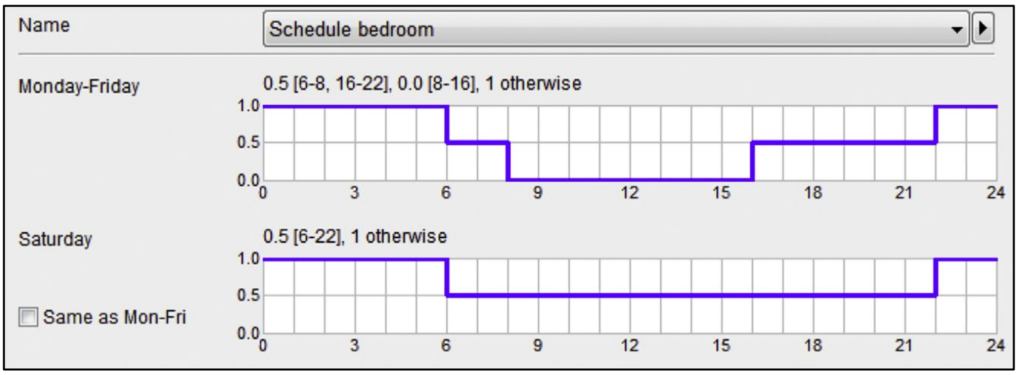
In simulation number two, 26 different design options were simulated and assessed in IDA ICE. The ambition levels and ventilation systems are tested for the case of manual window opening, the hatch technology, ventilated window, and two different automation levels, displayed in ***Table 16***. In the following subsections for chapter 4.2, explanations and validations for the various technologies and automation systems will be conducted.

Table 14 **Design options simulation 2**

Building envelope	**Ventilation system**	**Manual window opening**	**Ventilation Window**	**Hatch**	**Medium automation**	**High automation**
		* No-automation	* No-automation	* Automatic temperature control	* Heating based automation	* Heating and ventilation automation
Passive	Exhaust		✓			
Passive	Exhaust	✓				
Passive	Exhaust	✓			✓	
Passive	Exhaust	✓				✓
Passive	Exhaust			✓		
Passive	Exhaust			✓	✓	
Passive	Exhaust			✓		✓
TEK 17	Exhaust		✓			
TEK 17	Exhaust	✓				
TEK 17	Exhaust	✓			✓	
TEK 17	Exhaust	✓				✓
TEK 17	Exhaust			✓		
TEK 17	Exhaust			✓	✓	
TEK 17	Exhaust			✓		✓
Passive	Balanced	✓				
Passive	Balanced	✓			✓	
Passive	Balanced	✓				✓
Passive	Balanced			✓		
Passive	Balanced			✓	✓	
Passive	Balanced			✓		✓
TEK 17	Balanced	✓				
TEK 17	Balanced	✓			✓	
TEK 17	Balanced	✓				✓
TEK 17	Balanced			✓		
TEK 17	Balanced			✓	✓	
TEK 17	Balanced			✓		✓

4.2.1 Input data for apartment 1.5

To have a realistic scenario for apartment 1.5, a new occupancy schedule was developed for the bedrooms and the living room/kitchen. The occupancy schedule for the living room and bedrooms is taken from research on highly insulated buildings in Norway, conducted by(Berge, Laurent, & Mathisen, 2016). The occupancy schedule for the bedroom can be seen in ***Figure 38***, and living room/kitchen in ***Figure 39***.



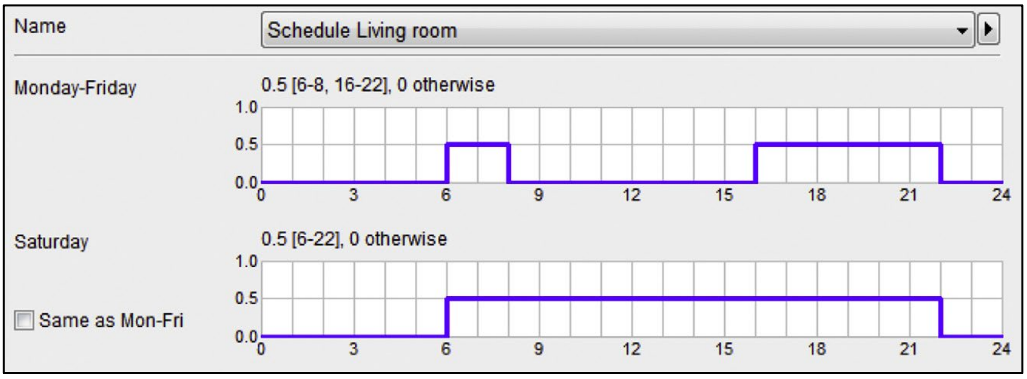
Name: Schedule bedroom

Monday-Friday: 0.5 [6-8, 16-22], 0.0 [8-16], 1 otherwise

Saturday: 0.5 [6-22], 1 otherwise

☐ Same as Mon-Fri

Figure 37 Occupancy schedule for bedrooms (Berge et al., 2016)



Name: Schedule Living room

Monday-Friday: 0.5 [6-8, 16-22], 0 otherwise

Saturday: 0.5 [6-22], 0 otherwise

☐ Same as Mon-Fri

Figure 38 Occupancy schedule for living room (Berge et al., 2016)

The ventilation air flows have also been modified to be as realistic as possible for the different rooms in apartment 1.5(***Table 17***). According to TEK17 §13-2 (2), the supply airflow in the bedrooms should be a minimum of 26 m^3 air per hour per occupant when the room is in use. Also, according to TEK17 §13-2 (3), rooms that are not in permanent use should have a minimum supply of 0.7 m^3 air per hour per m^2 floor area. The minimum exhaust values for bathroom, WC, and the kitchen is listed in table 14, according to TEK17 §13-2 table 1.

Table 15 Supply-and exhaust air for apartment 1.5

Rooms in apartment 1.5	Supply airflow [m^3/h]	Exhaust airflow [m^3/h]
Bedroom 1	52	-
Bedroom 2	52	-
Living-room/kitchen	15	36
Bathroom	-	54
WC	-	36
Storage room	7	-
Total	126	126

The water radiators in the apartment are dimensioned in IDA ICE for the different design conditions displayed in ***Table 18*** .The water radiators are dimensioned similarly as for **4.1 Simulation 1** with an external design temperature for Stavanger of -12℃. As can be seen from the table, the different water radiators dimension varies for both the ventilation systems and the building ambition levels.

Table 16 Heating units for the different designs and rooms

Rooms in apartment 1.5	TEK 17 EXHAUST [watt]	PASSIVE EXHAUST [watt]	PASSIVE BALANCED [watt]	TEK 17 BALANCED [watt]
Bedroom 1	325	300	150	200
Bedroom 2	450	300	150	200
Living-room/kitchen	1200	1100	550	675
Bathroom	100	100	100	100
WC	25	25	25	25
Storage room	-	-	-	-
Total	2100	1950	975	1200

4.2.2 Realistic window opening control

For the simulations with realistic window opening control, a maximum window opening area of 10 percent was assumed. The windows are located as displayed in ***Figure 39***.

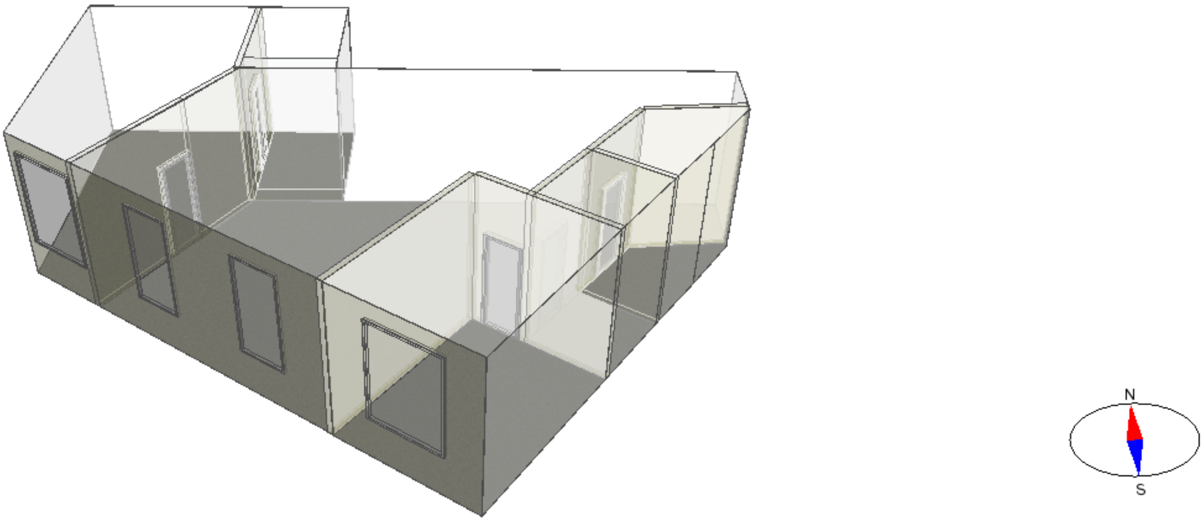


Figure 39 3D visualization of apartment 1.5 with conventional windows

To emulate the window opening behavior for occupants, the upper thermal comfort limit defined by (Peeters et al., 2009) was used to control the window opening. The upper comfort limit was calculated hourly during one year for both the living room and bedrooms. The operation for the window is controlled by three signals illustrated in ***Figure 40***. The first signal 1 sends a signal if the operative temperature is higher than the upper comfort limit, and sends a closing signal if the operative temperature is 3°C lower than the upper comfort limit. The source-file in signal 1 contains a file with hourly data of the upper comfort temperature. In signal 2, the setpoint for the CO_2 level is set to 900ppm, and 700 ppm to close the window (deadband -200). In signal 3, the occupancy schedule is connected where a signal is sent whenever someone is present in the zone. All the signals are now multiplied, where an output of 0 closes the window, and a signal of 1 opens the window. The final step is a first-order component, which smooths the results over a timestep of 300 seconds. This will reduce fluctuations in the temperature output, thus effectively increase the simulation speed.

