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MASTER'S THESIS

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ABSTRACT:

Ventilation plays a significant role in overall residential buildings' energy budget. This thesis takes a closer look at decentralised ventilation system with heat recovery (DV) and compares it to well-known centralised ventilation system (CV) in terms of energy. Two DV systems are investigated: Pair-Wise and Single-Unit. IDA-ICE building simulation software has been used to execute several different simulations for a model of small apartment placed in Oslo climate. Main goal of the thesis was to investigate whether DV systems can outperform typical CV system in terms of energy, while keeping the indoor air quality on acceptable levels in terms of CO_2 concentrations. Side research questions regarded heat recovery function, placement of DV units within the apartment space. Additionally, the question about modelling decentralised ventilation units was investigated.
Results show that, given the chosen set of boundary conditions and model of DV in IDA-ICE, it is centralised ventilation system that offers best performance energy wise. Single-Unit DV came out with slightly worse energy performance, while Pair-Wise turned out to be the least efficient system. CV met TEK17 energy requirements (§ 14-2) in all analysed scenario while DV-P exceeded this requirement, especially due to substantial energy used for heating. Indoor climate results show that all systems are within acceptable levels, with DV showing better conditions then CV in some cases. Analysis of the placement of DV within apartment space, together with potential consequences has been presented. Impact of air pressure differences due to buoyancy and wind-stack effect has been investigated and simulated, without concluding evidence as to how they affect energy consumption.

KEYWORDS (one per line):
Decentralised ventilation
Residential buildings
Energy efficiency
Air pressure difference

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I would like to also thank my family and friends, here in Norway as well as back in Poland. Going through challenging times, lack of motivation and struggle to "get back to work" I find their presence and kind words tremendously important. I am happy to deliver this master thesis with feeling of great accomplishment and faith in myself and the future ahead.

Oslo Metropolitan University

Oslo, November 2022

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Abstract

Ventilation plays a significant role in overall residential buildings' energy budget. With constantly rising ambitions towards energy savings and improving indoor air quality, there lies a potential to test novel approaches and ventilation systems. This thesis takes a closer look at decentralised ventilation system with heat recovery (DV) and compares it to centralised ventilation system (CV) with hybrid ventilation component in terms of energy efficiency. Two different DV systems are investigated: Pair-Wise and Single-Unit. The former is characterized by simpler construction and installation, while the latter offers better heat recovery and possibility for heating and cooling built into the unit itself.

IDA-ICE building simulation software has been used to execute several different simulations for a model of 3 small apartments placed in Oslo climate. Results on energy used, together with indoor climate indicators were obtained. Effects of wind- and buoyancy-driven air pressure difference have been taken into account when carrying out the simulation of DV systems, based on the literature.

Main goal of the thesis was to investigate whether DV systems can outperform typical CV system in terms of energy, while keeping the indoor air quality on acceptable levels in terms of CO_2 concentrations and thermal comfort. Side research questions regarded Adaptive Thermal Comfort for hybrid and natural ventilation simulations, placement of DV units within the apartment space and comparison between IDA-ICE and SIMIEN when it comes to compliance test according to TEK17 has been investigated.

Results show that, given the chosen set of boundary conditions and model of DV in IDA-ICE, it is centralised ventilation system that offers best performance energy wise. Single-Unit DV came out with slightly worse energy performance, while Pair-Wise turned out to be the least efficient system. CV met TEK17 energy requirements (§ 14-2) in all analysed scenario while DV-P exceeded this requirement, especially due to substantial energy used for heating. Indoor climate results show that all systems are within acceptable levels, with DV showing better conditions then CV in some cases. Analysis of the placement of DV within apartment space, together with potential consequences has been presented. Impact of air pressure differences due to buoyancy and wind-stack effect has been investigated and simulated, without concluding evidence as to how they affect energy consumption.

Sammendrag (summary in Norwegian)

Ventilasjon spiller en betydelig rolle i det totale energibudsjettet til boligbygg. Med stadig økende ambisjoner om energisparing og forbedring av inneluftkvaliteten, ligger det et potensial for å teste nye tilnærminger og ventilasjonssystemer. Denne oppgaven ser nærmere på desentralisert ventilasjonssystem med varmegjenvinning (DV) og sammenligner det med velkjent sentralisert ventilasjonssystem (CV) når det gjelder energi forbruk. To DV-systemer er undersøkt: Pair-Wise og Single-Unit. Førstnevnte kjennetegnes ved enklere konstruksjon og installasjon, mens sistnevnte gir bedre varmegjenvinning og mulighet for oppvarming og kjøling innebygd i selve enheten.

IDA-ICE simuleringsverktøy har blitt brukt til å utføre flere ulike simuleringer for en modell av en liten leilighet plassert i Oslo klima. Det ble oppnådd resultater på energi forbruk, sammen med inneklimaindikatorer og følsomhet for varmegjenvinningsfunksjon. Simuleringer ble utført i dimensjonerende sommer- og vinter forhold. I tillegg ble det gjennomført årlige og sesongmessige energi simuleringer..

Hovedmålet med oppgaven var å undersøke om DV-systemer kan utkonkurrere typiske CV-systemer når det gjelder energi, samtidig som den holder inneluftkvaliteten på akseptable nivåer når det gjelder CO_2-konsentrasjoner og termisk komfort. Sideforskningsspørsmål betraktet Adaptive Thermal Comfort for hybrid- og naturlig ventilasjonssimuleringer, plassering av DV-enheter innenfor leilighetsrommet og sammenligning mellom IDA-ICE og SIMIEN når det gjelder samsvarstest i henhold til TEK17 er undersøkt.

Resultatene viser at, gitt det valgte settet med grensebetingelser og modell av DV i IDA-ICE, er det sentralisert ventilasjonssystem som gir best ytelse energimessig. Single-Unit DV kom ut med litt dårligere energiytelse, mens Pair-Wise viste seg å være det minst effektive systemet. CV oppfylte TEK17 energikravene (§ 14-2) i alle analyserte scenarier mens DV-P oversteg dette kravet, spesielt på grunn av betydelig energi brukt til oppvarming. Inneklimaresultater viser at alle systemer er innenfor akseptable nivåer, med DV som viser bedre forhold enn CV i noen tilfeller. Analyse av plassering av DV innenfor leilighetsareal, sammen med potensielle konsekvenser er presentert. Påvirkning av lufttrykksforskjeller på grunn av oppdrift og vindstabeleffekt er undersøkt og simulert, uten konkluderende bevis for hvordan de påvirker energiforbruket.

Glossary

0_BOT: Bottom apartment in the simulation with separate apartments.

2_MID: Middle apartment on the 2nd floor in the simulation with separate apartments.

3_TOP: Top apartment on the 3rd floor in the simulation with separate apartments.

AHU Heating, AHU Cooling: Energy used for heating or cooling delivered through AHU, expressed as energy [kWh] and as specific energy [kWh/m2]

ACS: Adaptive Comfort Standard

ATC: Adaptive Thermal Comfort

AHU: Air Handling Unit

BREEAM: Building Research Establishment Environmental Assessment Method

CDF: Cumulative Distribution Function

CO_2: Concentration of carbon dioxide, averaged value expressed in part per million [ppm]

CV: Centralised Ventilation (one AHU per building or multiple apartments)

CAV: Constant Air Volume (ventilation system)

DCV: Demand Controlled Ventilation (system)

DP_Link: Differential Pressure Link in IDA-ICE macro setting

DV: Decentralised Ventilation (one AHU per apartment or zone)

DV-P: Decentralised Ventilation (Unit) Pair-Wise Type

DV-S: Decentralised Ventilation (Unit) Single-Unit Type

EPW: Energy Plus Weather (Climate) Format

HRU: Heat Recovery Unit

HVAC: Heat, Ventilation and Air Conditioning

IAQ: Indoor Air Quality

LCC: Life Cycle Cost (calculates the costs of a product throughout its life cycle (which can include giving a monetary value to environmental externalities)

LCA: Life Cycle Analysis (assesses the environmental impacts, such as global warming potential, over the life cycle.)

NoAHU: No Air Handling Unit (No mechanical ventilation present, natural ventilation only)

PI (Controller): Proportional Integral Controller

PLR: Partial Load Ratio

PPD: Percent of dissatisfied people, according to Fanger expressed in percent [%]

PMV: Predicted Mean Vote, indicator of people's satisfaction with thermal indoor climate from -3 to +3, 0 (neutral) is most desired

PRN: Print to file format, mostly used by IDA-ICE to generate reports.

RH: Relative Humidity, averaged value expressed in percent [%]

SFP: Specific Fan Power [kW/m3/s]

VAV: Variable Air Volume (ventilation system)

VOC: Volatile Organic Compounds

Total Deliver Energy: Sum of Zone heating, Zone Cooling, AHU heating and AHU cooling expressed as energy [kWh] and as specific energy [kWh/m2]

Zone Heating, Zone Cooling: Energy used for local heating or cooling units, expressed as energy [kWh] and as specific energy [kWh/m2]

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Introduction

1.1 Background

In recent years there have been number concerns raised about energy usage worldwide and its consequences on use of fossil fuels leading to negative climate change. Last IPCC report on climate change does not leave a trace of a doubt that humanity runs towards uncertain times and the reason to it can be found in rising production, construction, and usage of goods. Since 1990 global direct and indirect emissions from buildings rose by 50%. (IPCC, 2022). Norway's highly developed economy (OECD, 2022) and rising demographics (Statbank, 2022) pose a challenge towards reducing electricity usage and accomplishing national and European climate targets. Norway's ambitious climate targets of reducing emissions by 55% by 2030 compared with 1990 level, together with ultimate reduction towards zero emissions by 2050 are under great dispute. According to reports (DNV, 2021) those goals will most likely not be met.

Considering this substantial pressure, both from above as worldwide and European regulations set bounds and goals for energy reductions, as from below, as each different consumer strives for lowest energy costs, it is of foremost importance to seek energy reducing measures. This study turns focus on residential buildings and potential of using decentralised instead of centralised ventilation to save energy. Ventilation represents significant part of buildings' energy usage (Santos & Leal, 2012) and DV systems has been tested and proofed to perform better than their CV counterparts in residential buildings. (Merzkirch et al., 2017) Norwegian housing market being constantly in the development (Larsen, 2021) and the fact that people spend even more time at home now due to post-pandemic job market situation (Rouleau & Gosselin, 2021) makes residential buildings interesting field of study.

An online search on what is being offered of DV units on Norwegian market as of November 2022 has been conducted and effects of it are presented in *Table 1*. Worth pointing out is different interpretation of what is regarded as "decentralised ventilation" between manufacturers. Some of the solutions require use of ducts in order to supply or extract air of zones. It is needed to introduce not only differentiation between centralized and decentralized, but also "ducted" and "non-ducted". For example, Swegon's Freeair 100 is described as decentralized solution that needs ducted connection to kitchen and bathroom in order to function as designed.

There has been done research in form of academic papers and theses on the various aspects of decentralised ventilation in Scandinavian and Norwegian setting. A economic studies on centralised and decentralised ventilation system in form of both LCA (*Life Cycle Analysis) (Lindvall, 2018)* and LCC (*Life Cycle Cost) (Thorstensen, 2022),* performance and energy analyses (Magagna, 2016; Strand, 2021; Thorstensen, 2022), control strategies for DV (Carbonare, 2021), among others. This study's main ambition is to investigate further use of 2 specific types of DV units in a rehab apartment in Norwegian climate.

UN-DUCTED (DV) UNITS IN THE NORWEGIAN MARKET - November 2022										
		DV Pair-Wise					DV Single-Unit			
Manufacturer	[-]	**Lunos**	**Lunos**	**Lunos**	**Helios**	**Flexit**	**Airmaster**	**Airmaster**	**TROX**	**SWEGON**
Product	[-]	e2 60	eGO	Silvento	EcoVent Verso	Roomie Dual	AM series, example 150. **Filter ePM_10 50%**	AM series, example 150. **Filter ePM_1 80%**	FSL B ZAB SEK	Freeair-100 * with premium cover (for noise dampening)
NS-EN 13141-8 *Test, documentation*	[-]	Yes	Yes	Yes	Not documented	Not documented	Yes	Yes	Not documented	Yes
Sound power Lp(A)	[dB(A)]	10 - 48 (at 1m distance, 5-55 m3/h)	Not specified	22 - 35 (at 1m distance, 15-60 m3/h)	14 - 34 (14-45 m3/h)	20 - 39 (10-30 m3/h)	30 - 35 (35-147 m3/h)	30 - 35 (25-115 m3/h)	22 - 35 (80-150 m3/h)	22 - 35* (at 1 m distance, 50-85 m3/h)
Airflow capacity, max	[m3/h]	60	20	90	45	30	147	115	150	100
Fan type	[-]	Axial	Axial	Axial	Axial	Axial	Not specified	Not specified	Centrifugal	Not specified
SFP	[kWh/m3/s]	0,37 (40 m3/h) 0,43 (60 m3/h)	Not specified	Not specified	Not specified	Not specified	0,53 - 0,95	0,53 - 1,15	1	0,22 - 0,24
Power usage, max	[W]	0,3 - 3,3	Not specified	Not specified	1,6 - 4,5	2,9 - 6,8	38	38	23	38
HRU type	[-]	Regenerative	Regenerative	Regenerative	Regenerative	Regenerative	Recuperative	Recuperative	Recuperative	Recuperative
HRU eff, max	[%]	88% (40 m3/h) 83% (60 m3/h)	Not specified	Not specified	88 %	70 - 80%	80 - 86%	80 - 86%	60 %	94% at 50% RH
Filter	[-]	G3	Not specified	Not specified	G3	G3	ePM_10 50%	ePM_1 80%	Extract: G3 Supply: F7	Supply: ePM10 or ePM1 (pollen filter) Extract: ePM10
Cooling capacity	[W]	-	-	-	-	-	700	700	400	-
Heating capacity	[W]	-	-	-	-	-	500-1000	500-1000	1000	-
Frost protection	[-]	Not specified	Not specified	Not specified	Not specified	Down to -15 Celsius	Not specified	Not specified	Not specified	Automatic bypass-control at about -5°C outside
Installation	[-]	Outer walls from 280mm, ø160.	Outer walls from 280mm, ø160.	To be installed in a recessed cabinet in the wall	Outer walls from 280mm, ø160.	Outer walls from 280mm, ø160.	Ceiling mounted, condense water extract needed	Ceiling mounted, condense water extract needed	Under ceiling, under sill, wall mounted	In the external wall, from 320mm wall thickness
Controls	[-]	Possible.	Possible.	Humidity, temp sensors, schedules, VOC, occupancy.	Software from Helios for advanced controls from PC	Flexit software for synchronising pairs of DV-P units	Not specified	Not specified	Modular control system FSL-CONTROL II, specially for decentralised ventilation systems	CO2, temperature control + 5 levels
Comments	[-]		Can be used as forced extract, up to 45 m3/h but then without HR.							