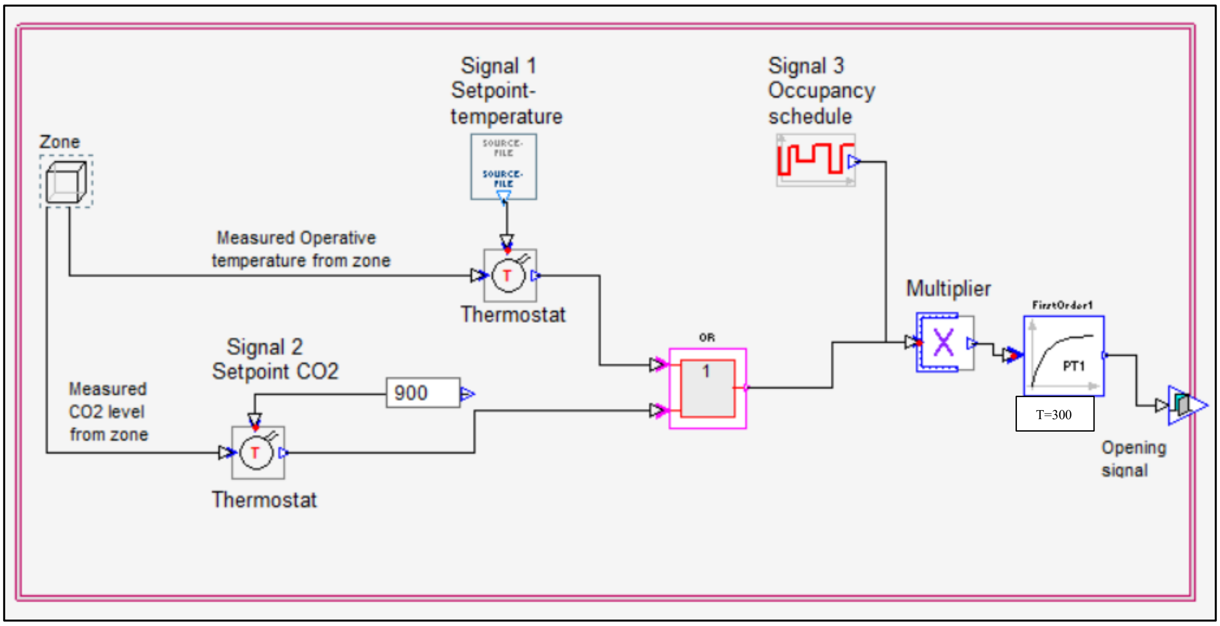


Figure 40 Macro for opening of the window (developed by Laurina C. Felius)

4.2.3 Validation of realistic window opening control

To ensure that the macro is operating without malfunctions, a validation of the macro was conducted. The validation was done for both the bedroom and living room macro. The upper limit for the bedroom is usually lower than for the living room; as a result, the window will open more frequently for the bedroom. This is due to a heating setpoint of 21 for both the rooms. Whenever the window opens, the heating unit will try to reach 21. In ***Figure 41***, the bedroom window opening macro can be seen during an hour timestep for the 21st of April. At 16:16, the operative temperature is 3℃ higher than the setpoint, which will send an opening signal. The window opens gradually from 16:16 to a fully open position at 16:17. The zone will get cooled down, and at 16:36, the temperature is 3℃ lower than the setpoint. At this point, the window will close.

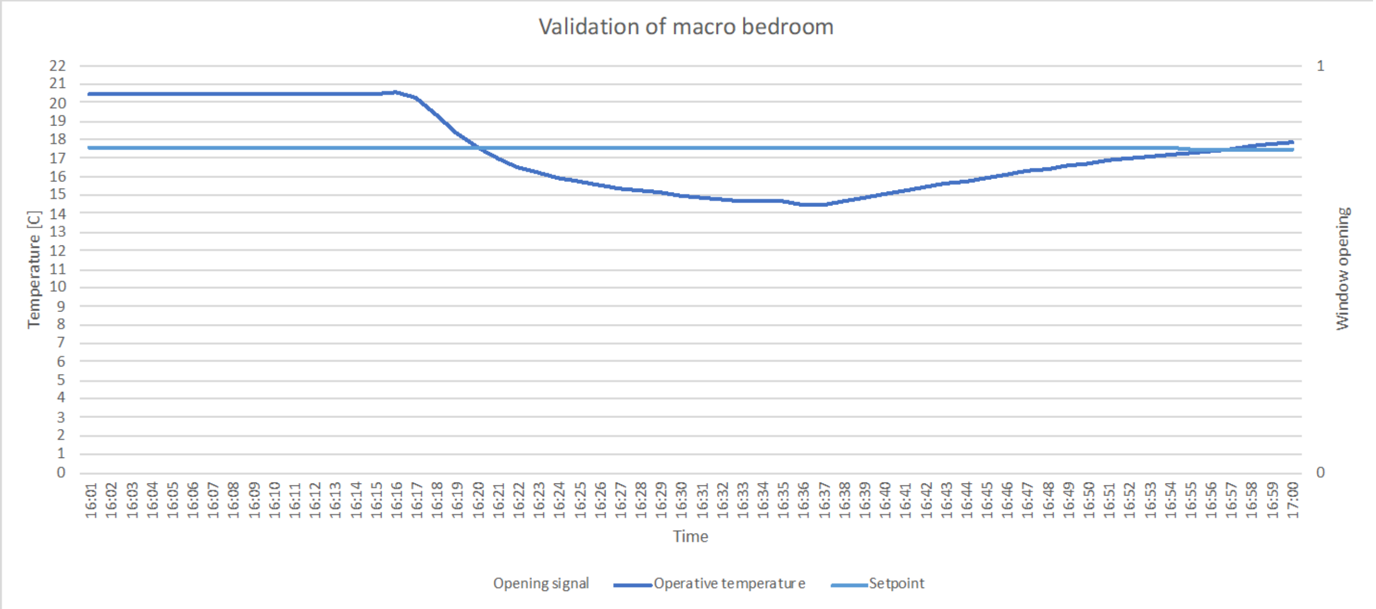


Figure 41 Validation of the bedroom window opening macro

In the living room, the upper limit setpoint is higher than for the bedroom. In ***Figure 42*** the validation of the living room window macro is shown on the 21st of April. The window opens at 16:11 when the operative temperature is 3°C higher than the setpoint and closes again at 16:17 when the operative temperature is 3°C below the setpoint. The window macro in the living room haven a longer opening time. This is mainly due to a larger room volume to cool down; in addition, the heating unit will always supply 21°C to the room.

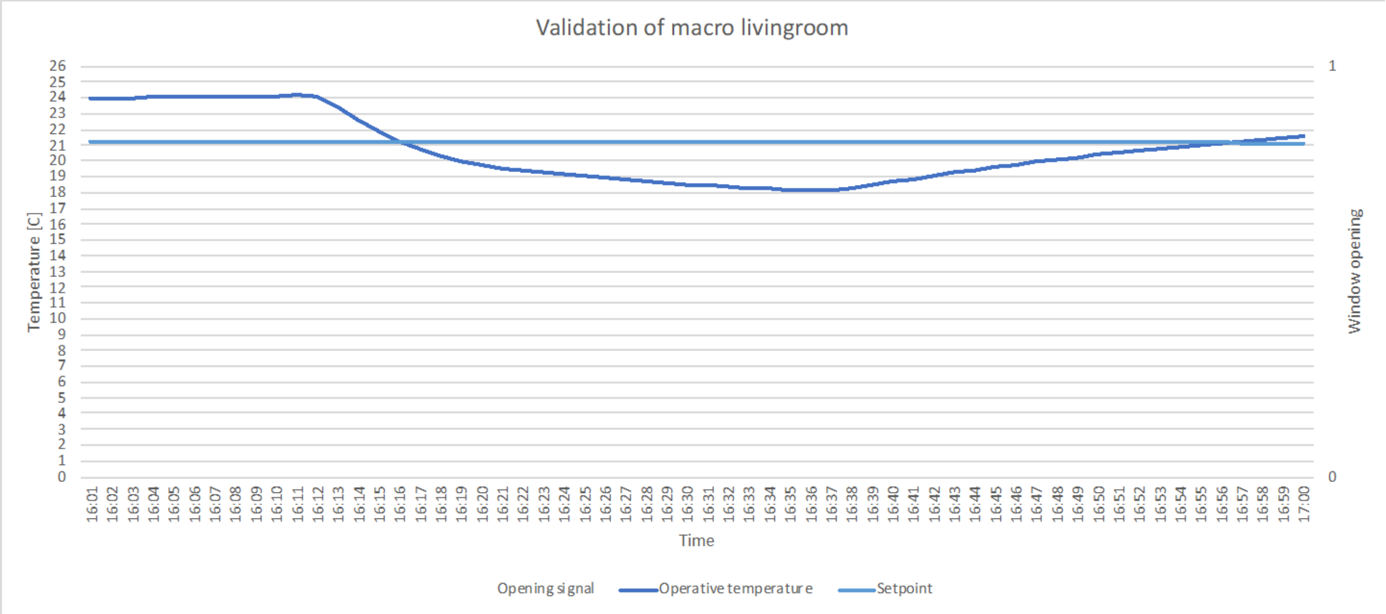


Figure 42 Validation of the living room window opening macro

4.2.4 Automation system

In simulation 2, two automation systems were simulated for the different ventilation systems and building ambition levels. The automation system is developed in the "IDA ICE zone advanced tab," where two different zone central control macros (ZCCM) is created. In this simulation, the occupant's opening of the windows will be referred to as "manual window opening." The second control is "medium-automation," which is an automation system that turns off the heating unit when the windows are open. The third control is "high-automation," which is an automation system that will turn off the heating unit and ventilation system when the windows are open. During periods with heating demand, the opening of windows can lead to excessively energy use. Also, the use of mechanical ventilation can sometimes be redundant when the windows are left open.

4.2.5 Automation control macro

In ***Figure 43*** , the automation macro, which is used for medium and high automation, is displayed. When the medium-automation macro is in use, the minimum mechanical supply and return air are set to be equal to the maximum levels. In this way, the ventilation will not turn off when the window is opened. When the high automation macro is in use, the minimum mechanical supply and return air is set to zero, thus turning the ventilation off when the window is open.

In the upper branch of the macro, the control of the heating system takes place. When the window opens more than 0.1 m^2, an opening signal of 1 will be sent to the multiplier. The multiplier will multiply opening signal 1 with -99 or closing signal 0 with -99. Further, the value from the multiplier ether -99 or 0 will be sent to an adder with a setpoint of 21°C. The adder will either add 21 + 0 or -99+21 and further convey it to the thermostat, which controls the heating setpoint. The lower branch of the macro controls the ventilation system, where the ventilation will turn off whenever the window opens more than 0.1 m^2.

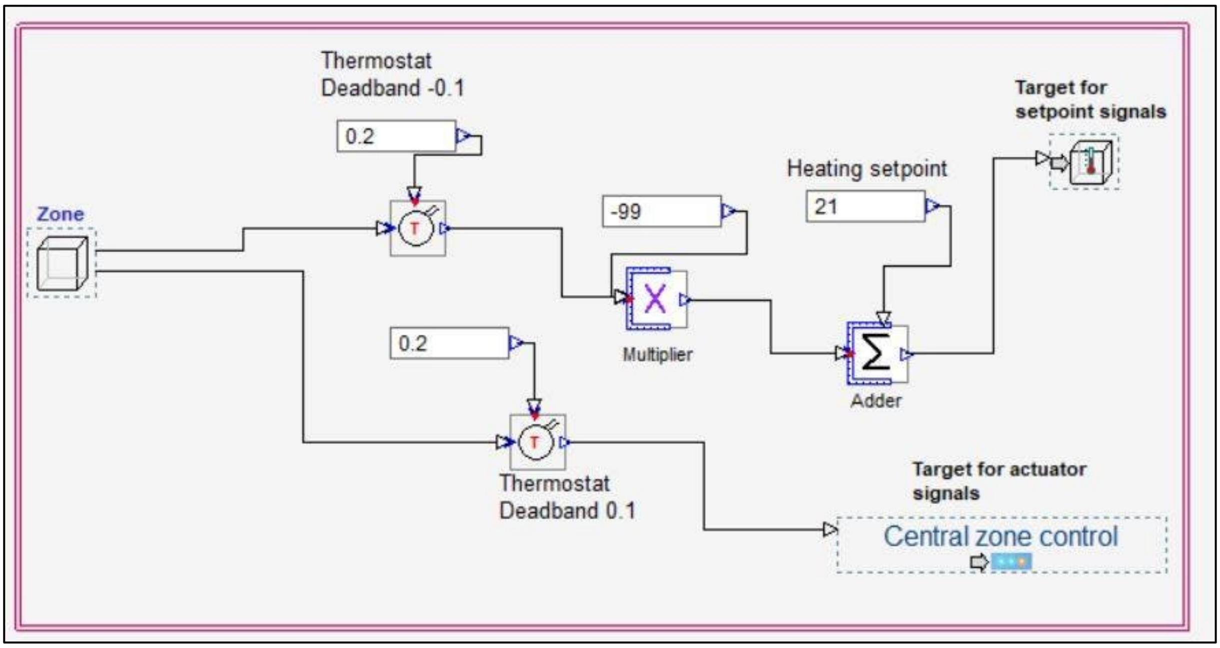


Figure 43 Automation control macro for medium and high automation level

4.2.6 Validation of "medium-automation"

The "medium-automation" turn off the heating unit whenever the window opens more than 0.1 m^2. In ***Figure 44***, the validation of the "medium-automation" can be seen in the living room/kitchen for 13th of May. The window opens 06:00, while the automation control sends a closing signal to the water radiators, which will gradually turn the water radiators off. The mechanical ventilation system is not affected by the control macro, and the mechanical inflow and outflow remain constant when the window opens.

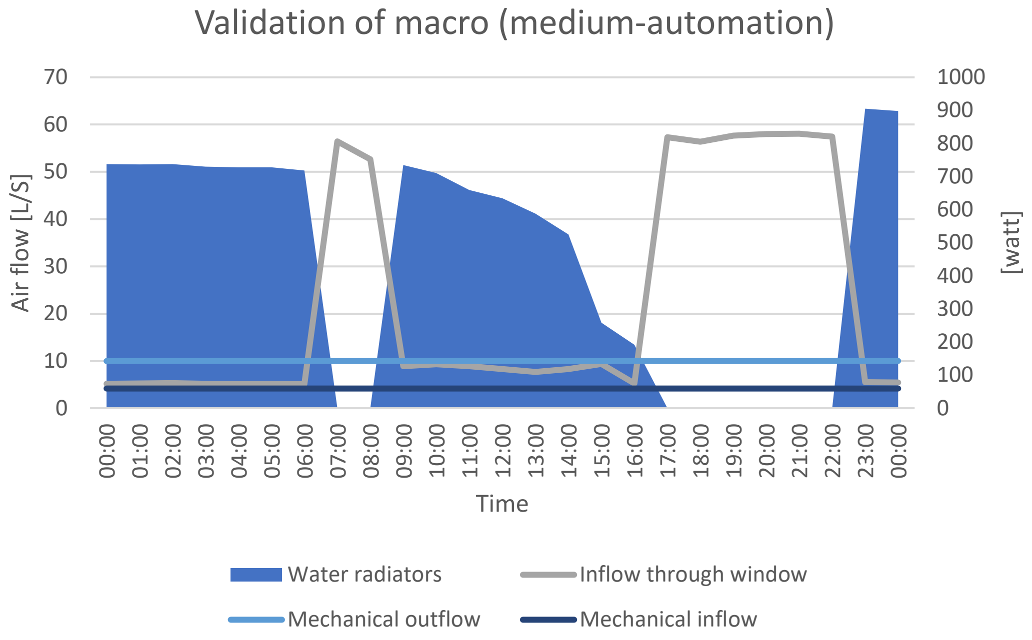


Figure 44 Validation of macro for medium-automation

4.2.7 Validation of “high-automation”

The “high-automation” turns off the heating and supply/exhaust ventilation whenever the window opens more than 0.1 m^2. ***Figure 45*** visualizes the macro's effects; the window opens 06:00, and the water radiators and ventilation system gradually turn off. The validation is conducted in the living-room/kitchen, resulting in a different mechanical inflow and outflow.

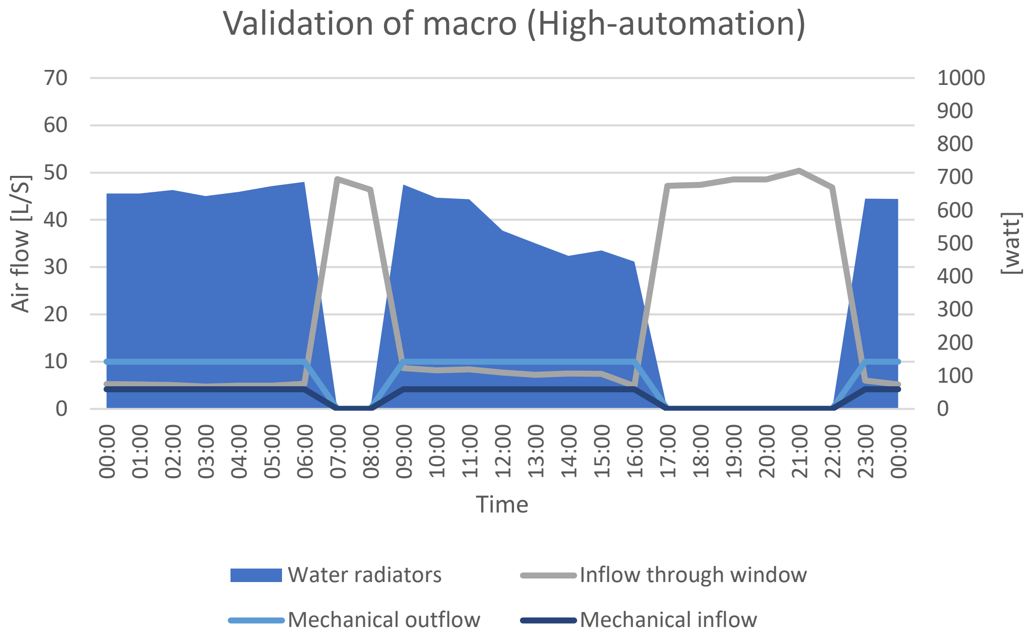


Figure 45 Validation of macro high automation

4.2.8 Ventilation hatch

The ventilation hatch used in simulation two is based on the "ducogrille night vent," which is described in **2.8.2 Ventilation hatches**. The hatch is made in IDA ICE by applying 1 in the frame to window factor, resulting in a "window" with a 100% frame area, thus an opaque solution. Besides, a u-value of 1.5W/m^{2}K is applied for the hatch, which is the same as "ducogrille night vent". The opening control macro for the ventilation hatch is similar to the one used in **4.2.2 Realistic window opening control**. The differences are the schedule for the opening, where the realistic window opening control was based on an occupancy schedule. The other difference is that the deadband is set to 3, resulting in smaller temperature gap when the windows is opened and closed. The hatch's opening schedule is set to always on, assuming a mechanically controlled system that opens the hatch whenever the upper limit of comfort is reached.

The IDA ICE model with the hatches was made with non-openable windows supplemented with a window hatch beside every window. As earlier mentioned, the opening area for design with only windows was set to 10%. To have a comparable result for the ventilation hatch, the ventilation hatch was constructed to be 10% of the window area and to have an opening area of 100%. The windows in the IDA ICE models with hatches were reduced to an area of 10% compared to the case with only windows. An example of how the dimension of the window area and window opening area of the hatches were conducted to have a comparable result is shown in ***Table 18***. The automatic hatches and the non-openable windows are visualized in ***Figure 46***.

Table 17 Comparison of the window area/opening area for to designs

	Opening area	**Window area**	**Total window area**
Unit	[%]	[m^2]	[m^2]
Design with only windows	10	2	2
Hatch	100	0.2	
Non- openable window	0	1.8	2

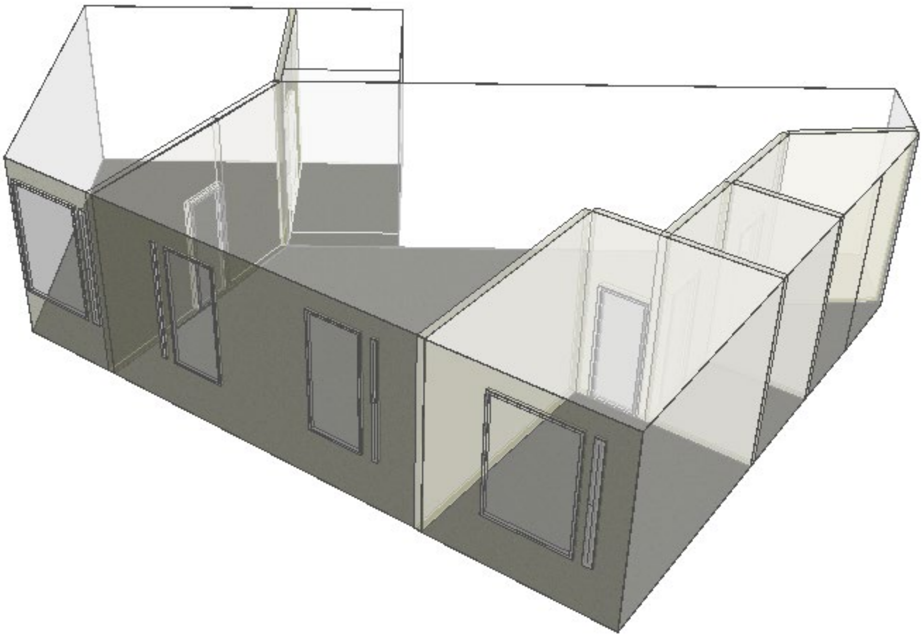


Figure 46 3D visualization of the non-openable windows with automatic hatches

4.2.9 Ventilation window

The ventilation window is built with the functions of the Horn groups ventilation window, described in chapter **2.8.3 Ventilation window** The ventilation windows were placed in the same place as the conventional windows, with the exact same window area, as seen in ***Figure 47***. Besides, the u-value of the windows was set to 0.91 W/m^{2}K,the same as for the Horn group windows. A more detailed overview of the ventilation window and the input values are visualized in **Appendix 4. Indata Ventilation window**.