Table 1: Overview on DV units on Norwegian market, November 2022.

1.2 Research questions

The main research question of this master thesis is the comparative study of energy performance between decentralised ventilation (DV) systems and centralised ventilation (CV) system in a typical small rehab Norwegian apartment. The goal is to answer the question whether DV systems are advantageous in terms of delivered energy or if so, on what conditions and what time of the year. The analysis will be performed on three different apartments within a one block of flat. Apartments differ in height (different floors), size and orientation.

Main hypothesis: decentralised systems will turn out to be the most energy efficient comparing to NoAHU (natural ventilation) and centralised system due to lack of ducting (lesser pressure loss) and modern fans with heat recovery.

The side research questions are concerned with placement and installation of DV units in an apartment where the space is confined. Another question that turned out to be worth answering regards TEK17 compliance test and whether IDA-ICE can be used as a simulation tool for this purpose, in line with SIMIEN that is a tailored piece of software nowadays in Norway.

Other research questions developed during writing this thesis were Adaptive Thermal Comfort vs. Fanger's comfort indices in case of decentralised ventilation with hybrid ventilation component. Secondly the effects of wind- and buoyancy-driven air pressure difference across the wall on the performance of DV systems are to be investigated using advanced modelling in IDA-ICE.

Side hypothesis: pressure difference across the external wall will affect DV more in the apartments located higher than those closer to the grand, because of buoyancy and stack-wind effect.

1.3 Study limitations

The study focuses exclusively on residential buildings by taking exemplary rehab apartments located Oslo. Moreover, only one location is considered and therefore one climate type, namely Oslo climate which is Baltic semi-continental. All parameters related to the building envelope has been kept constant throughout simulations. Three apartments consisting of 14 different rooms all together were modelled. Occupancy profile, internal gains, windows and their opening controls, shading controls, and indoor climate setpoints were set as constants throughout the study.

Only recovery of sensible heat has been analysed. This study does not consider latent heat or recovery of cooling in simulations in IDA-ICE. Pressure drop and extra fan load are not included in the results, neither for CV, nor for DV set-ups. On the other hand, for DV simulations, there has been introduced a more detailed model for Fan Performance curves, as described in methodology section. Moreover, an advanced simulation model in IDA-ICE has been used in order to use the signal from DP_Link (differential pressure across the outer wall) as an input to supply and exhaust in case of DV systems.

In general, the comfort indicators were used only to show which scenario is viable in terms of liveability. No further study on indoor climate has been performed.

DV units

It has been chosen to avoid using actual products' names in this study and instead use literature backed-up generic decentralised ventilation units, inspired by what is available in the Norwegian marked nowadays. Advantage of such approach is being able to base on researched and tested data, not relying on manufacturers' specifications. Drawback, on the other hand, is the fact, that because of the generic nature of data presented in this study one will not be able to draw a conclusion about a given existing product that is available on the market. Only a general impression of the system in each set of boundary conditions can be obtained here. The most important parameters in question are SFP values, Fan performance curves and HRU efficiencies. More about these can be found in chapter 2.

1.4 Assessment of the tools used

In this study there were used three software tools: IDA-ICE and SIMIEN for building and physics modelling purposes and simulation and Excel for organising simulation data and presentation of results.

IDA-ICE is a dynamic, multi zone building simulation software developed by Swedish company EQUA Labs. Current version 4.8 SP2 supports multiple types of simulations: heating and cooling loads, overheating, full year energy simulations, daylight, and shading simulations. IDA-ICE enables user to model the studied building in 3D starting from a floor plan, adding windows and other openings, defining building envelope and specifying various parameters as constants or variables connected to various parts of the building, getting inputs, and reacting to them. Being able to use hourly climate data, dynamic changes in occupation and internal gains ensures that the modelled building's reflect real world behaviour in terms of energy usage.

The parts of the software that was actively used in this study were Air Handling Unit modeller and simulation tools. According to the studies (Cornaro et al., 2016) IDA-ICE performs well and its results are comparable with on-site measurements when boundary conditions are set alike. Norwegian researchers (Sara Saade, 2021) and engineers widely use IDA-ICE as a simulation tool in order to model and investigate different aspects of buildings' physics.

Excel, a well-known part of Microsoft Office basic software package, will not be described in detail here. It's function in this work was to organise data, perform calculation and present results in form of tables and diagrams. Linking IDA-ICE Excel reports with pre-made tables for simulation scenarios greatly reduced user errors and improved execution time.

Why using IDA-ICE instead of SIMIEN for energy simulations?

Both IDA-ICE and SIMIEN are simulation applications based on a dynamic multi-zone models for study of indoor climate of individual zones as well as the energy consumption on the building and zone level. According to the validation process EN15265 both applications lay within C as shown in class when it comes to simulation accuracy (Equa-LABS, 2010). The difference between these programs lay in applicability and complexity.

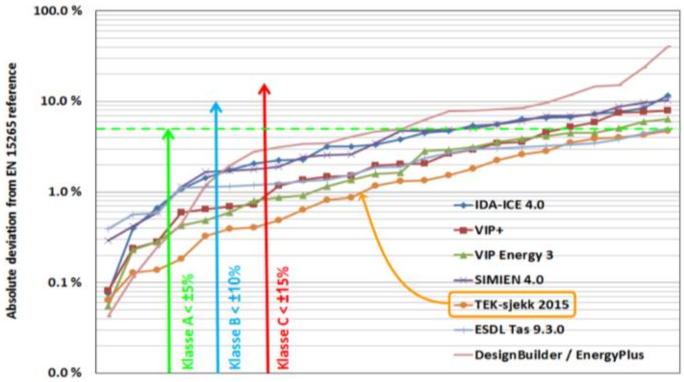


Figure 1: Absolute deviation from EN 15265 reference. Building Energy Simulation Software.(Schild, 2019)

SIMIEN has been designed by a Norwegian company Programbyggerne specifically for Norwegian marked as it enables for, among other uses, easy evaluation according to Norwegian building code TEK17 and Norwegian standard for calculation of the energy performance of buildings NS3031(Programbyggerne). It makes it the most widespread and popular application of choice among energy engineers in Norway. (DJURIC, 2010)

IDA-ICE, application designed by Swedish company EQUA on the other hand does not allow for direct check for compliance with the Norwegian building code TEK17 as it aims for broader spectrum of uses. The program uses 2D and 3D platform to design the body of the building and each zone with corresponding openings and construction details, based on user input or pre-made IFC files.

The physical models reflect the latest research within areas like daylight simulation, natural and hybrid ventilation and ventilated windows and facades. SIMIEN gives one node per each thermal zone, while IDA-ICE operates by using one node per analysed surface. Additionally, IDA-ICE, unlike SIMIEN, uses multiple nodes for thermal mass calculations. When it comes to climate data, IDA-ICE takes use of EPW (EnergyPlus Weather) hourly climate files, while SIMIEN is based on sinus-curve outdoor temperature readings. When it comes to simulation of airflows, IDA-ICE enables for scheduled variation of amount of air entering and leaving the zones, changing heat recovery rate and heat recovery efficiency that is being affected by oscillating airflows.

NS3031 standard considers net energy results, that is the building's energy needs without regard to the energy system's power factor, efficiency, or losses in the energy chain. No distinction is made between energy supplied and energy produced in the building (NEMITEK, 2019b). IDA-ICE can differentiate between net and deliver energy needs thanks to the option for setting energy system's efficiencies and accounting for different system losses.

Versions of the software used in this study: IDA ICE (ver. 4.8 SP2, published on 11.09.2020), SIMIEN (ver. 6.017, 2021), Excel 365 (updated as of November 2022).

1.5 Structure of the thesis

The thesis consists of 9 parts: pre-introductory (from acknowledgments to list of contents), introduction, theory chapter about decentralised ventilation and energy performance, methodology, results, discussion, conclusions, further research, and appendices section. Each chapter is divided into smaller sections that follow a logic step-by-step approach. All figures and tables are cross-referenced and list of each is presented in pre-introductory section. The same applies to references that are connected to the corresponding list on the end of the document and formatted using APA 7th style with help of EndNote software.

2 Theoretical background

2.1 Energy performance assessment

Energy goes a long way from being captured, through various way of transfer and finally arriving at the end user. Then it is being used in many ways, covering different demands. Some of it is lost due to inefficiencies and other passive system losses. *Figure 2* shows the breakdown of energy from its beginning on the left to its uses in a typical building. This thesis is mostly interested in net energy demand used for ventilation which is a part of HVAC system.

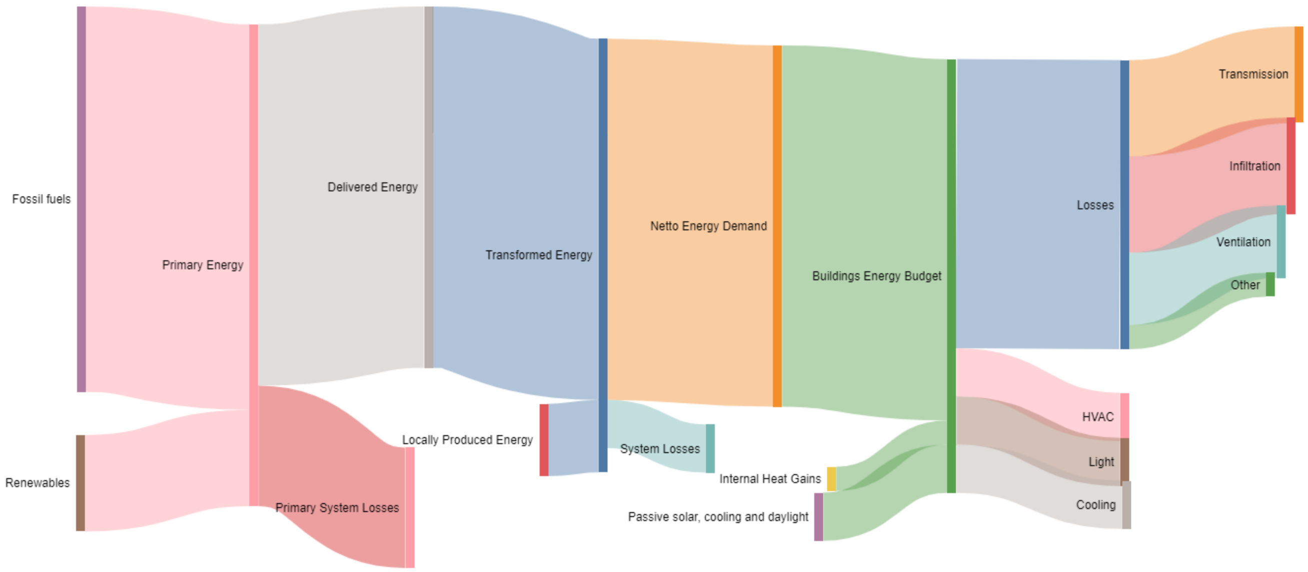


Figure 2: Breakdown of energy delivery chain and the definition of net energy demand. Reproduced from (NEMITEK, 2019a)

According to *Figure 3* and Figure *4* around 39% of energy is being used for HVAC systems which of 34% goes for fans, 27% for cooling and 17% for heating. (HESS, 2013)

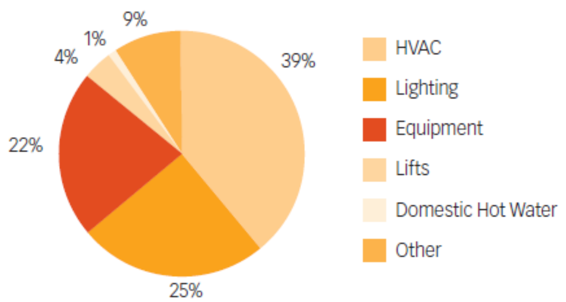


Figure 3: Typical energy consumption breakdown in an office building. (HESS, 2013)

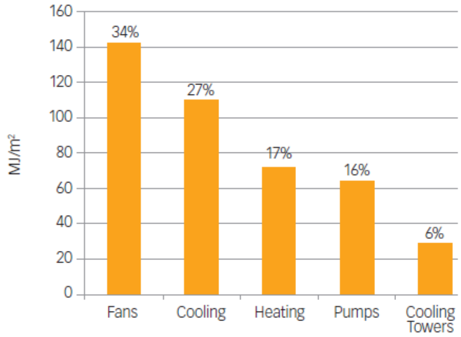


Figure 4: Typical HVAC end use breakdown. (HESS, 2013)

By keeping boundary conditions and all different system losses constant one can find differences of the varying components of HVAC and its consequences on overall energy usage. It will be presented in chapter 3 and 4 that each parameter of those different systems affect each other so the resulting picture cannot simply be derived by looking on separate parts, but the complex and dynamic view of the whole shall be investigated. (Farrokhi et al., 2021)

2.2 Wind- and buoyancy driven flows, air leakage

When analysing natural or hybrid ventilation systems, it is important to discuss the forces that drive airflows within the insides and outsides of the building in question. These are wind, buoyancy, and combination of both in different settings.