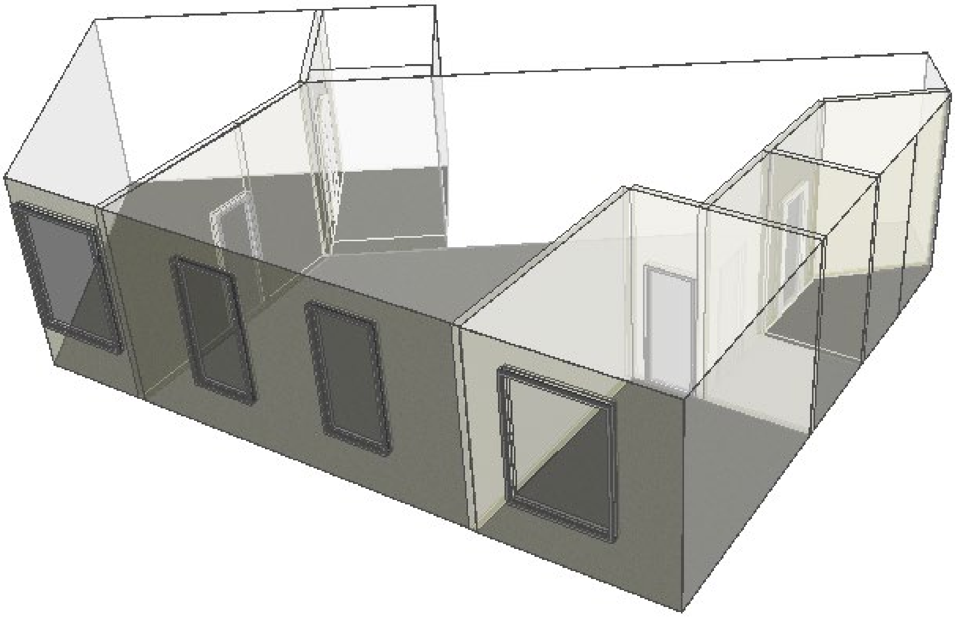


Figure 47 Visualization of the ventilation windows placement in apartment 1.5

4.2.10 Ventilation window macro

The ventilation window macro is made in collaboration with Mika Vuolle from EQUA Finland. To make the macro, the IDA ICE model had to be built in the "advanced level," enabling the user to make in-depth adjustments to components like the ventilation window. The ventilation window macro is presented in ***Figure 48*** with the associated components, which control the cavity's opening. The Pi controller receives the measured temperature from the window cavity. If the window cavity temperature is above 26, the Pi control will send a closing signal to the damper, and no air will leak from the window cavity into the zone. At the same time, air will leak directly from ambient air to the zone, bypassing the window cavity. When the window cavity temperature is below 26, the Pi control will send an opening signal to the damper, and the air from the window cavity will leak into the zone. At the same time, the valve that controls the air passing directly from the ambient air will be closed.

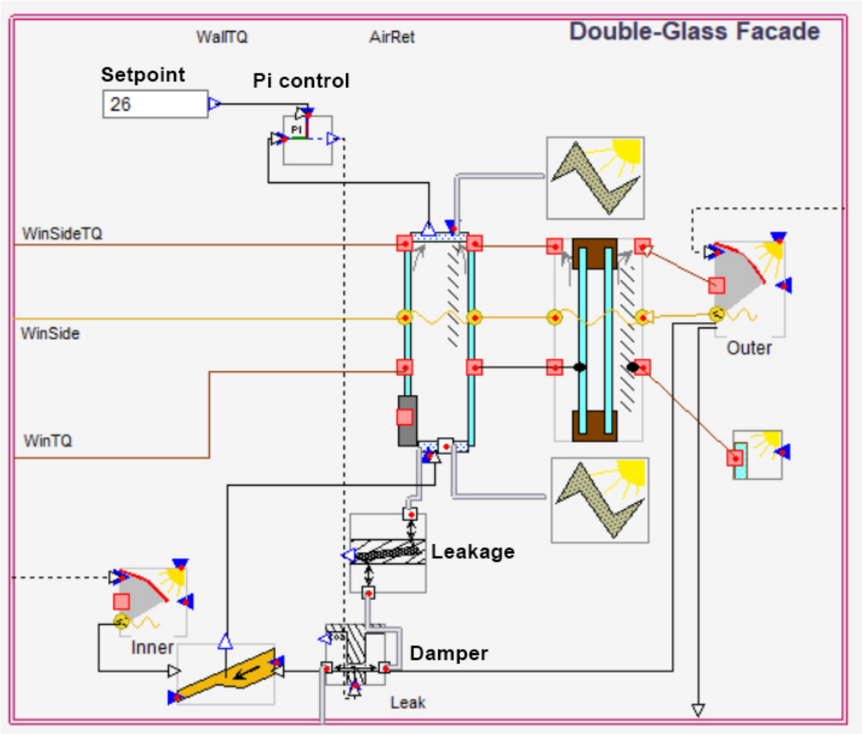


Figure 48 Ventilation window macro

4.2.11 Validation of the ventilation window

The validation of the ventilation window is conducted on the 7th of August, where ***Figure 49*** displays the closing of the valve from the window cavity when the cavity temperature is above 26 °C. Accordingly, ***Figure 50*** presents the mass-flow from the window cavity and mass-flow directly from ambient air to zone when the damper opens or closes. As shown in ***Figure 49***, the cavity valve will close around 11:00 am until 21:00 when the cavity temperature is above 26 °C. During the same time, the mass-flow from the window cavity to the zone will decrease, and the mass-flow directly from ambient air will increase, as shown in ***Figure 50***.

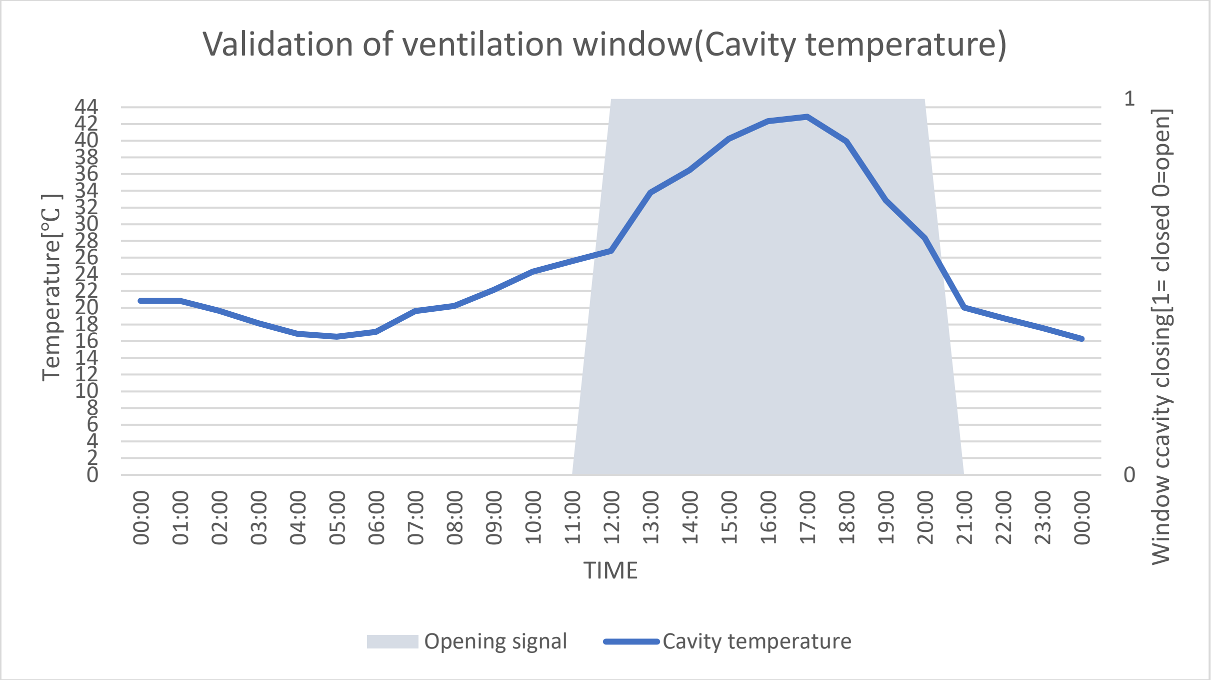


Figure 49 Validation of the ventilation window, cavity temperature during 7th of August