Wind-driven flows occur due to pressure differences caused by wind, that is moving air, on different facades or parts of facades. In building and physics simulation context one is concerned mostly with what happens with pressure difference between outside and inside of the building when airflow crosses the openings in the façade. Variation in wind angle and velocity causes variations in pressure regions which leads to air flowing constantly from the positive pressure region to the negative one.

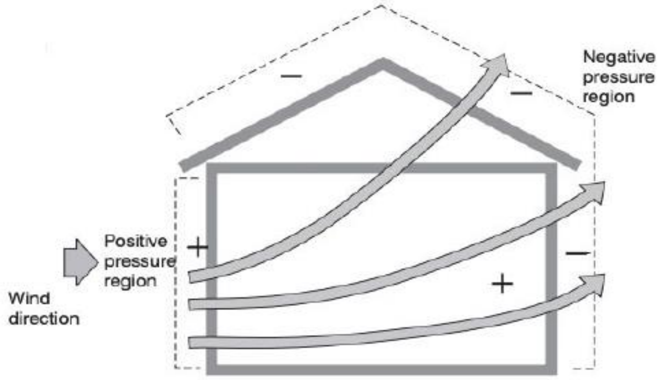


Figure 5: Principle of wind-driven flow across the building body. (Liddament, 1996)

Figure 6 illustrates the principle of wind-driven flow. There are couple different parameters that need to be taken into account when analysing this phenomena: shape of the building, placement of the opening, relative wind direction, wind speed, level of exposition of the building (presence of obstructions, other buildings), terrain, climate. (Cibse, 2005)

Formula for static wind pressure *p_wind* [Pa] outside the building facades is as follows:

$$p_{wind} = C_p \cdot \varrho_a \cdot U^2/2,$$

Where *Cp* is the dimensionless pressure coefficient, *rho_a* is the air density [kg/m3] and *U* is the local wind velocity [m/s]. Local wind velocity is calculated according to the ASHRAE LBL method (ASHRAE, 1993), the following formula is used in IDA-ICE:

$$U(h) = U_m \cdot k \cdot (h/h_m)^a,$$

Where *U_m* [m/s] is the measured wind speed at the given weather station (depends on the climate chosen, H=10m), *h* [m] is the height from the ground, *h_m* [m] is the height of the measuring equipment, while the constants *k* and *a* are the terrain coefficients. Defaults values for, respectively *k* and *a* coefficients in urban, semi-exposed terrain are 0,67 and 0,25.

When it comes to buoyancy-driven flow (also known as stack effect), as shown in *Figure 6,* it occurs due to density difference between airflows, often between the indoor and outdoor air due to temperature difference. Warmer air, having higher kinetic energy rises up towards lower pressure region, leaving colder air underneath in the higher-pressure region.

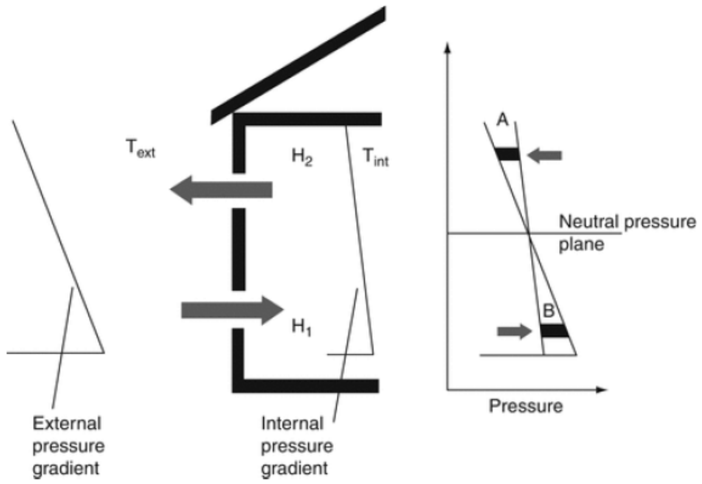


Figure 6: Pressure variation across the vertical openings in the building facade. Buoyancy-driven flow. (Liddament, 1996)

Following formula expresses the relation for two vertical openings *H1* and *H2*:

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

Where *P_s* [Pa] is the pressure difference between the openings, *rho_0* is the air density [1,29 kg/m3] at 273K, *g* is the gravitational acceleration [9,81 m/s^2], *T_ext* is the outdoor [K] and *T_int* is the indoor air temperature [K] and *H_1* and *H_2* are the heights of openings [m].

The way that IDA-ICE emulates wind- and buoyancy-driven flows is by introducing pressure coefficients. These are calculated automatically by considering the physical volume of the building, its height, orientation, wind profile and climate. When IDA-ICE calculates air leakage through the façade, the empirical power law equation is used: (Jokisalo, 2009)

$$Q = C \cdot \Delta P^n$$

Where *C* is a dimensionless flow coefficient (depends on the opening), *d_P* [Pa] is the given pressure coefficient for the opening and *n* is a dimensionless flow exponent, characteristic for a given flow regime. (Mikola et al., 2019)

2.3 Indoor Climate Indicators

Indoor air quality is important for well-being of occupants, their performance, health, and level of experienced comfort. Ventilation is a well understood and tested mean towards removing and diluting indoor pollutants such us carbon dioxide, formaldehyde, and volatile organic compounds (VOC). (Liu et al., 2021) These unwanted particles and substances have both internal and external sources. Emissions from occupants and internal processes, together with emissions coming from materials and furniture constitute the interior sources. Pollutants coming from outside in come often from burning fossil fuels, i.e., transportation and industrial processes. (Hoang et al., 2022) Not regulating and thus exceeding concentration norms of various air contaminants can lead to physical and psychical issues like dry eyes and dry nose, headache, fatigue, and lack of concentration, together with allergic symptoms and other related health issues. (Wolkoff et al., 2021).

Therefore, it is particularly important when performing any kind of study on ventilation to consider its ability to regulate indoor air quality by taking a closer look at so called Indoor Climate Indicators. These relate to mentioned pollutants and their concentration indoors, whose requirements and well documented for both residential and non-residential buildings. (Folkehelseinstituttet, 2016)

2.4 Fanger's Thermal Comfort Indices and Adaptive Thermal Comfort model

To evaluate indoor thermal comfort from human perspective, Povl O. Fanger created an equation that ties together several parameters: (CLO), level of activity (MET) and four environmental variables in each zone (air speed, air temperature, mean radiant temperature and humidity). As a result, two indices PPD and PMV have been derived. PPD stands for Predicted People Dissatisfied and PMV for Predicted mean vote. PMV indicates the response of group of people on the satisfactory level of the indoor climate. It is presented in a scale from -3 (very cold) to +3 (very hot), with 0 being the neutral, most preferred state. It implies that most desired state is the neutral one when neither additional cooling or heating is needed for a given set of parameters and occupants.

PMV can be obtained by means of calculation, tabular data or by measurements. PPD on the other hand gives information about the amount of people that are dissatisfied with indoor climate. It is calculated based on following formula:

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

Worth noting is also relation between PPD and PMV indices illustrated in *Figure 7*. Standard NS-EN ISO 7730:2005 (Standard.no, 2005) states that recommended value of PPD is below 10% and PMV should lay between -0,5 and +0,5. Worth noting that according to PMV model it is impossible to obtain 100% satisfaction among occupants, that is 0% PPD. With PMV equal 0 (perfect, neutral conditions) one needs to account for minimal value of 5% dissatisfied.

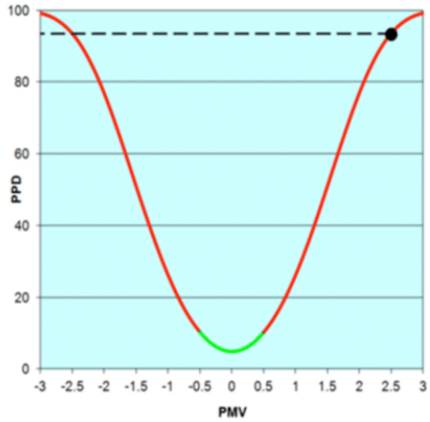


Figure 7: Relation between PPD and PMV indices.

A different approach to PMV and PPD indices has been proposed, so called Adaptive Thermal Comfort (ATC) method. The main difference between the two is that Fanger's indices have been developed in steady-state laboratory experiments and are calculated based on constant values of CLO and MET values mostly. ATC on the other hand takes into account dynamic by nature effects of anticipation, adaptation and changing expectations of occupants when evaluating satisfactory indoor climate. (M. Humphreys, 2007; R. de Dear, 2002).

The main conclusion of researchers conducting field experiments across different climates and several types of building indicate that preferences of occupants allow for broader spectrum of thermal conditions that is stated by Fanger's formula. ATC method is to be used mainly in buildings without complete mechanical cooling. The method builds on the argument that occupants, when faced with a possibility to influence their own thermal comfort by opening windows, have broader spectrum for which temperatures are tolerable, as shown in *Figure 8*.

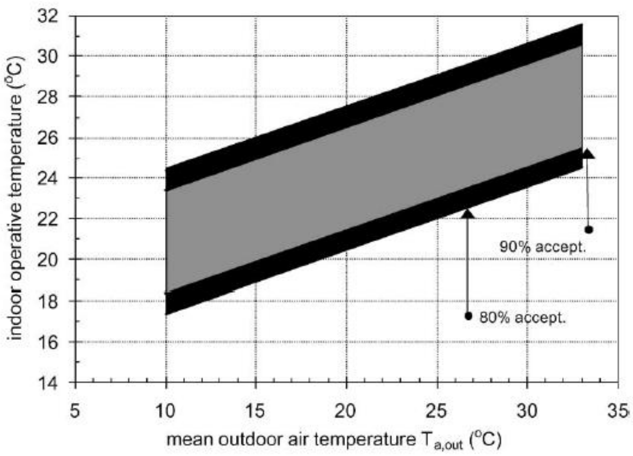


Figure 8: Proposed Adaptive Comfort Standard for ASHRAE Standard 55, applicable for naturally ventilated buildings.(R. de Dear, 2002)

In IDA-ICE one can evaluate indoor thermal comfort in means of the abovementioned Adaptive Comfort Standard, by choosing evaluation according to EN-15251, without cooling (according to IDA-ICE nomenclature).

2.5 Air distribution types

Ventilation in general is a way of primarily removing pollutants and other harmful agents from the enclosed space through air exchange, which is supplying fresh air and routing the used one through return and exhaust ducts. All that should be done in a controlled manner and there are different approaches as how to do that.

Displacement and mixing ventilation

There are two basic ventilation principles when it comes to the way air flows and is being supplied on a room level: displacement and mixing ventilation. These have differences when it comes to volume of the room they shall be used in, placement of supply and return units and advantages. Displacement ventilation can be used for both cooling and heating, achieves high performance and is relatively well-understood and common way to design and install. Its drawbacks consist of risk of short-wire effect, significant energy demand and likelihood of uncomfortable air draughts. Mixing ventilation is a solution of choice for most residential buildings, especially those of smaller sizes with normal, that is around 2-3m, ceiling heights. (S. Liu et al., 2022)

Mixing ventilation on the other hand is suitable for rooms with bigger volumes, because the airflow speed is much lower than in the case of displacement ventilation. It performs especially good in regulating temperature in such sizeable rooms with high ceilings. Where it falls short is when there is extensive heating demand and when furniture obstructs passing of air. This, in turn, can lead to substantial vertical temperature gradient, i.e. local discomfort. (Sturla Ingebritsen, 2019a)

Natural, mechanical and hybrid ventilation

Ventilation strategies differ depending on various of conditions and design goals. Different countries tend to have different overall approaches to this subject as the big part of decision making whether which ventilation system to choose depends on climate and geometry to the room and/or building. (Dimitroulopoulou, 2012) In short, we distinguish three main types of ventilation systems in terms of how the air is supplied to the building: natural, hybrid (or semi-natural) and mechanical ventilation.

Natural ventilation first one relies solely on the buoyancy and pressure forces between regions of different temperatures and pressures. Air is then flowing from region of higher pressure towards region of lower pressure. Fresh air intakes within facades walls, wall leaks and opening of windows on each far-end sides of the apartment leads to such natural flow and is widely used in buildings without mechanical ventilation. (S. Liu et al., 2022) Advantages of natural ventilation are very low investing costs, little to no maintenance and lack of noise coming from the system itself. Disadvantages on the other hand are high total cost, inability to filter the air coming from outside, inability to regulate and balance airflows within apartment, risk of cold air drafts and thus discomfort.(R. de Dear, 2002)

Balanced mechanical ventilation with forced extract moves air by using fans and leads them inside and through the building via ducts. Air is being sucked inside and extracted to the outer space in a balanced matter such us the system stays in pressure balance between zones (rooms). Sometimes lack of pressure equilibrium is desired and then we are talking about over- and under-pressured rooms. Balanced mechanical ventilation solves a lot of problems that natural ventilation has and gives the users control on filtering, airflows and air speeds entering the zones. Additionally with this approach it is possible to regulate the supply temperature and heat recovery from extracted air. On the downside, this system generates comparatively higher maintenance costs, demands knowledge and skill in operating different components and relies on electricity for functioning in general. (SINTEF, 2017a)

Mechanical extract ventilation works similar to natural ventilation one described above with a difference that instead of buoyancy and wind driven forces, it is fans that generate under pressure within the apartment letting air come from the outside through leaks, air intakes, windows, and other openings. Again, low installation costs and easy regulation are on the plus side for this system, while substantial energy consumption and heat losses are among the disadvantages here. (SINTEF, 2017a)

Semi-natural ventilation system on the other hand is an in-between approach where some of air is controlled by fans and ducts and some air are allowed to flow solely due to pressure gradients. Mechanical supply and extract ventilation with possibility of opening windows when outdoors conditions are acceptable is an example of such hybrid ventilation solution. (Dimitroulopoulou, 2012)

Another distinction that can be made about ventilation systems and which is a focus of this study is about how the air is distributed in the building. Here we can differentiate centralised, semi-decentralised and decentralised ventilation systems. (Mikola et al., 2019)

2.6 Ventilation system types

Centralised ventilation

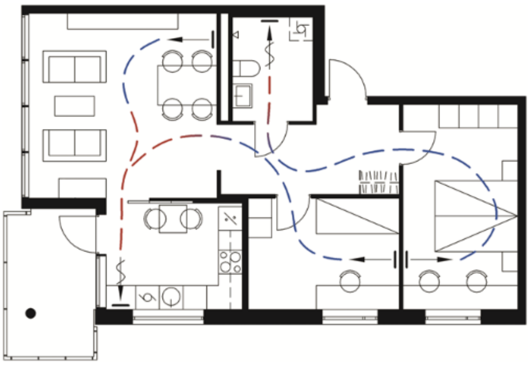


Figure 9: Centralised ventilation principle and air flowing through the zones. (SINTEF, 2017a)

The former is characterized by using one, central Air Handling Units that then is connected through a duct network to all rooms that will be supplied with fresh air, together with ducts for return and exhaust of used air. In the case of this study, it is a central AHU for a whole building (or all simulated apartments). *Figure 9* illustrates a principle of such system. CV system is the most popular one in all types of buildings. Its principles are good understood by professionals and it is being designed most frequently due to versatility and known parameters. (Magagna, 2016). Drawbacks of such system are amount of ducting that is necessary to distribute air, big volumes of AHU together with a need for extra equipment for zone-based control. Demand Control Ventilation is a solution to allow such control on zone level thanks to array of automation components. (Lu et al., 2022)

Decentralised ventilation

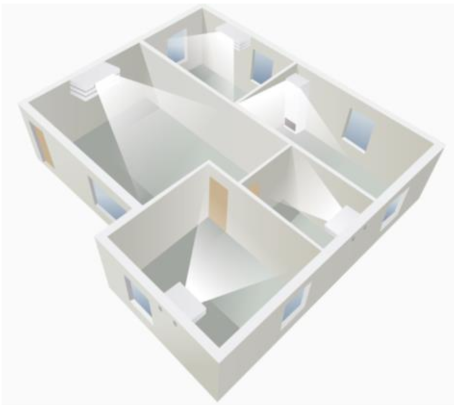


Figure 10: Decentralised ventilation principle. Source: (AIRMASTER)

Decentralised ventilation systems work in a way that instead of one, centralised unit there are multiple ones, each supplying different zone. This way, ideally, each person occupying different zone can control its indoor environment, which is temperature and airflow locally, thanks to the DV unit placed right next to the user. Advantages of such system are minimizing or even lack of ducting which gives more space for higher ceilings or other installations, more ways for adapting existing spaces due to smaller dimensions of units and better control flexibility that lets the end user change supply airflow and temperature locally. DV units take less space within the apartment and allow more flexibility in placing them, in comparison to centralised AHUs. (Carbonare, 2021)

Within DV systems there exists different approaches which will be described in the next section. The ones that this thesis is concerned with are so called Pair-Wise and Single-Unit DV systems.

2.7 Pair-wise, regenerative DV system

Pair-Wise DV system are the simpler of two analysed in this study. It generally consists of a collection of tubular parts that house an axial fan, typically a ceramic regenerative heat exchanger (HRU), filter, outdoor and indoor grille. Their function is based on alternating between intake-supply and return-exhaust states between which the unit oscillates periodically. In practice Pair-Wise DV units are mounted on the far ends of a building or apartment such as they can supply fresh air and remove the used one effectively through their cycles. Common placement of DV-P units are above windows and doors such us they do not take space, which is a big advantage. In *Figure 11* the construction principle and exemplary placement of Pair-Wise unit is shown. The term "Pair-Wise" itself comes from its inherent cooperation potential between two or more units. Moreover, there is an advantage to connect set of Pair-Wise units through a wire or wireless connection to achieve dynamic balanced ventilation setup. (Mikola et al., 2019; Zender – Świercz, 2020)

This simple type of room-based DV unit is not equipped with either heating or cooling unit so the only source of added heat to the room is through heat recovery. Regenerative heat exchanger installed in this unit works also based on periodicity principle. While being in return-exhaust mode heat from the used air gets transferred to the ceramic HRU in Pair-Wise DV. When the mode switches to intake-supply, heat flows from the HRU to the flowing air due to temperature difference. Cycle repeats after, for example, one minute loading and unloading heat from HRU to and from the air.

Figure 11: Construction and installation example of Pair-Wise DV unit. (Mikola et al., 2019)

Figure 12 and *Figure 13* show principally how Pair-Wise DV should be placed for it to play it is designed role. The way this thesis approached placement of DV units will be described in chapter 3.

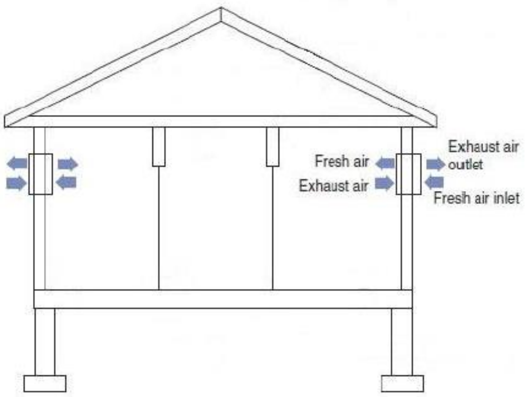


Figure 12: Principle of placement of Pair-Wise DV, section of a building (Magagna, 2016)

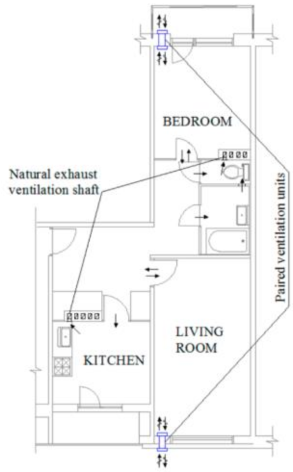


Figure 13: Principle of placement of Pair-Wise DV, plan view (Mikola et al., 2019)

2.8 Single-unit, recuperative DV system

The second type of DV analysed in this study is Single-Unit DV. As the name suggests, this type consist only of one unit placed by the façade or roof of a building, often sticking out into the room taking its space. This type of DV differs from Pair-Wise in couple ways. Firstly, it is often equipped with bigger centrifugal fans or higher number of them which enables it to deliver higher airflow rates. Another thing is its heating and cooling capabilities as it is often equipped with both heating and cooling coils. (Baldini et al., 2014) Therefore Single-Unit can regulate temperature of incoming air to the room. Some models are also able to control and extract heat from moisture and phase change of cooling fluid such us water. (M. Beccali, 2019)

Heat exchanger in Single-Unit DV here described is of type recuperative cross heat exchanger, as shown on *Figure 14*. It has often better performance than small regenerative HRU in Pair-Wise models. SFP of the fans installed in DV-S are also lower than in DV-P. (Merzkirch et al., 2017).

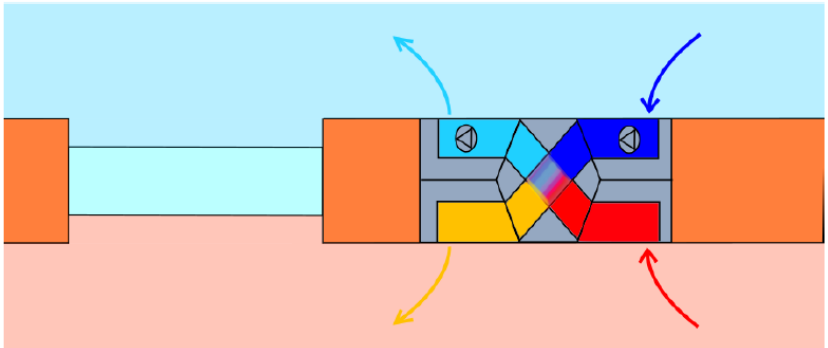


Figure 14: Principle of installation and function of Single-Unit DV installed in a building's façade (Strand, 2021).

2.9 Air pressure difference and the performance of DV

Both Pair-Wise (DV-P) and Single-Unit (DV-S) decentralised ventilation units are to be installed in the external wall of the building. This means that both units are being influenced by the pressure difference between inside and outside. Based on literature research, it has been found that both stack effect and wind-driven airflow affect performance of ventilation units with smaller fans and that single-room decentralised units. (A. Acred, 2016; Kalamees, 2010; Khoukhi, 2007, 2011). Strongly connected to air pressure is air temperature which enhances the buoyancy effects and in turn stack effect. According to the studies performed in Baltic Countries, air-tight buildings suffer bigger air-pressure differences during heating season when the outside air is much colder then inside air. (Mikola et al., 2019)

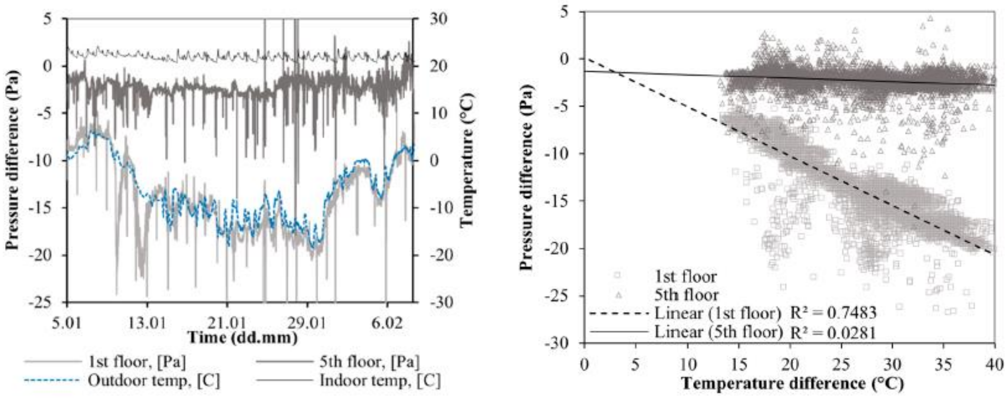


Figure 15: 1st and 5th floor of residential apartment building. On the right: Pressure difference (measured) between indoor and outdoor. On the left: Pressure conditions and indoor/outdoor temperature.(Mikola et al., 2019)

2.10 Residential aspect of DV system

DV systems are a viable solution for existing residential buildings, as a matter of retrofitting strategy (J. Zemitis, 2020; Rose et al., 2022) as well as new housing that shall be built within contemporary building code (M. Beccali, 2019). Common aspects that shall be investigated when designing a DV system in a residential building are climate and location, building envelope, size of the apartment, its geometry, occupancy profiles and internal gains. (Coydon et al., 2015) Since the DV units are to be placed within the interface between inside and outside there should be put extra care on surrounding buildings, immediate air pollution right outside and availability of façade in terms of installation space. (M. Beccali, 2019)

Norwegian building code TEK17 states requirements on minimal ventilation airflows that should ensure necessary air exchange rate given building envelope tightness and geometry of the residential areas. In chapter 3 a relevant study and calculation of these prerequisites is performed. Moreover rooms such us kitchen and bathroom require separate treatment due to the moist nature of air that is present there, in comparison to rooms such as bedroom, entrance and living room. (Sturla Ingebritsen, 2019b)

Placement of DV units is important since often the intake, supply, return, and exhaust units are placed in the same place all together or in near vicinity of each other. Use of ducts is possible to redirect airflows and ensure that fresh and used air don't mix, but this would take from space saving advantages of DV system. (Zender – Świercz, 2020)

Following principles of centralised ventilation design, fresh air intake and exhaust of used air should not be place in a way that can lead to short-circuit between them. (S. Ingebritsen, 2019) It is challenging with DV design but by using finned structures that separate in- and outflows of air within a DV unit itself, a satisfactory solution can be obtained and therefore sustainable levels of indoor air quality can be assured by using smaller, decentralised units in residential context. (Silva et al., 2017)

Advantages of using DV system in residential buildings is its flexibility, both when it comes to installation and use. Automation solution can be easily implemented and the service of the units is comparatively less complicated and with easier access to key components. (Coydon et al., 2015) Field studies on DV system showed that keeping CO_2 and temperature level within required values is well within reach if DV ventilation systems (Sassi, 2017) so indoor climate aspect shall not be of concern.

When it comes to downsides of DV system one needs to consider worse HRU performance in comparison to ones installed in CV systems. Airflows that flow through decentralised units are smaller than those that big air handling units supply. That, together with the fact that heat exchangers in CV AHU are most often bigger lead to higher HRU efficiencies overall. (F. Liu et al., 2022) Another problem that often apartments with DV systems, especially in colder climates experience is downfall of pressure due to pressure differences between inside and outside. So called stack effect occurs on lower floors of buildings that cause the DV units equipped with regenerative HRU axial fans to stop functioning when the pressure difference is too high. (Mikola et al., 2019)

As described in Building detail 552.305, chapters 31-33 and 41-43 on Byggforskserien (SINTEF, 2017b), there are also challenges around servicing and maintenance. Having several ventilation units in one apartment means that occupants/users must spend more time on taking care of the components such us filters and fans. Moreover, noise can be a problem with DV units placed in direct vicinity of occupants at all times. Lastly, worth mentioning are problems with condensation on the fresh air intake side that are only multiplied when freezing temperatures occur.

Frosting problems are not described in detail in this study. This is a real challenge though, for both CV and DV systems and shall be dealt with accordingly to setup of choice. (Gendebien et al., 2019) A presentation of non-ducted DV systems with defrosting solutions present in Norwegian marked will be shown in Methodology section.

2.11 Building code TEK17 and compliance testing

Lastly, in theoretical background section, question of evaluation of energy performance is discussed. In Norway the main regulatory body DiBK (Direktoriatet for Byggkvalitet) is responsible for issuing the Regulations on technical requirements for construction works, so called TEK17. This building code "*to ensure that projects are planned, designed and executed on the basis of good visual aesthetics, universal design, and in a manner that ensures that the project complies with the technical standards for safety, the environment health and energy.".(DiBK, 2017).*

For this thesis, the most important part of the regulations is the energy requirement stated for residential building, and according to paragraph *§ 14-2. Krav til energieffektivitet* (Energy efficiency requirements) it is 95 kWh/m2/gross areal/year. Simultaneously, requirements stated *in § 14-3. Minimumsnivå for energieffektivitet* (Minimal level for energy efficiencies) must be fulfilled (building envelope). There is, though, a room for flexibility. According to § 14-2. (2) it is possible to disregard partly when designing a building with natural or hybrid ventilation, as long as overall heat loss coefficient (*varmetapstall*) does not increase.