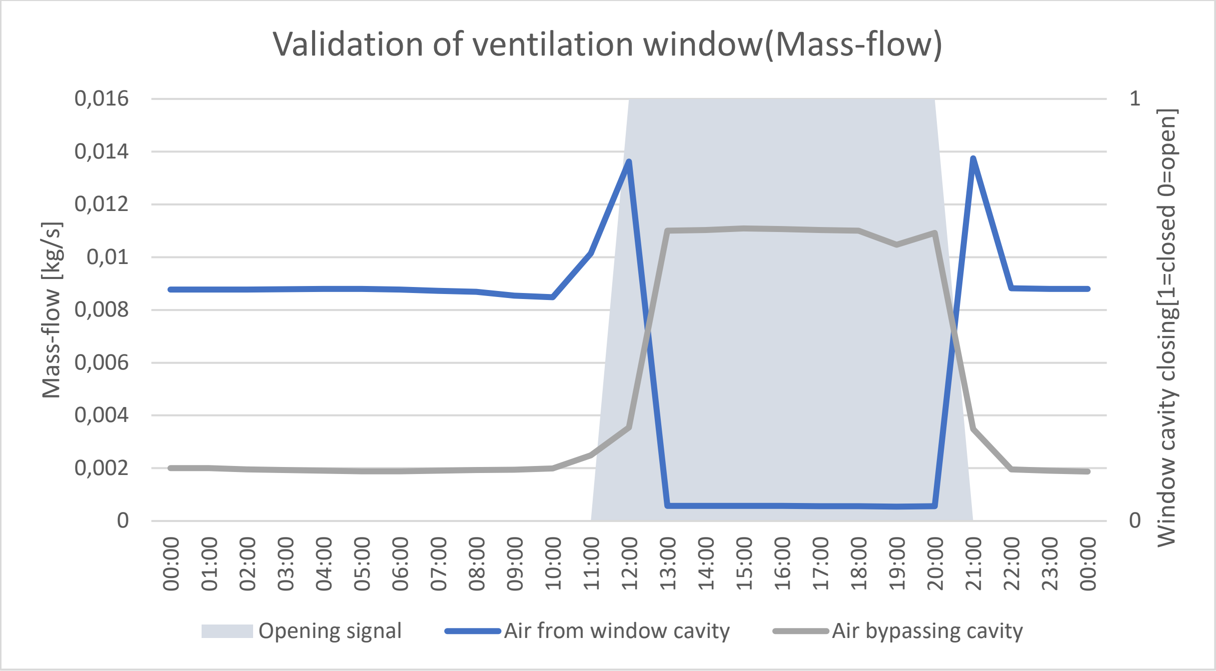


Figure 50 Validation of ventilation window, mass-flow during 7th of August

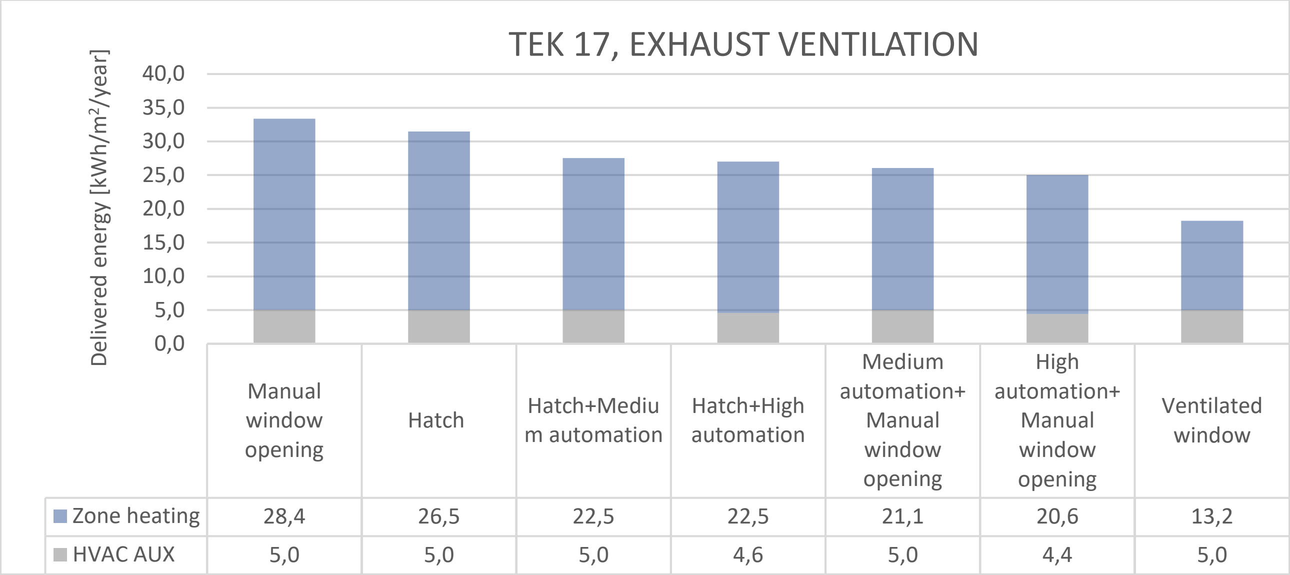
4.3 Results and discussion simulation 2

For simulation two, the results will be divided into four parts. The different design options will be presented as following firstly the TEK 17 ambition + exhaust ventilation, secondly the passive ambition +exhaust ventilation, thirdly the passive ambition + balanced ventilation, and lastly, the TEK 17 ambition with balanced ventilation. The ventilation window simulation is only conducted for the designs with exhaust ventilation. This is since the ventilation window requires under-pressure in the zone to suck the air from the ventilation window cavity. For the energy demand in apartment 1.5, the energy used and distributed from domestic hot water, lighting, occupants, and equipment is kept constant for all the simulations described in ***Table 10 Standardized values for energy per year NS 3031(2016)***. The delivered energy in this part will be assessed for zone heating and HVAC AUX (electricity for pumps and fans in the ventilation system). The thermal comfort will be assessed for (Peeters et al., 2009) thermal comfort upper limit and lower limit for bedrooms and living-room described in chapter **2.5.4 Thermal adaption in bedrooms** and **2.5.5 Thermal adaption in living rooms**. If the operative temperature is above or equal to the defined T_{upper} limit, it will be noted as overheating. Whereas the operative temperature is lower than or equal to the defined T_{lower} limit, it will be referred to as undercooling. The overheating and undercooling presented in the upcoming sub-chapters will be the total average accumulated for the two bedrooms and living room/kitchen. It should also be noted that the overheating and undercooling hours are only assessed when occupants are present in the bedrooms and living room/kitchen.

4.3.1 TEK 17 ambition level with an exhaust ventilation system

The first assessment was conducted for seven different design options with the ambition level of TEK17 with an exhaust ventilation system. For this case, the design with the most considerable delivered energy is the manual window opening (emulated occupant opening) with around 33.4 kWh/m^2/year followed by the automatic hatch design with 31.4 kWh/m^2/year. The reason for the high energy consumption for the automatic hatch is the more frequent opening of the window and a relatively high u-value of 1.5 W/m^{2}K compared to 0.8 W/m^{2}K for the case with a manual window opening ***Figure 51***. However, when comparing the two cases with the most significant energy consumption in terms of overheating and undercooling shown in ***Figure 52*** it is clear there is a vast difference in overheating. Whereas for the hatch, there is 0 accumulated overheating or undercooling hours compared to 1023 hours of overheating for the case with manual window opening. The ventilation window has a delivered energy consumption of around 18.2 kWh/m^2/year, which is a decrease by approximately 45.5% compared to the manual window opening. On the other hand, the ventilation window is the design with the most overheating of 1589 hours.

The designs with automation also perform well in terms of delivered energy. The automation system with the lowest energy consumption “High automation+ manual window opening” has a total delivered energy reduction of 25% compared to the manual window opening. In terms of thermal comfort, the manual window opening design with automation performs worse than for the case without automation. The reason for this is that the exhaust ventilation is turned off when the windows open, and the system does not remove air, causing the zone to overheat. Also, some undercooling hours will occur because the heating systems are turned off when the window opens. Thus, it seems that the heating unit in the zone doesn’t manage to heat the zone fast enough when the windows are closed again. The system which performs best considering excellent thermal comfort and the relatively low energy consumption is the design “hatch+ high automation.”



	Manual window opening	Hatch	Hatch+Medium automation	Hatch+High automation	Medium automation+ Manual window opening	High automation+ Manual window opening	Ventilated window
■ Zone heating	28,4	26,5	22,5	22,5	21,1	20,6	13,2
■ HVAC AUX	5,0	5,0	5,0	4,6	5,0	4,4	5,0

Figure 51 Delivered energy for TEK 17 ambition level with exhaust ventilation system

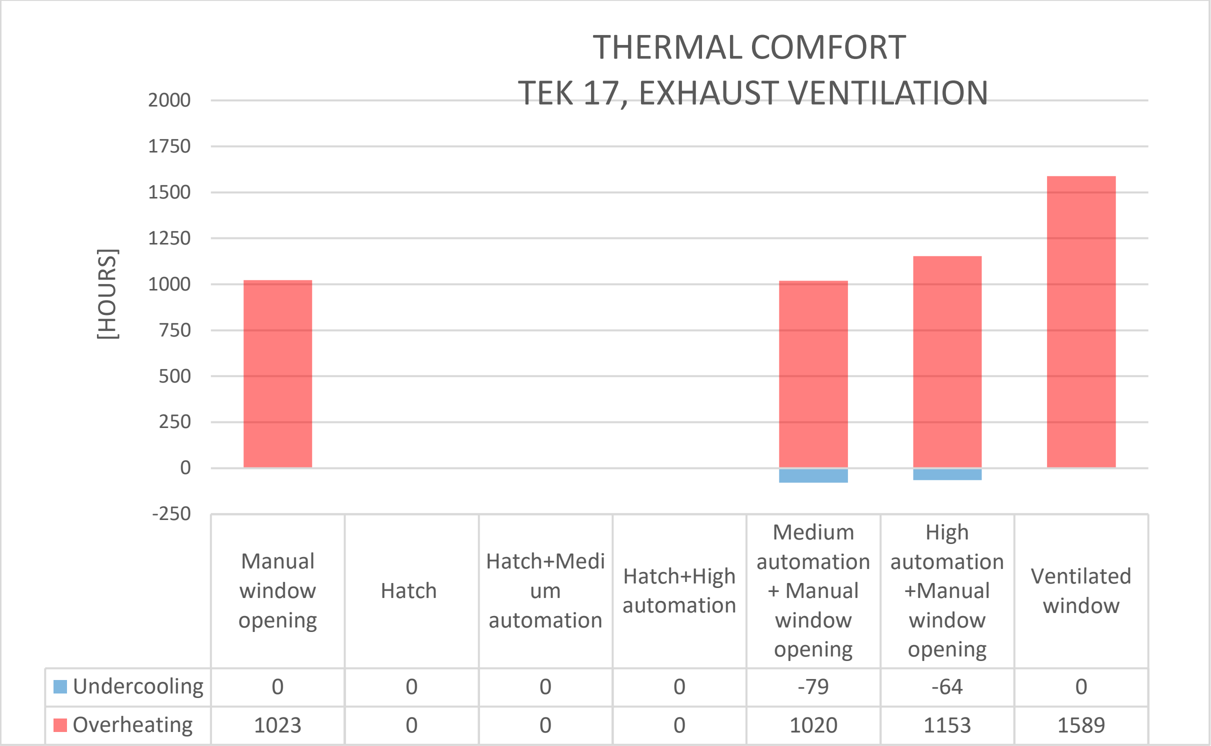
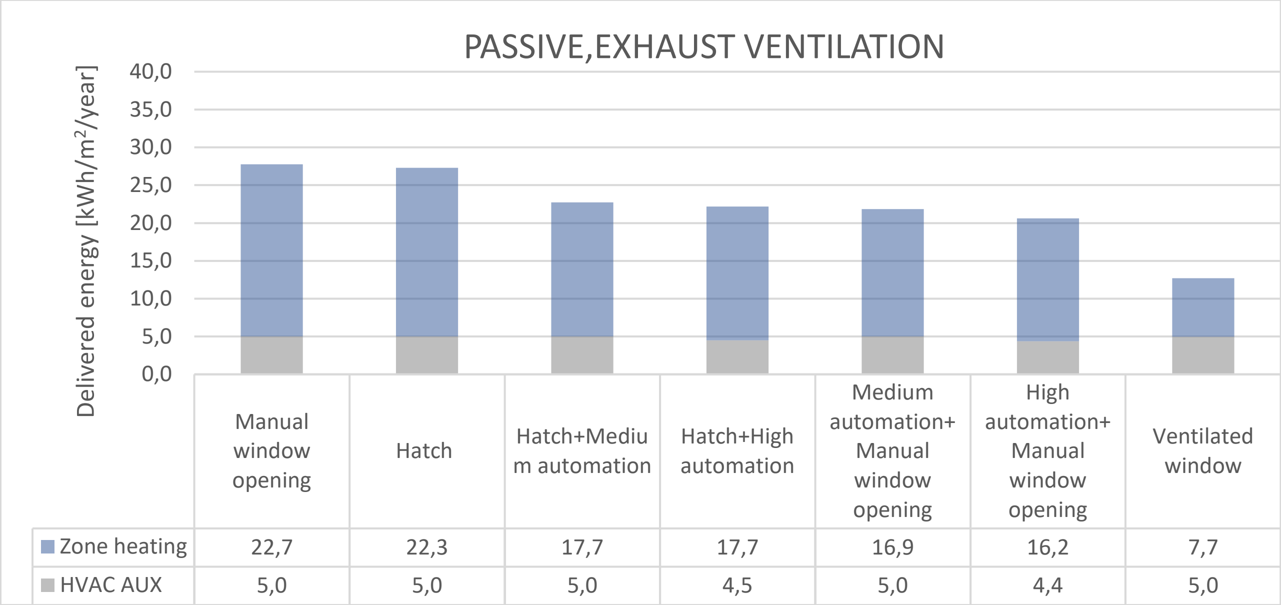