The today's standard NS3031 that is being mentioned in TEK17 has been withdrawn by the publishing body Standard Norge as of 01.10.2017 and replaced by new standard SN-NSPEK 3031:2021. Despite NS3031 being withdrawn, it shall continue to be used when controlling compliance to TEK17, The Norwegian energy label scheme (*Energimerkeordningen*), BREEAM NOR and passive house standards NS3700 and NS3701.

This new approach that can be based on more realistic set of rules presented in SN-NSPEK 3031:2021enables for accounting for distribution and regulation losses which in turn gives a more truthful picture of the energy consumption of the building. (Sæter, 2021) In general NS3031 focuses only on the net delivered energy, while SN-NSPEK 3031:2021 uses delivered energy. Another aspect is that only Oslo climate is used as a reference for NS3031 calculations, ignoring the vast variation in local climate across Norway. Another simplification regards internal heat gains and schedules that are simplified in NS3031 method.(VKE, 2021)

3 Methodology

3.1 Introduction to the methodology chapter

This thesis' scope is primarily a comparison of energy consumption between different ventilation systems: centralised and decentralised. To build the simulation framework and different models a step-by-step strategy has been chosen that works in an iterative way. First an overall, whole building's simulation model in SIMIEN has been created in order to find a "starting point" for further simulations.

This model has been used to find the parameters for building envelope that ensure validation according to TEK17. In *Appendix F*, a detailed overview of both simulation files with corresponding parameters and an iterative process of aligning the IDA-ICE model with the one from SIMIEN is shown.

As shown in *Figure 16*, a building on the left-hand side was used as a basis for TEK17 done in SIMIEN where a simplified, single volume zone was used for TEK17 evaluation using standard values from NS3031 set as defaults: local climate, constant heat gain values, etc.

On the left-hand side on the same *Figure 16* a building consisting of 4 zones (one zone per floor) has been created for TEK17 § 14-2 evaluation in IDA-ICE. This is a simulation with a set of simplifications and changes done to bring it closer to the SIMIEN model, see *Appendix F* for details as how it was done. The changes and assumptions regarded, among other things, local climate, constant heat gains, SFP, heat recovery, system losses and more.

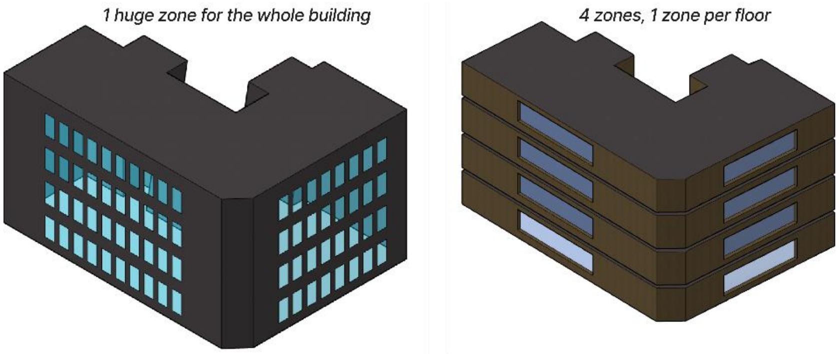


Figure 16: 3D views of whole building simulations done in SIMIEN (on the left) and in IDA-ICE (on the right)

After the models for whole building have been evaluated and fulfilled TEK17 energy requirements, a model consisting of 3 separate models in IDA-ICE was created. <u>This was done to model Centralised Ventilation system so that one AHU serves 3 apartments at the same time</u>, <u>supplying and extracting air from all zones.</u> In *Figure 17* an illustrative representation of the model file is shown. The whole model had 14 zones in total, please see *Table 6* for an overview over zones and their areas.

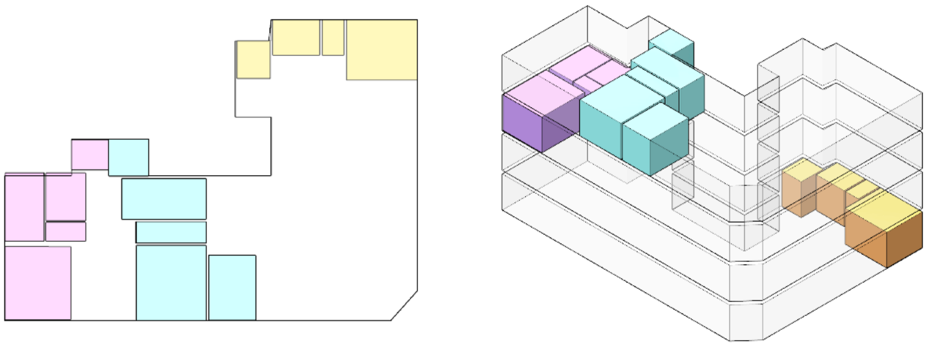


Figure 17: 2D and 3D view of the IDA-ICE model consisting of 3 apartments for CV simulation purposes.

Next, there were created separate files for 3 apartments: 0_BOT (smallest, bottom apartment on the 1st Floor), 2_MID (middle apartment, on the 2nd Floor) and 3_TOP (top apartment, placed on the 3rd floor). In these files, DV units are placed in the chosen rooms (zones) only. 3D views of the apartment within the body of the building can be seen in *Figure 18*, while the 2D plans *Figure 19*.

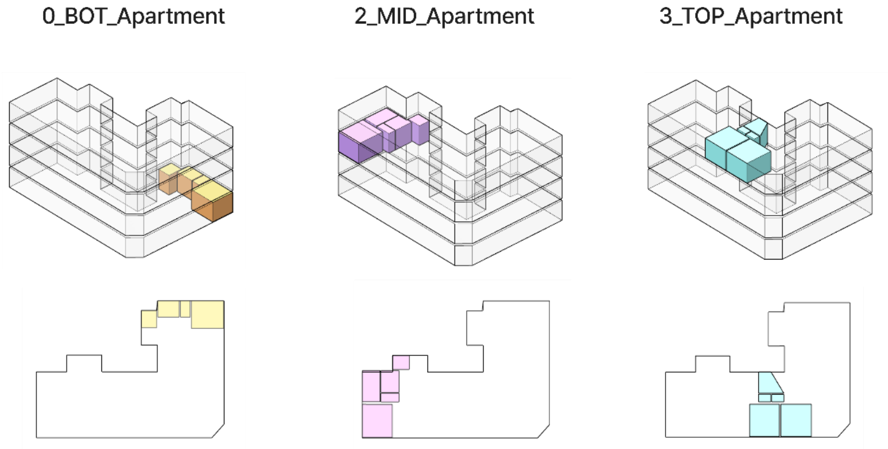


Figure 18: 3D views of the apartments within the building body.

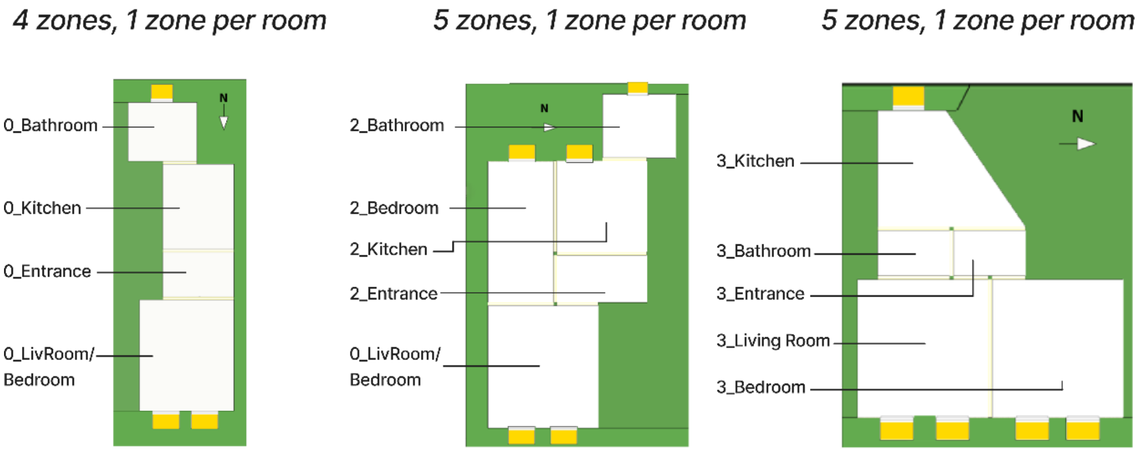


Figure 19: 3D and plan views of 3 separate apartments in IDA-ICE.

3.2 Building requirements and data collection

The first step in modelling the building and apartments was to gather knowledge about applicable building requirements according to Norwegian law. Building code TEK17 for residential building has been used to establish leading guidelines in terms of energy, building construction and indoor climate. Total net energy demand expressed in kWh/m2 of usable area per year for this type of building is 95,00, according to TEK17 § 14-2. U-values for the construction envelope has been chosen to be better than what is required. Detailed list over requirements can be seen in *Table 2*, which shows requirements from TEK17 with reference to NS3031 and SN-NSPEK 3031:2021. In the last column, the chosen U-values are presented.

BOLIGBLOKK - REQUIREMENTS					
CONSTRUCTION TYPE, U-VALUES		**TEK17 NS3031: Minstekrav**	**TEK17 NS3031: Energitiltak**		**Choosen construction**
Source: TEK17 § 14-3					
External walls	[W/m²K]	≤ 0,22	≤ 0,18		0,14
Internal walls	[W/m²K]	-	-		0,53
Internal floors	[W/m²K]	-	-		0,16
Roof	[W/m²K]	≤ 0,18	≤ 0,13		0,09
External floor	[W/m²K]	-	-		0,10
Basement wall towards ground	[W/m²K]	-	-		0,22
Slab towards ground	[W/m²K]	≤ 0,18	≤ 0,10		0,10
Glazing	[W/m²K]	≤ 1,2	≤ 0,80		0,77
Door construction	[W/m²K]	≤ 1,2	≤ 0,80		0,77
Integrated window shading	[W/m²K]	-	-		1,00
Normalised thermal bridges	[W/m²K]	-	≤ 0,07	For "boligblokk"	0,03
Infiltration, 50 Pa pressure diff	[W/m²K]	≤ 1,5	≤ 0,6		0,50
Proportion of window, door area to heated area	[%]	-	≤ 25%		9,40
HEAT RECOVERY, SFP		**TEK17NS3031**			**Comments**
Source: TEK17 § 14-2.					
Annual average temperature efficiency for heat recuperators in ventilation systems	[%]	≥ 80%			
SFP	[kW/m3/s]	≤ 1,5			
VENTILATION AIRFLOWS		**TEK17 NS3031**		**SN:NSPEK 3031:2021**	**Comments**
Source: Table A.6. NS 3031					
For apartments Area ≥ 110m2					
Minimum required airflow while room is in use	[m3/h/m2]	1,2		1,2	
Minimum required airflow while room <u>is not</u> in use	[m3/h/m2]	1,2		1,2	
For apartments Area < 110m2					
Minimum required airflow while room is in use	[m3/h/m2]	1,6 - 0,007 * (Area - 50)		1,6 - 0,007 * (Area - 50)	Apartment < 110m2
Minimum required airflow while room <u>is not</u> in use	[m3/h/m2]	1,6 - 0,007 * (Area - 50)		1,6 - 0,007 * (Area - 50)	Apartment < 110m2
ENERGY		**TEK17 NS3031**			**Comments**
Source: TEK17 § 14-2.					
Energy frame for "Boligblokk"	[kWh/m2]	95			

Table 2: Building and indoor climate requirements according to Norwegian norms and standards for residential buildings

Climate, weather, location

There have been used three types of climate data files in this thesis, depending on the simulation. *Table 3* shows the overview of simulation files with the corresponding building code or standard used, number of zones in the simulation file and the program that run the given simulation. Please not that there were 3 distinct IDA_ICE simulation files for "Apartment simulations". This will be described in later sections.

Overview simulation files				
Simulation file	**Simulation type**	**Building code, standard**	**Number of zones**	**Program**
Building_SIMIEN	Whole building simulation	TEK17, NS3031	1 zone for the whole building	SIMIEN
Building_IDA	Whole building simulation	TEK17, NS3031	1 zone for the whole building	IDA-ICE
0_BOT, 2_MID, 3_TOP	Apartment simulations	NS-NSPEK 3031:2021	1 zone per room, 14 zones	IDA-ICE

Table 3: Overview of simulation files.

Table 4 on the other hand gives an overview of different climate files used in each simulation file, together with other details like wind profile, shading, holidays used for scheduling. Each of these climate files will be described in this section as there are differences between them.

First, a whole building simulation performed in SIMIEN used a synthetic climate file, *Oslo.dat* downloaded from the SIMIEN database. Second file comes from ASHRAE database and is used as a default Oslo climate file in IDA-ICE, it is *NOR_OSLO-GARDERMOEN_013840_IW2.PRN*. The third file comes from outside of the built-in database of IDA-ICE, namely EPW climate file *NOR_Oslo_Blindern_1992-2014.EPW*. The latter one consists of meteorological data for building energy simulation, based on 11 years of observations (2003-2013). File has been generated by program EPW-Gen by P.G.Schild, based on EN-ISO 15927-4.

Values have been adjusted to fit CDF for all years. Cumulative Distribution Function (CDF) is a technique used in order to adjust temperature values between the ends of the duration curves for the whole of analysed period (20 years). Such continuous transition between periods makes it more suitable for average energy consumption calculations. It is in contrast to the method advised by ISO standard EN-ISO 15927-4 that recommends flattening out the curves instead of incorporating them in the climate file.(Artyukova, 2021)

A comparison between the different climate files is presented in *Figure 20*. Daily averaged dry-bulb temperature variations for the synthetic SIMIEN file (orange colour), ASHRAE IDA file (blue) and Oslo-Blindern updated EPW file (yellow) is shown. From that we can see that both SIMIEN and ASHRAE file overestimate colder temperatures in comparison with the EPW file. See *Appendix E* for detailed view of three distinct climate files diagrams showing dry-bylb temperature variation.