Figure 52 Thermal comfort for TEK 17 ambition level with exhaust ventilation system

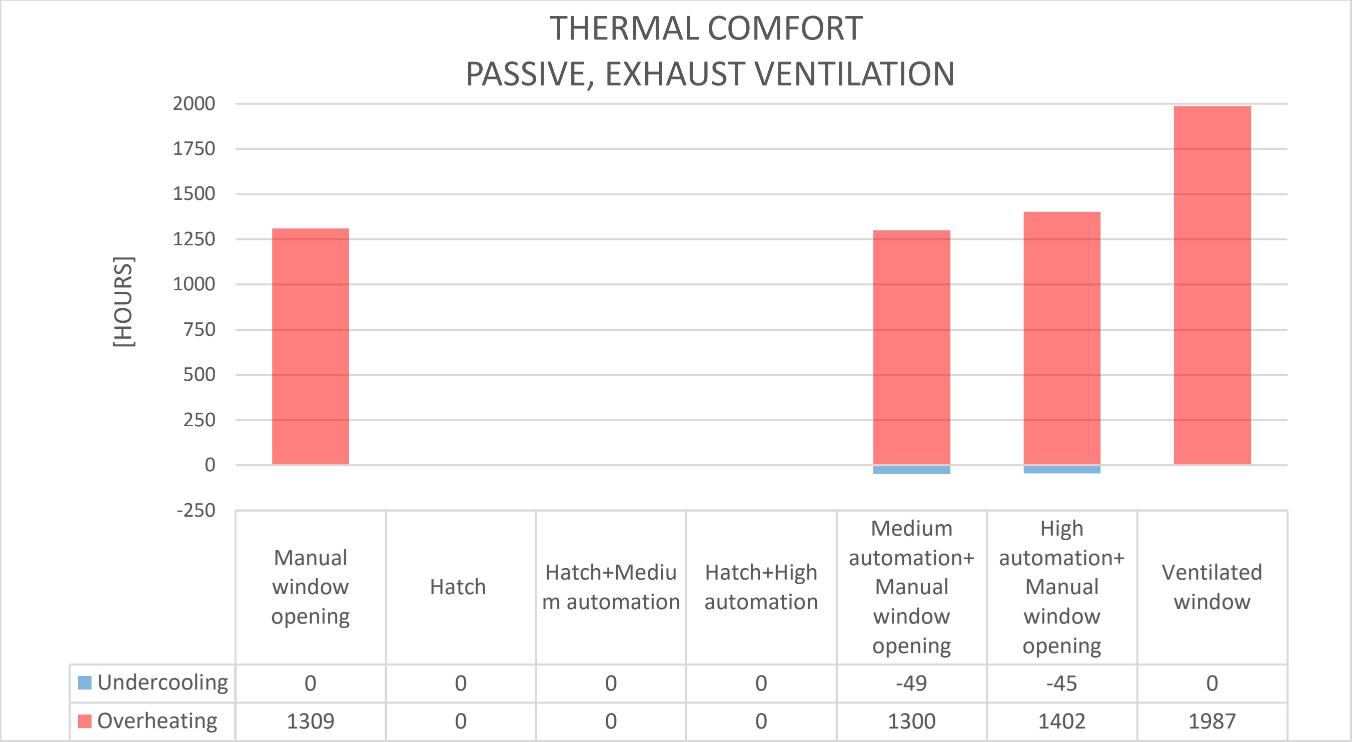
4.3.2 Passive ambition level with an exhaust ventilation system

The passive with exhaust ventilation design also has seven different designs. From an energy perspective, the zone heating and HVAC AUX have similar distribution as for the previous case with TEK17 ambition level and exhaust ventilation. The design with the most significant energy consumption is the “manual window opening” with a total energy consumption of 27.7 kWh/m^2/year (**Figure 53**) whereas the lowest total energy consumption is from the design with “ventilation window” with an energy consumption of 12.7 kWh/m^2/year. The ventilation window has a significant energy reduction of nearly 55% in comparison to the “manual window opening” design. At the same time, the “ventilation window” design has approximately 52% more overheating hours than for the “manual window opening” design (**Figure 54**). Also, for this building ambition level and ventilation system, the design “hatch + high automation” seems to perform best considering good thermal comfort and low total energy consumption.



	Manual window opening	Hatch	Hatch+Medium automation	Hatch+High automation	Medium automation+ Manual window opening	High automation+ Manual window opening	Ventilated window
Zone heating	22,7	22,3	17,7	17,7	16,9	16,2	7,7
HVAC AUX	5,0	5,0	5,0	4,5	5,0	4,4	5,0

Figure 53 Delivered energy for passive ambition level with exhaust ventilation system

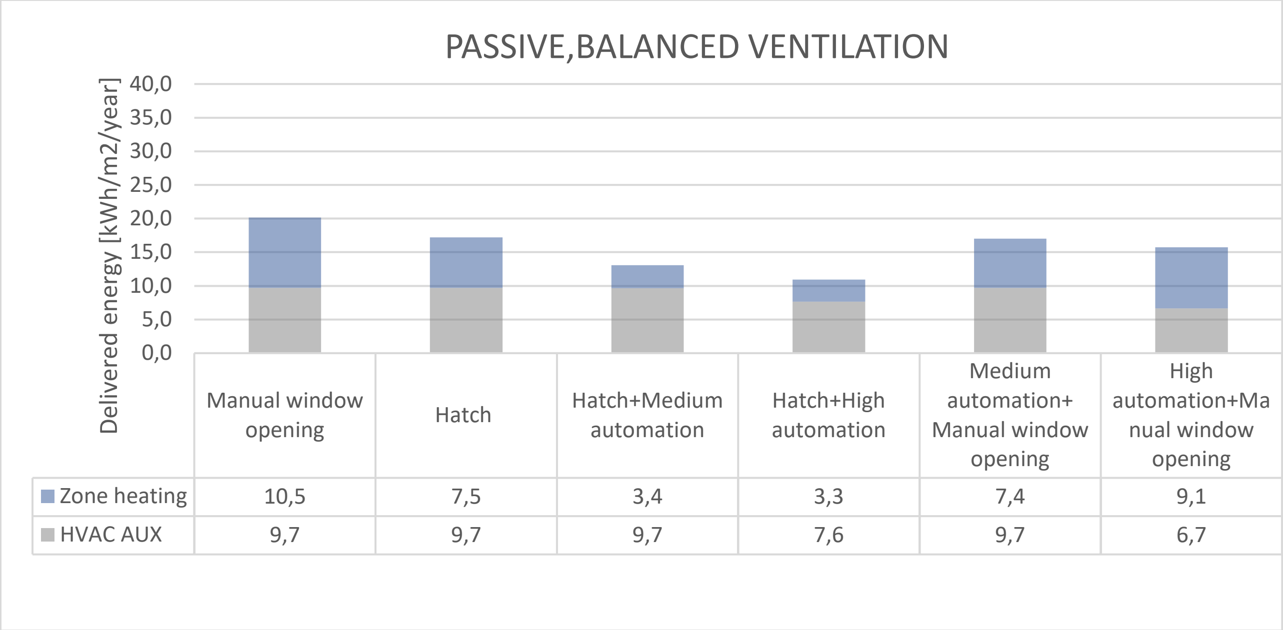


	Manual window opening	Hatch	Hatch+Medium automation	Hatch+High automation	Medium automation+ Manual window opening	High automation+ Manual window opening	Ventilated window
Undercooling	0	0	0	0	-49	-45	0
Overheating	1309	0	0	0	1300	1402	1987

Figure 54 Thermal comfort for passive ambition level with exhaust ventilation system

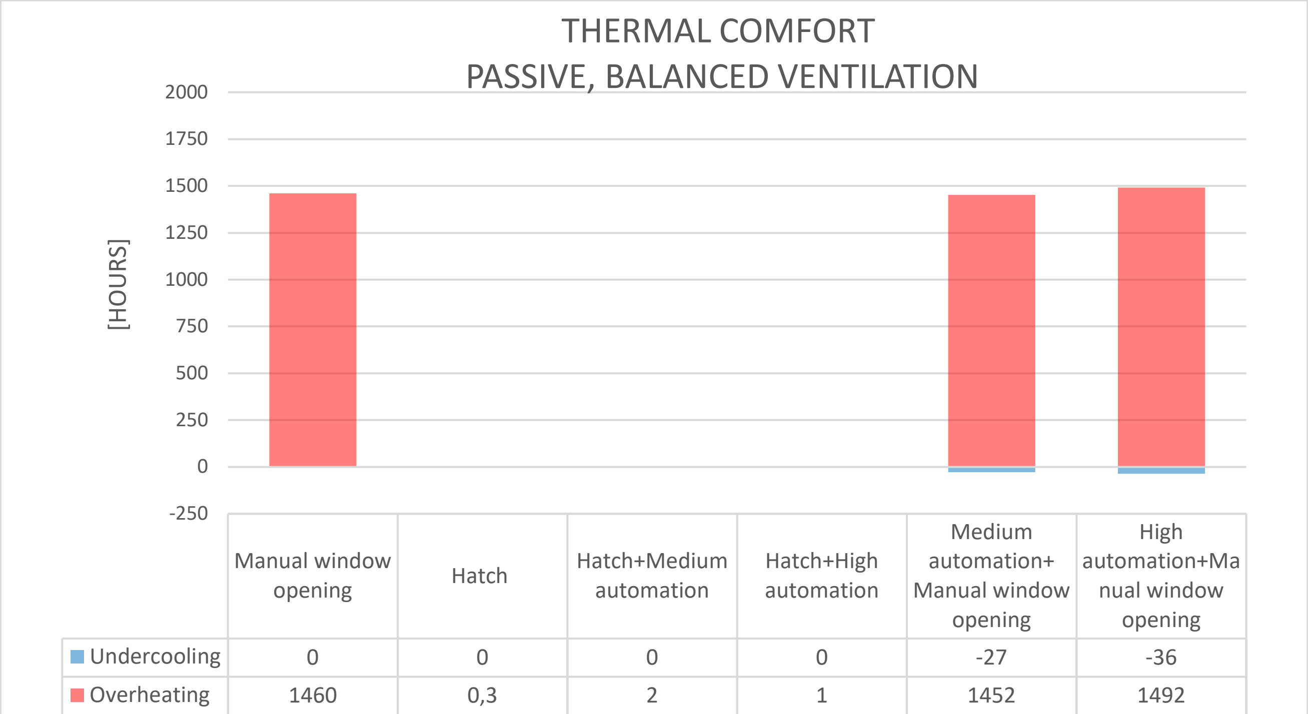
4.3.3 Passive ambition level with a balanced ventilation system

The designs with passive ambition level with balanced ventilation have six different designs; for the balanced ventilation system, the ventilation window is disregarded as described in chapter **2.8.3 Ventilation window**. For the case with balanced ventilation, the designs with hatches perform better than for "manual window opening" opening in an energy point view compared to the previous designs with exhaust ventilation. The reason is that when there is exhaust ventilation, there will be under-pressure in the zone, which draws air to the zone from the ambient air. Because the hatches are open more frequently, there will be a higher energy consumption than the "manual window opening." When there is a balanced ventilation system with hatches, less air is drawn from the ambient air to the zone, resulting in lower energy consumption compared to the "manual window opening." The design with" hatch + high automation" has approximately a total energy consumption of 10.9 kWh/m^2/year with around 46% decrease in energy consumption compared to the "manual window opening" (**Figure 55**). When comparing the hatch without additional automation to "hatch+ medium automation", it can be seen that the effect of turning off the heating system when opening the window can save up to 55% of the energy for zone heating. If the ventilation is turned off when the window is opened, a saving up to 22% can be achieved for electricity from HVAC AUX. This means that the most effective measure to reduce energy consumption is by having a sensor that can turn off the heating system when the window opens. The overheating is significant for the designs with manual window opening with or without automation, show in **Figure 56**. The thermal comfort of the designs with hatch is performing well for all the three cases. As for the previous examples with exhaust ventilation, the design "hatch+ high automation" is the best overall solution for good thermal comfort and low energy consumption.



	Manual window opening	Hatch	Hatch+Medium automation	Hatch+High automation	Medium automation+ Manual window opening	High automation+Manual window opening
▨ Zone heating	10,5	7,5	3,4	3,3	7,4	9,1
▨ HVAC AUX	9,7	9,7	9,7	7,6	9,7	6,7

Figure 55 Delivered energy for passive ambition level with balanced ventilation system

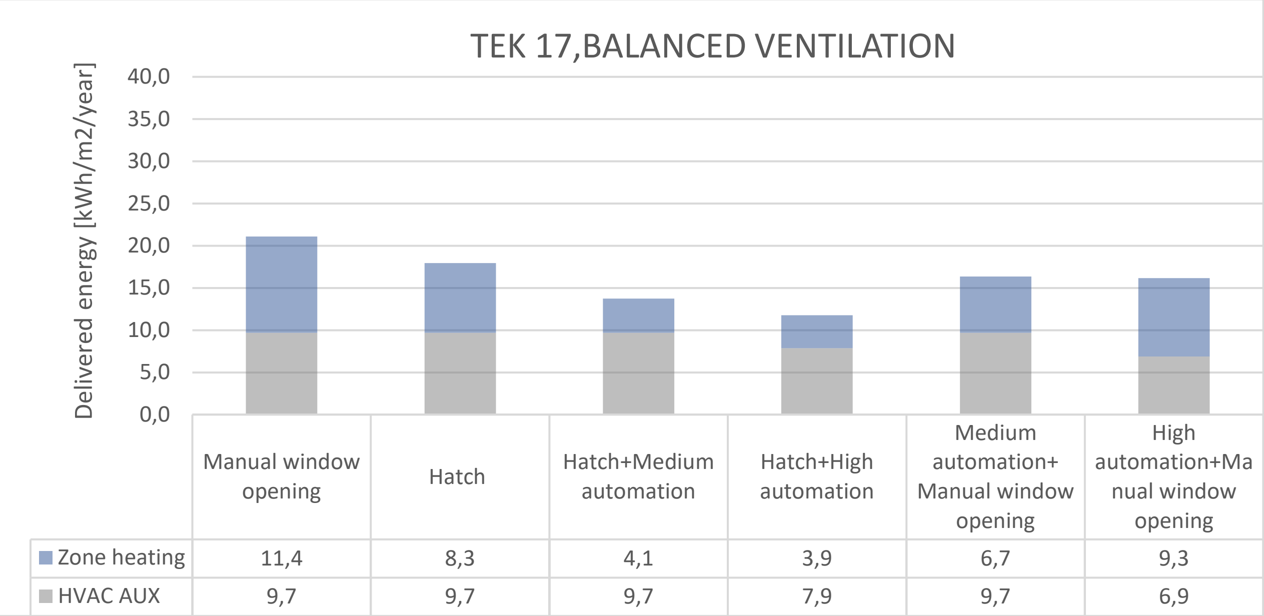


	Manual window opening	Hatch	Hatch+Medium automation	Hatch+High automation	Medium automation+ Manual window opening	High automation+Manual window opening
🟦 Undercooling	0	0	0	0	-27	-36
🟥 Overheating	1460	0,3	2	1	1452	1492

Figure 56 Thermal comfort for passive ambition level with balanced ventilation system

4.3.4 TEK 17 ambition level with a balanced ventilation system

The different designs for the TEK 17 ambition level with balanced perform similar to the previous design with passive-house ambition. The main differences are a minor increase in the energy consumption shown in **Figure 57**, and a significant reduction in the overheating for the three cases with the manual window opening, shown in **Figure 58**. The reason for the decrease in overheating for these designs is mainly due to lower levels of insulation for the TEK 17 designs compared to the passive-house designs. When comparing the "manual window opening" with the design with the most moderate energy consumption "hatch + high automation," an energy saving of 44% is achieved. Also, the automation system will have no overheating or undercooling at all. When applying automation to the design "manual window opening," the highest energy saving achieved is around 23%, but on the other hand, there is an increase in overheating hours of 45 hours.



	Manual window opening	Hatch	Hatch+Medium automation	Hatch+High automation	Medium automation+ Manual window opening	High automation+Manual window opening
■ Zone heating	11,4	8,3	4,1	3,9	6,7	9,3
■ HVAC AUX	9,7	9,7	9,7	7,9	9,7	6,9

Figure 57 Delivered energy for passive ambition level with balanced ventilation system

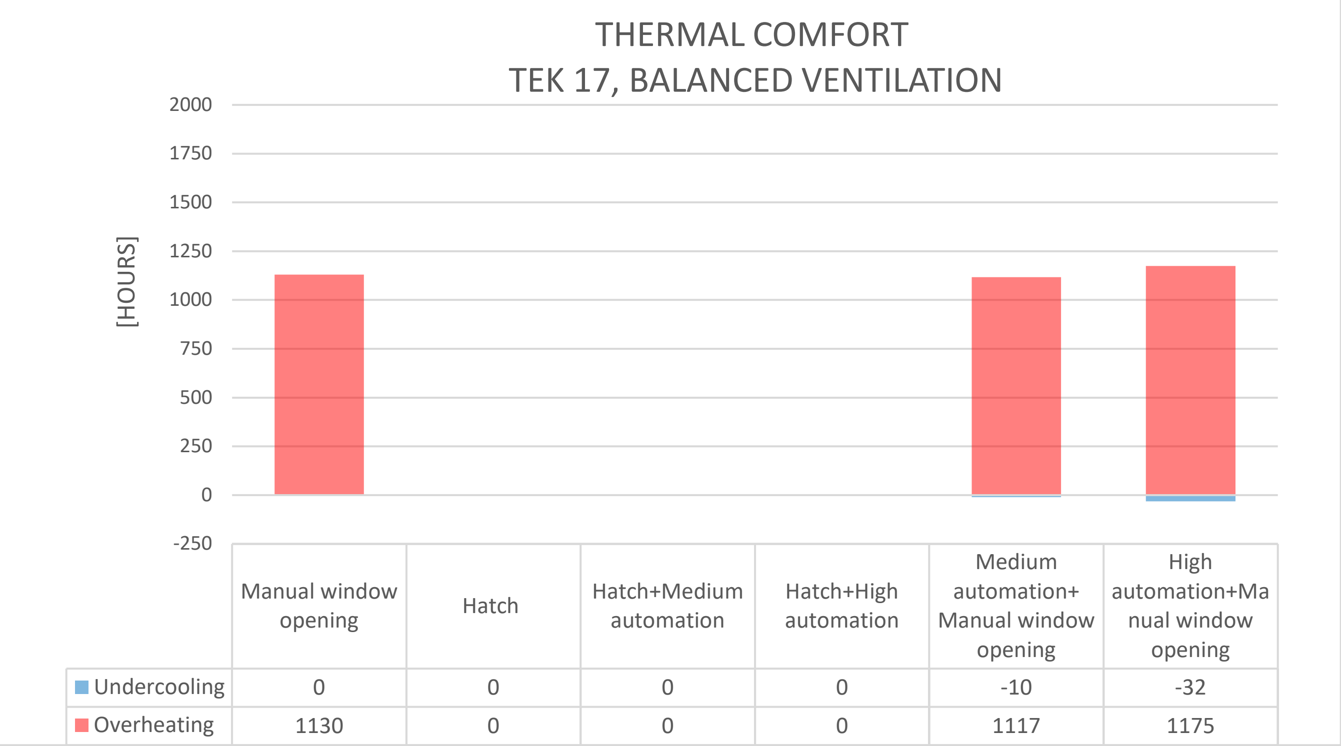


Figure 58 Thermal comfort for passive ambition level with balanced ventilation system

Comments:

The occupants are not present in either the bedroom or living-room/kitchen during the weekdays from 8:00 am to 16:00. Especially during summer, this timeframe is the most critical to cool down. As a general remark for all the cases with the manual window opening, significant overheating is occurring because the windows are closed when the occupants are not present. At the time the occupants are present to open the windows, the zones are already overheated.

The reason for increased amount of overheating when having balanced ventilation compared to exhaust, is due to the heat exchanger in the balanced ventilation system.

5. Conclusion

From the literature review, it was found that few residential buildings in Norway have sophisticated ventilative cooling technologies. However, there is a growing interest in the industry to investigate the potential of ventilative cooling, and some projects are already in the construction phase. The impact of letting people control the windows themselves can lead to excessive energy consumption for both balanced and exhaust ventilation with either combination of passive or TEK 17 building envelopes. Also, it was seen that significant overheating hours and some undercooling would appear; this was especially the case for the passive-hours designs. The maximum energy saving potential when applying an automation system for the manual window openings was up to 26%. Despite the decrease in energy consumption, the automation system increased the hours of overheating.

For all the cases, the optimal realistic solution for ventilation cooling was the passive-house envelope and balanced ventilation with a "high-automation" hatch system. The energy-saving potential for this system was up to 46% compared to a system without automation. Besides, the thermal comfort was improved significantly. In the case of using hatches, the amount of received daylight and also the view can be limited in contrast to using windows for ventilative cooling. The ventilation windows had a significant energy reduction for the designs with exhaust ventilation and were the superior choice regarding energy consumption. However, significant overheating was observed, mainly due to a smaller fresh air opening compared to the designs with conventional windows and hatches.

As a final remark, it is worth highlighting the importance of evaluating the thermal comfort on room level rather than for a building as a whole. There are significant differences in the neutral zone of thermal comfort for the different rooms, and when designing buildings with sophisticated ventilative cooling, this is recommended to consider.

6. Further work

Further work can be conducted for the macros and IDA ICE model, which is developed in this thesis.