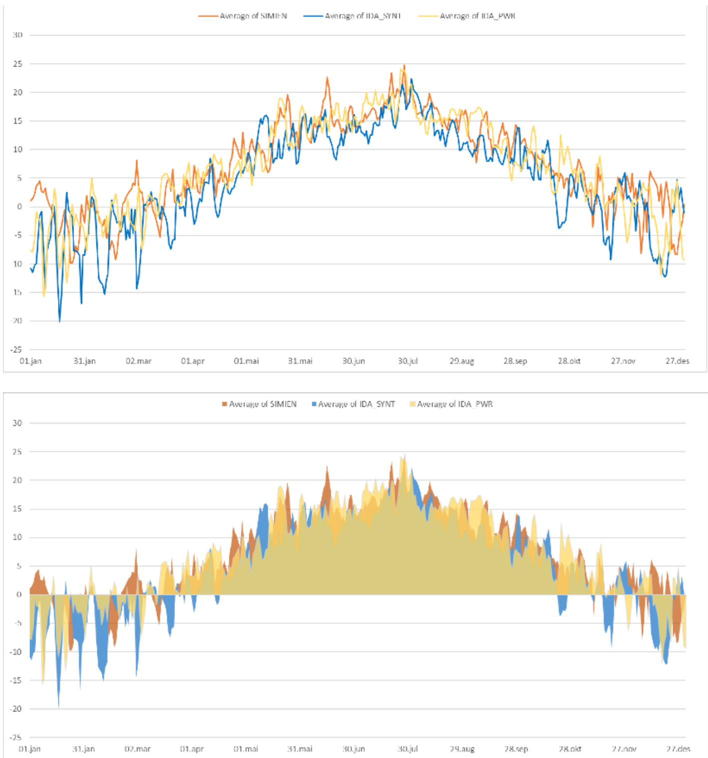


Figure 20: Yearly dry-bulb temperature variation, comparison of three different weather files: SIMIEN, IDA-ICE synthetic and IDA-ICE PWR file.

Figure 20 gives an overview over parameters like location, climate, wind profile, shading and holidays used in different simulations.

Location and climate			
Parameter / file	**Building_SIMIEN**	**Building_IDA**	**0_BOT, 2_MID, 3_TOP**
Location	Oslo	Oslo	Oslo
Climate	Oslo, synthetic climate file	Oslo ASHRAE Database	Oslo-Blindern PWR Climate File
Wind profile	"Mer en vind utsatt fasade"	City centre	City centre
Shading	"Moderat skjerming"	Realistic shading, central Oslo	Realistic shading, central Oslo
Holidays	Public holidays in Sweden	Public holidays in Sweden	Public holidays in Sweden

Table 4: Overview of climate files, location, wind profiles, shading and holidays.

Site shading, orientation, and background for floor plan

Orientation of the building has been based on an existing building located in Oslo at Fossveien. In *Figure 21* building together with shading is shown as modelled in IDA-ICE and *Figure 22* show satellite view of the existing building and apartment that the model has been based on. The original orientation of the building has been preserved in the simulation as well.

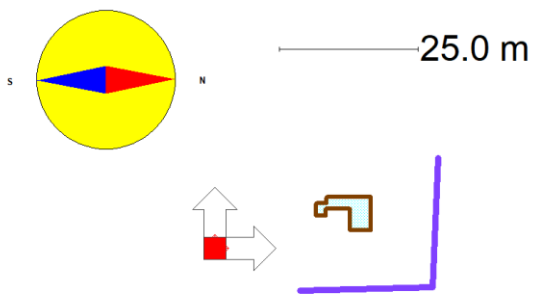


Figure 21: Site shading and orientation, IDA-ICE. Apartment in blue, shading in purple.

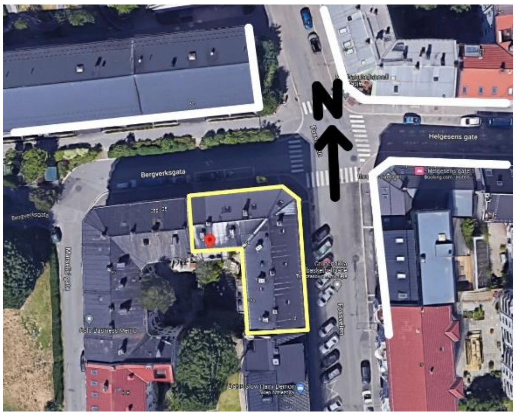


Figure 22: Picture from satellite view of Google Maps showing the existing building in question. North direction to the right. Yellow: building boundary. Blue: apartment boundary.

Floor plan of the modelled apartment took also starting point at the existing plan drawings found on the Norwegian building directorate database. Plan drawing in question is shown in *Figure 23*. Using the old plan drawing was done in order to set the simulation in terms of a rehab project.

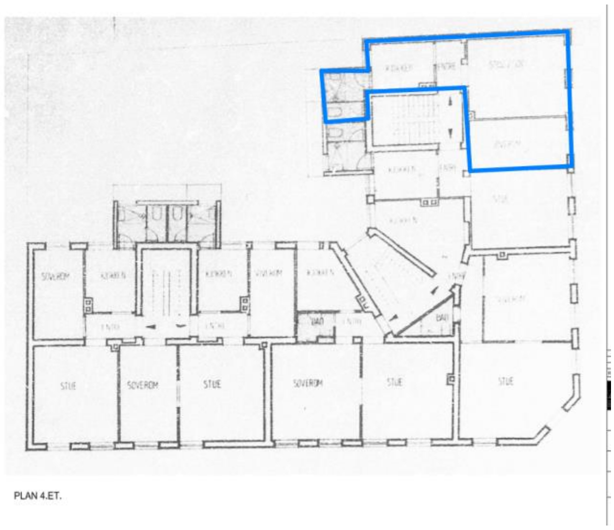


Figure 23: Plan drawing of the 4th floor of building at Fossveien 16. Modelled floor plan was based on this drawing. Blue stroke shows the 0_BOT apartment.

3.3 Modelled zones

Zones' geometry and boundary conditions

For the whole building there were two approaches for modelling zones: SIMIEN building was modelled as one big zone for the whole thing, in IDA-ICE each floor was modelled as different zone in the case of separate simulation for apartments, each room has been modelled as a separate zone and zones' geometry has been based on actual apartment plan of a typical residential housing block in Oslo, as described earlier. The same applies to internal and external openings, which are façade windows and internal doors. External doors, which is doors leading to stair-cases have not been modelled. Overview of the whole building's geometry together with 3D and 2D plan view can be seen in *Table 5*.

Geometry

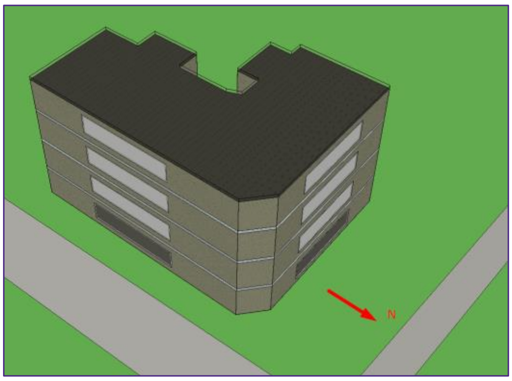
WHOLE BUILDING

BUILDING		
Floor height	[m]	2,60
Slab height	[m]	0,31
Number of floors	[-]	4,00
Floor area per floor	[m2]	360,90
Total height of the building	[m]	11,32
Total heatead area in the buildir	[m]	1 443,60
Building perimeter	[m]	96,60
Heated air volume	[m3]	3 753,36

FLOORS	Floor height above the	Ceiling height above
0_Bottom_Floor	0,00	2,60
1_Mid_Floor	2,91	5,51
2_Mid_Floor	5,82	8,42
3_Top_Floor	8,72	11,32
Roof	*11,32*	*11,63*

BUILDING TYPE	Boligblokk, rehab

FACADES	Wall area [m2]	Windows area [m2]	To	Wall area per floor [m2]	Wall length [m]
North	215,88	69,20		71,27	22,27
East	254,23	77,84		83,02	25,94
South	268,39	-		67,10	20,97
West	359,83	-		89,96	28,11



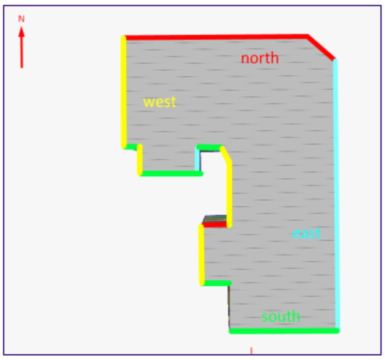


Table 5: Whole building's geometry with 3D and plan view.

For three apartments there has been modelled 14 zones in total, one zone per room. Specification on various zones' geometry parameters is shown in *Table 6*.

Zone (room)	Area [m2]	Zone (room)	Area [m2]	Zone (room)	Area [m2]
0_LivRoom/Bedroom	15,78	2_Bath	6,13	3_Bedroom	20,80
0_Entrance	4,82	2_Kitchen	10,78	3_LivingRoom	17,71
0_Kitchen	9,11	2_Entrance	5,56	3_Bath	5,83
0_Bath	6,09	2_Bedroom	12,12	3_Entrance	5,88
		2_LivingRoom	17,71	3_Kitchen	13,91
TOTAL Bottom Apartment	**35,81**	**TOTAL Middle Apartment**	**52,31**	**TOTAL Top Apartment**	**64,13**

Table 6: Zones' and apartments' areas.

Description of the apartments

0_BOT, Bottom Apartment is located on the 1st floor. Living Room has windows facing north, entrance is in the middle without any windows and kitchen and bathroom has one window each facing south. 2_MID is the apartment placed on the 2nd floor with windows in living room facing east, while the ones located in bedroom, kitchen, and bathroom face west. The last apartment, 3_TOP, located in 3rd floor is the biggest of them all. In both living room and bedroom windows face east, while in bathroom and kitchen, west. Each apartment has a long plan solution characteristic for old block of flats in Grünerløkka, Oslo.

Zones' setpoints

Temperature setpoints can be seen in *Table 7*. Aforementioned values have been applied to all zones globally in IDA ICE. In *Table 8* setpoints for CO_2 are presented. TEK17 and NS-EN ISO 7730:2005 were used as basis for the requirements.

When it comes to Adaptive Thermal Comfort model, only a limited study on broader spectrum of operative temperatures has been done. As will be presented in the results section, based on the simulation the number of hours in a year where temperature exceeded 25 °C was noted. This is to say that only one set of temperature setpoints was used, based on NS3031 and SN:NSPEK 3031:2021.

SET POINTS FOR HEATING AND COOLING		TEK17 NS3031	Comments	SN:NSPEK 3031:2021
Source: Table A.3 NS3031 & Table A.9. SN-NSPEK 3031:: Source: Table A.3 NS3031 & Table A.9. SN-NSPEK 3031:2021				
When in use	[Celsius]	21		22
When not in use	[Celsius]	19		22
Set point for cooling	[Celsius]	-		24

Table 7: Temperature setpoints for all zones in IDA-ICE.

Parameter	Value	Source
CO2, upper	1000 ppm	TEK 17
CO2, lower	400 ppm	Default value IDA-ICE

Table 8: CO_2 setpoints for all zones.

Occupancy profile, IDA-ICE

Occupancy profile, shown in Table 9, was chosen from a list of defaults in IDA-ICE. It assumes working week from Monday to Friday between 9:00 and 15:00. While at work occupancy is set to 0. From 15:00 to 17:00 it ramps up to 50% and is set to 100% all other times. Simulations consider holidays based on Swedish calendar that resembles the Norwegian one on an acceptable level.

Day of the week	Time	Occupancy	Occupancy
Monday-Friday	0-8	100 %	100 %
Monday-Friday	9-15	0 %	0 %
Monday-Friday	15-17	50 %	50 %
Monday-Friday	18-24	100 %	100 %
Saturday, Sunday	0-24	100 %	100 %

Table 9: Occupancy profile "Apartment living" used in simulation.

Room units, IDA-ICE

In IDA ICE each zone has been equipped with room units, so called Ideal Heaters and Ideal Coolers. It was done to ensure sufficient heating and cooling load. Ideal units in IDA-ICE supply the necessary load, either cooling or heating until the setpoint temperature for a given zone is reached or the capacity of the ideal unit has been used.

It is also possible to program other criteria that should be satisfied for it, but these were not used in this study. It has been chosen to apply 2000W for heating and cooling, respectively and the control between zone and setpoint temperature is controlled by PI controller, as shown in *Table 10*.

Room units in zones

Unit	Capacity [W]	COP [-]	Controller [-]
Ideal heater	2000,00	1,00	PI
Ideal cooler	2000,00	3,00	PI

Table 10: Specification of room units in zones.

Internal gains, IDA-ICE

Internal gains were specified in two ways: simplified, based on NS3031:2020 for the whole building simulation, and based on SN-NSPEK 3031:2020 for the sperate apartments. It has been assumed typical equipment setup in the given rooms. Typical values for specific heat gain from light, equipment and occupancy have taken from NSPEK 3031:2020 and applied to the zones based on their areas. Comparison between NS3031 and SN-NSPEK can be seen below in *Figure 24*. Resulting internal gains for whole building simulation are shown in Table 11 and for the separate apartments in *Table 12*.

Both schedules from SN-NSPEK 3031:2020 and internal gain values from *Table 12* were used in all simulations presented in this thesis for separate apartments.

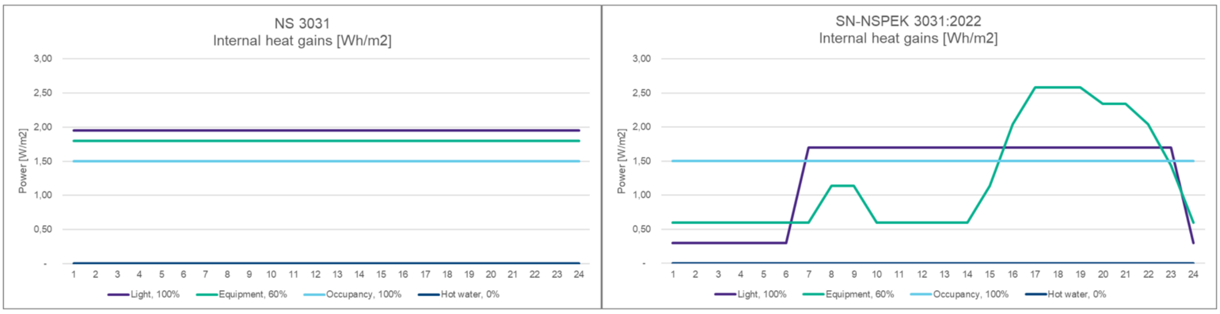


Figure 24: Internal heat gains, comparison between NS3031 and SN-NSPEK 3031:2022.

Heat gains based on NS3031					
For the whole building, TEK 17 evaluation					
Average value: 100% / 60% / 100%		*1,95 [W/m2]*	*1,80 [W/m2]*	*1,50 [W/m2]*	
Zone (floor)	**Area [m2]**	**Lighting [W]**	**Equipment [W]**	**Occupancy [W]**	These values have to be calculated from Area specific heat value (TEK17 requirement), to "Heat gain for the whole floor" given in [W] and finally to "Heat gain for a single unit" given in [W] for IDA-ICE
0_Bottom_Floor	360,90	703,76	649,62	541,35	
1_Mid_Floor	360,90	703,76	649,62	541,35	
2_Mid_Floor	360,90	703,76	649,62	541,35	
3_Top_Floor	360,90	703,76	649,62	541,35	
Totals	**1 443,60**	**2 815,02**	**2 598,48**	**2 165,40**	

Calculations of internal gains for IDA-ICE purposes, constant values					
Light		**Equipment**		**Occupancy**	
Units / apartment [pc]	6,00	Units / apartment [pc]	3,00	People / apartment [pc]	3,61
Apartments / floor [pc]	6,00	Apartments / floor [pc]	6,00	Apartments / floor [pc]	6,00
Units / floor [pc]	36,00	Units / floor [pc]	18,00	People / floor [pc]	21,65
Power / units [W]	**19,55**	**Power / units [W]**	**36,09**	**Power / people [W]**	**100,00**
Mean power / floor [W]	703,76	Mean power / floor [W]	649,62	Mean power / floor [W]	2 165,40
Mean power / building [W]	2 815,02	Mean power / floor [W]	2 598,48	Mean power / floor [W]	8 661,60

Table 11: Internal heat gains for the whole building simulation. SIMIEN and IDA-ICE.

Heat gains based on SN:NSPEK 3031:2021					
For the 3 chosen apartments, 14 zones in total, variable values according to schedules					
	Requirement: 100% / 60% / 100%	1,70 [W/m2]	1,55 [W/m2]	1,50 [W/m2]	
Zone (room)	**Area [m2]**	**Lighting [W]**	**Equipment [W]**	**Occupancy [W]**	**Totals heat gains per apt**
0_LivRoom/Bedroom	15,78	26,83	24,43	23,67	
0_Entrance	4,82	8,19	7,46	7,23	
0_Kitchen	9,11	15,49	14,11	13,67	
0_Bath	6,09	10,36	9,43	9,14	**170,01**
TOTAL Bottom apartment	**35,81**				
2_Bath	6,13	10,43	9,49	9,20	
2_Kitchen	10,78	18,33	16,69	16,17	
2_Entrance	5,56	9,46	8,61	8,35	
2_Bedroom	12,12	20,60	18,76	18,18	
2_LivingRoom	17,71	30,11	27,42	26,57	**248,35**
TOTAL Middle apartment	**52,31**				
3_Bedroom	20,80	35,36	32,20	31,20	
3_LivingRoom	17,71	30,11	27,42	26,57	
3_Bath	5,83	9,91	9,03	8,75	
3_Entrance	5,88	9,99	9,09	8,81	
3_Kitchen	13,91	23,65	21,53	20,87	**304,47**
TOTAL Middle apartment	**64,13**				

Table 12 Internal heat gains, separate apartments, IDA-ICE.

3.4 Windows, shading and external surfaces

Modelled apartments were designed including openings: façade windows and internal doors. In *Figure 25* the three apartments are shown with windows (blue rectangles) and internal doors (double-sided arrows between rooms).

Windows in kitchens, bedrooms and living rooms are of same dimension: 1m in width and 2 m high. Windows in bathrooms are smaller: 0,8m in width and 0,4 in height. All glazing has U-value of 0,77 W/m2*K and the same values for other related parameters such us g-value, transmittance, reflectance, and emissivity. Exemplary window set-up be seen in *Figure 26*.

Comment on Adaptive Thermal Comfort and "without cooling" (EN-15251) description

Adaptive Thermal Comfort aspect expressed as "without cooling" can be misleading. Thus, a short clarification about that is made in this section.

All systems have been modelled and simulated with window airing enabled, as can be seen in *Table 20* have window airing. Therefore, when using term "without cooling", it is to understood that it comes directly from IDA-ICE nomenclature and its purpose is to express wider acceptability of occupants in terms operative temperature spectrum. It should be noted that this is in part a discrepancy between the proper method and the one used in this thesis. A valid way to perform the simulation would be to not allow CV, DV-P and DV-S to use openable windows and make them purely mechanical ventilation systems. Then, to the opposition of mechanical systems, a NoAHU-natural ventilation system should be introduced.

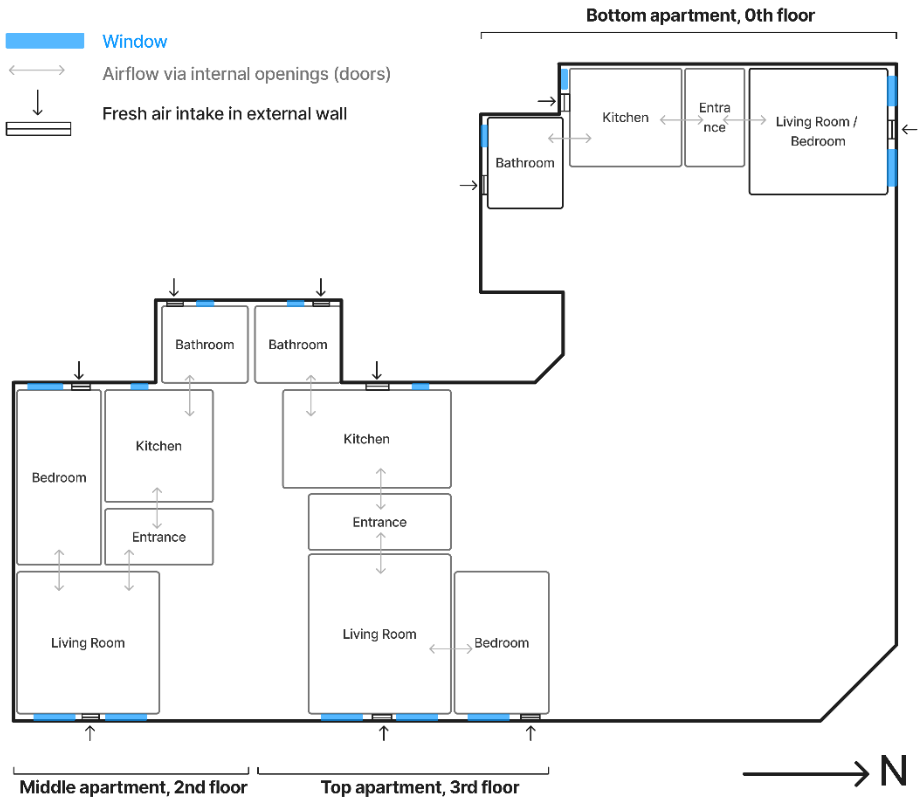


Figure 25: Plan view of 3 separate apartments.

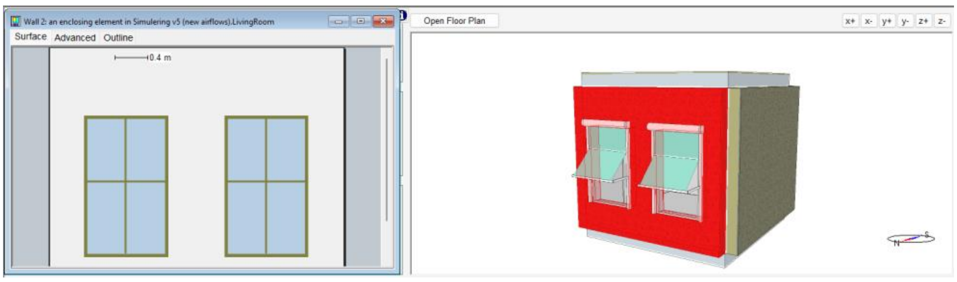


Figure 26: Exemplary wall with facade windows. Here: Living Room. IDA-ICE.

All façade windows have been equipped with integrated, external shading of type *Markisolette*, default, generic type of shading from IDA-ICE database. For the purposes of the simulation there has been used an automatic control based on previously mentioned schedule *Apartment living*. Shading control is in addition controller by PI temperature controller, as shown in *Figure 27*.

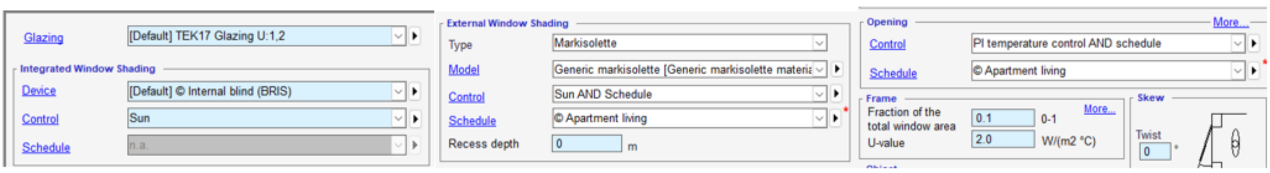


Figure 27: Window opening and shading control settings in IDA-ICE.

Internal doors' opening is also controlled by schedule *Apartment living*. That means that when there are occupants in the apartment, all doors are opened allowing airflow between zones. This also implies that doors to the bathroom are always opened under occupancy, which will be discussed later.

3.5 Calculation of required airflows

NoAHU – Natural ventilation airflows

In IDA-ICE, "No central AHU" alternative has been chosen to simulate natural ventilation conditions. Openable windows have been enabled, as it was described in previous section and standard values for infiltration has been used, as also described earlier. In order to validate amount of air flowing in and out of the zones, an analysis has been performed and compared with averaged measured results taken from national Norwegian research on residential ventilation (Schild, 2002). As we can see in *Figure 28*, blue horizontal line indicates air exchange rate averaged across all 14 zones in simulation file that is much lower than what is an average for Norwegian residential buildings with natural ventilation. This means that modelled NoAHU scenario has too low air exchange rate. Unfortunately, due to time-constraints, NoAHU model wasn't optimized based on the result of this comparison. Solution to that could be implementing fresh air intakes (exterior wall grilles), as presented in *Appendix P*. Please not that these grilles were finally not implemented in the NoAHU model.

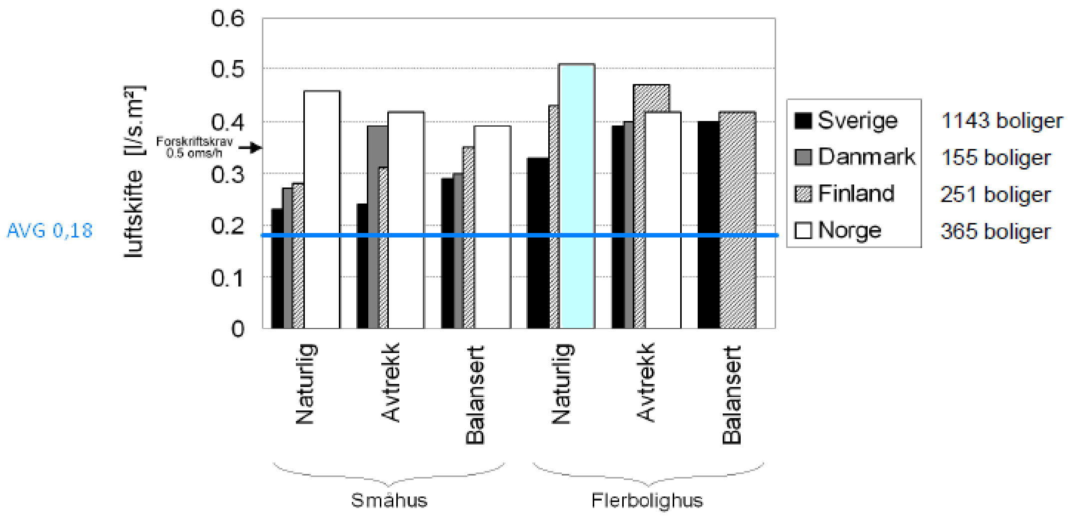


Figure 28: Comparison between measured average air change rate from project report and simulation. Light blue column is natural ventilation for block of flats, residential. Blue horizontal line is average value across all 14 zones for simulated NoAHU system.

CV, DV, DV-P airflows

To calculate how much airflow is needed in the modelled apartment, a modified version of "A+B+C" method from Byggforskserien 552.301 has been implemented. (SINTEF, 2017a). Normally used for offices and other public buildings, for the purpose of this thesis, it will be called "Max(A+B+C)" Apartments have been divided into rooms, from which, according to the method, corresponding requirements have been set. As can be seen in *Table 13* required airflows for normal, forced and "forced + kitchen hood" ventilation have been established.