The investigation of the ventilation window should be done to optimize the design further, finding the optimal leakage area from ambient air and leakage, cavity depth, leakage area from window cavity to the zone. This can be done in IDA ICE by performing parameter analysis with the inbuilt parameter function. Also, other designs combining ventilation windows and openable windows should be investigated further.

For the hatches, it would be interesting to conduct tests where the hatch had improved insulation properties. For this, the vacuum insulation panels (VIP) could be a good solution.

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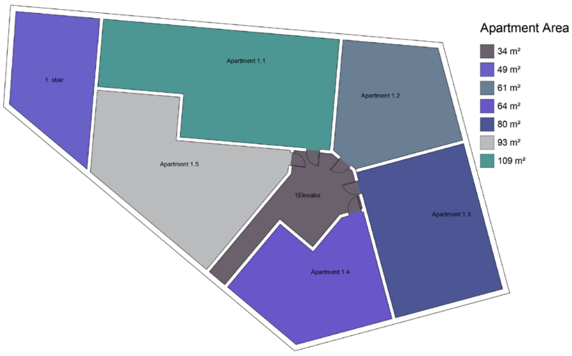
Appendix

Appendix.1 Floor plan

Level 1



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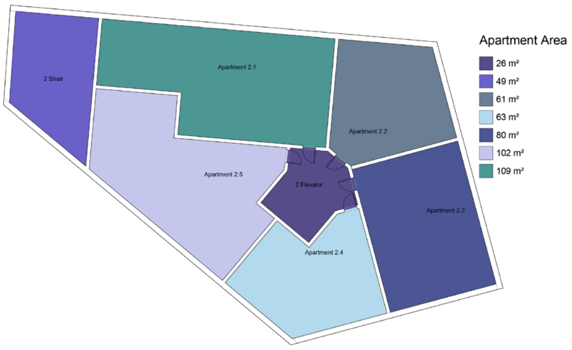

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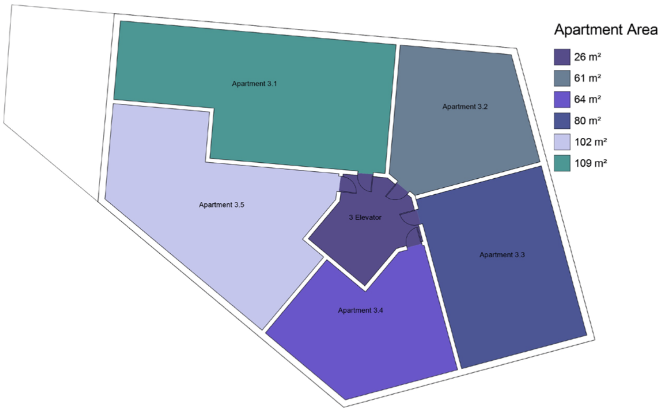

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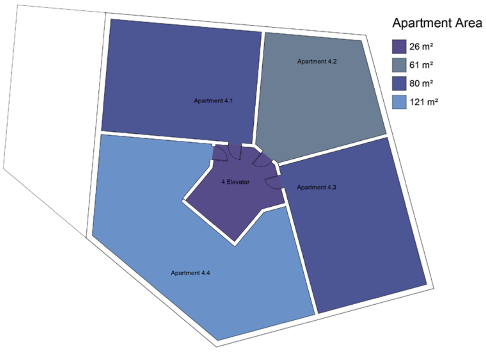

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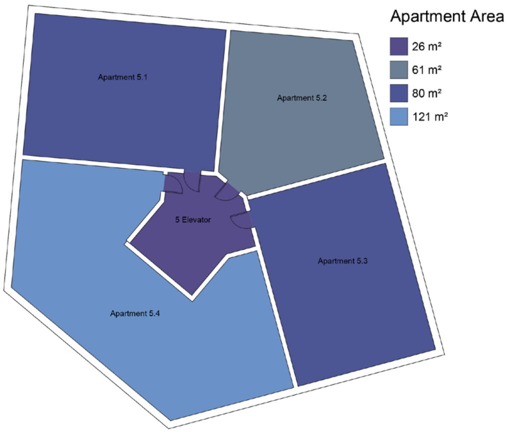

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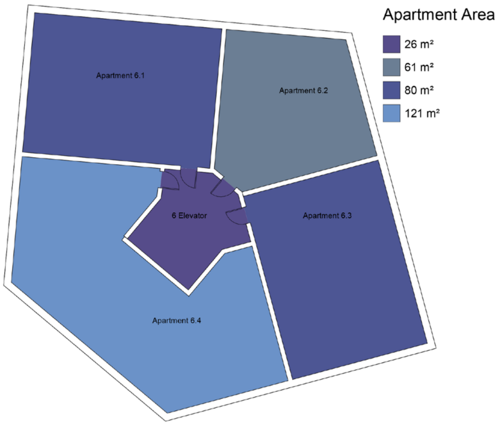
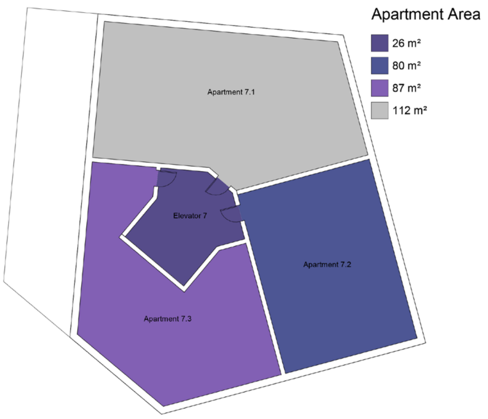
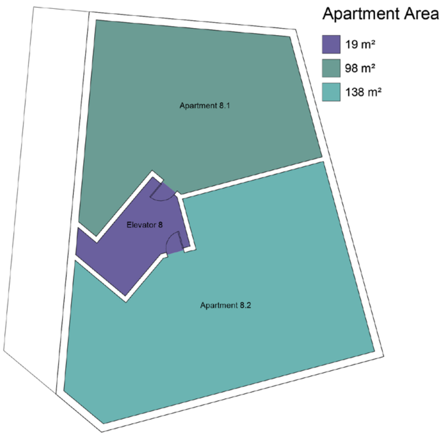


Level 7



Level 8



Appendix 2. Pressure coefficients for the different levels and facades

Face/Angle	0	45	90	135	180	225	270	315	Face azimuth	Cardinal direction
Level 1										
Roof 1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	360	North
Facade 1	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	5	North
Facade 2	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	75	East-North-East
Facade 3	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	165	South-South-East
Facade 4	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	220	South-West
Facade 5	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	274	West
Level 2										
Roof 2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	360	North
Facade 1	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	5	North
Facade 2	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	75	East-North-East
Facade 3	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	165	South-South-East
Facade 4	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	220	South-West
Facade 5	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	274	West

Level 3										
Roof 3	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	360	North
facade 1	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	5	North
facade 2	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	75	East-North-East
facade 3	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	165	South-South-East
facade 4	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	220	South-West
facade 5	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	275	West

Level 4										
Roof 4	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	360.0	North
facade 1	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	5	North
facade 2	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	75	East-North-East
facade 3	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	165	South-South-East
facade 4	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	220	South-West
facade 5	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	275	West

Level 5										
Roof 5	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	360	North
facade 1	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	5	North
facade 2	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	75	East-North-East
facade 3	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	165	South-South-East
facade 4	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	220	South-West
facade 5	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	275	West

Level 6										
Roof 6	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	360	North
facade 1	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	5	North
facade 2	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	75	East-North-East
facade 3	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	165	South-South-East
facade 4	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	220	South-West
facade 5	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	275	West

Level 7										
Roof 7	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	360	North
facade 1	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	45	North

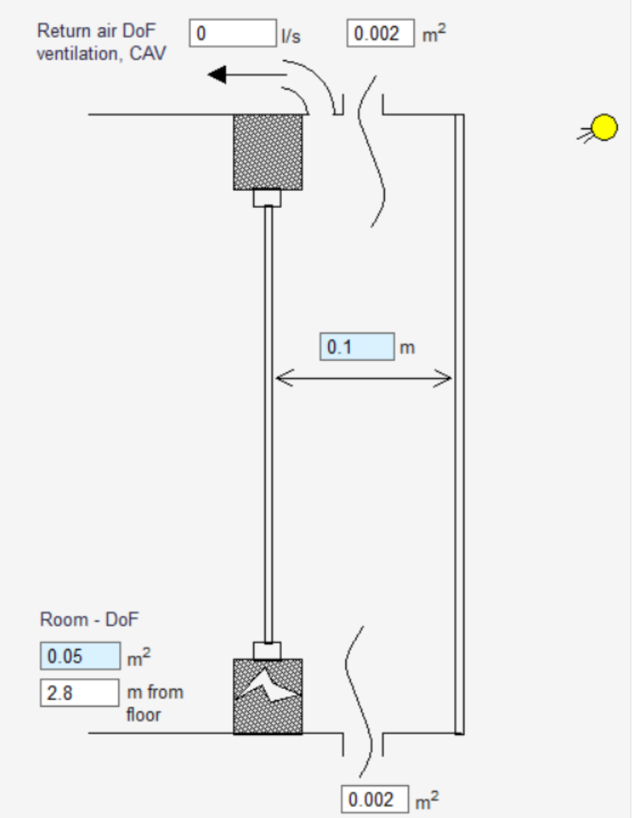
facade 2	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	75	East-North-East
facade 3	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	165	South-South-East
facade 4	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	220	South-West
facade 5	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	275	West
Level 8										
Roof 8	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	360	North
facade 1	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	5	North
facade 2	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	75	East-North-East
facade 3	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	165	South-South-East
facade 4	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	220	South-West
facade 5	0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06	275	West

Appendix 3. Supply disc valves for apartments

Name	Floor area, m^2	Number of disc valves
Apartment 1.1	109	4
Apartment 1.2	61	2
Apartment 1.3	80	3
Apartment 1.4	64	3
Apartment 1.5	93	4
Apartment 2.1	109	4
Apartment 2.2	61	2
Apartment 2.3	80	3
Apartment 2.4	63	3
Apartment 2.5	102	4
Apartment 3.1	109	4
Apartment 3.2	61	2
Apartment 3.3	80	3
Apartment 3.4	64	3
Apartment 3.5	102	4
Apartment 4.1	80	3
Apartment 4.2	61	2

Apartment 4.3	80	3
Apartment 4.4	121	5
Apartment 5.1	80	3
Apartment 5.2	61	2
Apartment 5.3	80	3
Apartment 5.4	121	5
Apartment 6.1	80	3
Apartment 6.2	61	2
Apartment 6.3	80	3
Apartment 6.4	121	5
Apartment 7.1	112	4
Apartment 7.2	80	3
Apartment 7.3	87	3
Apartment 8.1	98	4
Apartment 8.2	138	6

Appendix 4. Indata Ventilation window



Return air DoF ventilation, CAV: 0 l/s

0.002 m^2

0.1 m

Room - DoF

0.05 m^2

2.8 m from floor

0.002 m^2

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