In case of, for example, apartment 0_BOT normal ventilation airflow for the apartment is 90 m^3/h. Minimum airflow that has to be supplied to the bedroom is then 52 m^3/h. Remaining airflow that can be supplied to either Living Room or Bedroom is 38 m^3/h. Required extract during forced ventilation in kitchen and bathroom at the same time is 108 m^3/h and simultaneous forced extract is 394 m^3/h at the highest. Required dimensioning internal is then from 90 to 394 m^3/h, that is ventilation system should be capable of delivering these airflows, according to Byggforskserien 552.301(SINTEF, 2017a).

Airflows "MAX(A+B+C)" method	*Based on: Byggforskserien 552.301 (A+B+C method)*					
Airflows calculation						
Zone	**Area**	**Required airflow when the zone is occupied** ***1,44 m3/h/m2***	**Required supply airflow in the bedroom** ***26 m3/h/bed***	**Required extract, normal ventilation**	**Required extract, forced ventilation**	**Required extract, forced ventilation, kitchen hood +250m3/h**
[-]	[m2]	[m3/h]	[m3/h]	[m3/h]	[m3/h]	[m3/h]
0_LivRoom/Bedroom	15,78	22,72	52,00			
0_Entrance	4,82	6,94				
0_Kitchen	9,11	13,12		36,00		286,00
0_Bath	6,09	8,77		54,00	108,00	108,00
Totals, apartment 0_BOT	**35,81**	**51,56**	**52,00**	**90,00**	**108,00**	**394,00**
Totals [l/s]		14,32	14,44	25,00	30,00	109,44
2_Bath	6,13	8,83		54,00	108,00	108,00
2_Kitchen	10,78	15,52		36,00		286,00
2_Entrance	5,56	8,01				
2_Bedroom	12,12	17,45	52,00			
2_LivingRoom	17,71	25,50				
Totals, apartment 2_MID	**52,31**	**75,32**	**52,00**	**90,00**	**108,00**	**394,00**
Totals [l/s]		20,92	14,44	25,00	30,00	109,44
3_Bedroom	20,80	29,95	52,00			
3_LivingRoom	17,71	25,50				
3_Bath	5,83	8,40		54,00	108,00	108,00
3_Entrance	5,88	8,46				
3_Kitchen	13,91	20,03		36,00		286,00
Totals, apartment 3_TOP	**64,13**	**92,34**	**52,00**	**90,00**	**108,00**	**394,00**
Totals [l/s]		25,65	14,44	25,00	30,00	109,44

Table 13: Required ventilation airflows based on "A+B+C" method from Byggforskserien 552.301.

Using downdraft kitchen hoods as DV

As shown in *Table 13,* neither CV system nor DV units can deliver required forced airflow for kitchen. As a possible solution, a downdraft kitchen hoods are proposed. According to the latest research and experimental tests, downdraft kitchen hoods are a viable solution, capable of both recirculating and extracting air from above the kitchen tops. When it comes to indoor air capability and capture efficiency (CE), extracting turned out to be more effective, achieving high values of CE around 98%. (Alvestad, 2022) When analysing both energy consumption and capturing efficiency, downdraft hoods perform best with airflows above 108 m^3/h (minimum required forced extraction) reaching the absolute highest efficiency at 250 m^3/h.(Eliassen, 2022).

In this thesis, kitchen hoods were not analysed, nor modelled in IDA-ICE. There is generally an advantage to install kitchen hood extract duct in such a way that it goes through heat recovery system of the air handling unit. That way the heat from air produced over the kitchen top can be recovered.(Thorstensen, 2022) *SINTEF Building detail 361.411* suggests this solution, while at the same time advising against recirculating solutions with carbon filter.

Challenges around forced ventilation and DV in kitchens and bathrooms and possible solutions are going to be discussed in *Chapter 3.9*

3.6 Modelling and dimensioning the decentralised ventilation systems in IDA- ICE

In order to model three distinct systems (centralised and two decentralised) a set of different parameters has been established and used IDA-ICE, based on literature and previous research. "Standard Air Handling Unit" from IDA-ICE was a starting point. Both Pair-Wise and Single-Unit systems have been derived from it. Difference between centralised and decentralised ventilation systems are summed up in *Table 14*.

Information about specific fan power (SFP), that is a measure of energy used for moving air through, has been gathered from research done in Baltic countries (Estonia, Finland) where thorough studies on decentralised ventilation systems have bene performed. The same applies for research on heat recovery units present in both Pair-Wise and Single-Unit DV. (A. Merzkirch, 2015; Bonato et al., 2020; J. Zemitis, 2020; Mikola et al., 2019)

When it comes to effect of differential pressure across the wall, studies performed by A. Merzkirch and J. Kurnitski were of most inspiration and help. Finally, Fan Performance curves for axial fan (in case of DV-P) and a centrifugal fan (for DV-S) have been introduced and applied. These can be found in *Appendix G.*

Parameter / System	Centralised	Decentralised Pair-Wise	Decentralised Single-Unit
Specific Fan Power SFP [kW/m3/s]	1	0,23	0,22
Fan curve in IDA-ICE	Default Fixed Head Fan	Fan Performance curve for small axial fan	Fan Performance curve for small centrifugal fan
Type of heat exchanger	Regenerative	Regenerative	Recuperative
Heat Recovery Efficiency [%]	80 %	60 %	80 %
Air temperature rise over the fan [Celsius]	0,5	0	0
Max ventilation airflow rate (heat recovery mode) [m3/h]	Unlimited	50	150
Max ventilation airflow rate (exhaust mode) [m3/h]	Unlimited	50	150
Cooling capacity [W]	Unlimited	None	400
Heating capacity [W]	Unlimited	None	1000
Effect of differential pressure across the wall (DP_Link)	Not applied	Applied for supply and exhaust	Applied for supply and exhaust

Table 14: Overview parameters, differences between CV, DV-P and DV-S.

Starting point – default Air Handling Unit (centralised)

As mentioned before, the Standard AHU from IDA-ICE was used. In *Figure 15* a screenshot from AHU-window in IDA-ICE is presented showing "building blocks" such us schedules that control fans, fan types, heat recovery efficiency and heating- and cooling coil efficiencies set for CV system. *Appendix J* shows details on programming Fixed Head Fan, heating and cooling coils and heat recovery unit.

Standard CV AHU has been modelled as a balanced CAV mechanical ventilation system. See *Table 15* for airflows that have been finally chosen for CV. This AHU

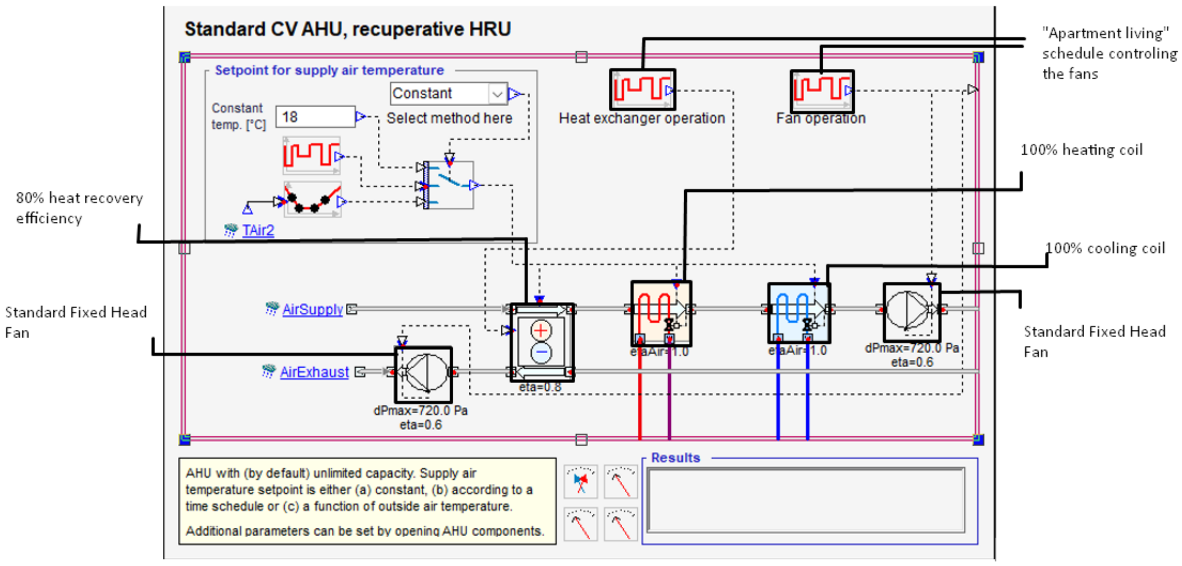


Figure 29: Centralised Ventilation AHU - default IDA-ICE component.

Modelling Pair-Wise DV and airflows strategy

Pair-Wise DV has been modelled as a balanced CAV mechanical ventilation, namely following the same approach as in CV case. It is a simplification that assumes that DV-P units are placed in two far-ends of the apartment supplying and extracting constant volumes of air. The way that was described in chapter 2.5 has not been implemented, since oscillating action of Pair-Wise system is not implemented in IDA-ICE. The system is, in that sense, stationary and does not switch between supply and return periodically. In *Figure 30* it's shown how differently has DV-P been modelled in IDA-ICE.

To start with, heat recovery has been reduced to 60% comparing to CV 80%. It is based on previously mentioned research that heat recovery in DV-P units perform worse than both CV and DV-S. Next, cooling and heating coil have been deactivated, that is their efficiency brought down to 0%. DV-P has, by design, no possibility for integrating auxiliary heating or cooling. Lastly, default Fixed-Head Fans have been switched to so called Fan-Curve fans where it is possible to implement custom Fan Performance curves. For DV-P, a small axial fan curve has been adopted, details can be seen in *Figure 31*. Advantage with a custom Fan Performance curve is better accuracy of the results obtained from the simulation.

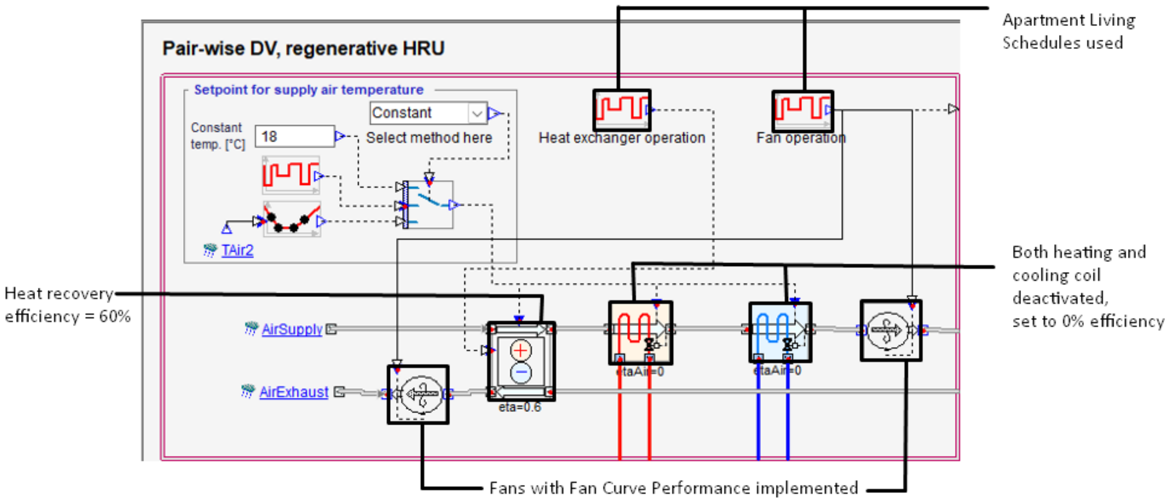


Figure 30: Modelling of DV-P in IDA-ICE.

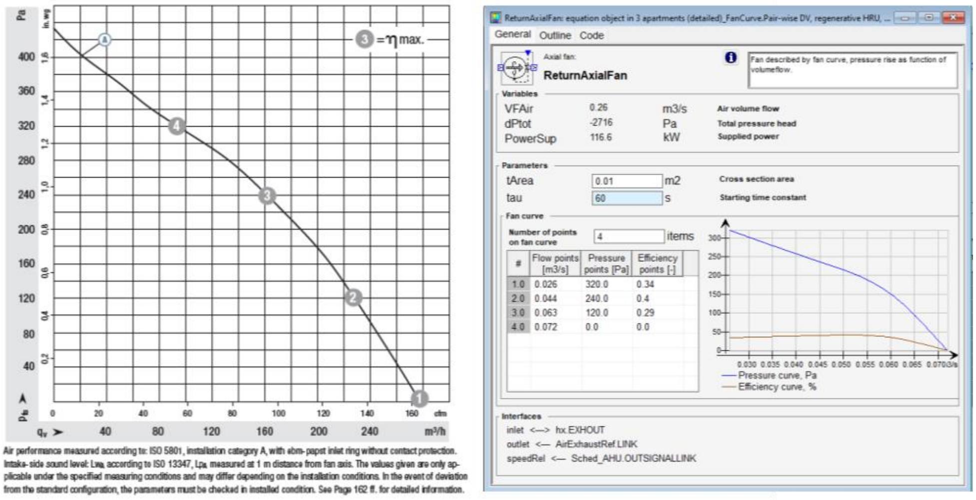


Figure 31: Fan performance curve for DV-P (on the left) and Fan-Curve macro (on the right) in IDA-ICE. Supply and Return Axial Fans use the same Fan Performance curve.

Airflow strategy for Pair-Wise DV-P can be seen in *Table 15*. As we can see, 75 m³/h is supplied and extracted from Bathrooms and Living Rooms / Bedrooms (rows coloured green). It reflects the aforementioned strategy of DV units where air is being supplied and returned in far ends of apartment and then flows through the apartment through opened doors.

Modelling Single-Unit DV and airflows strategy

By following example of previous studies that compared CV and DV systems (Magagna, 2016) DV-S is modelled similarly to DV-P, that is air is being supplied from far ends of the apartment and the flow is balanced.

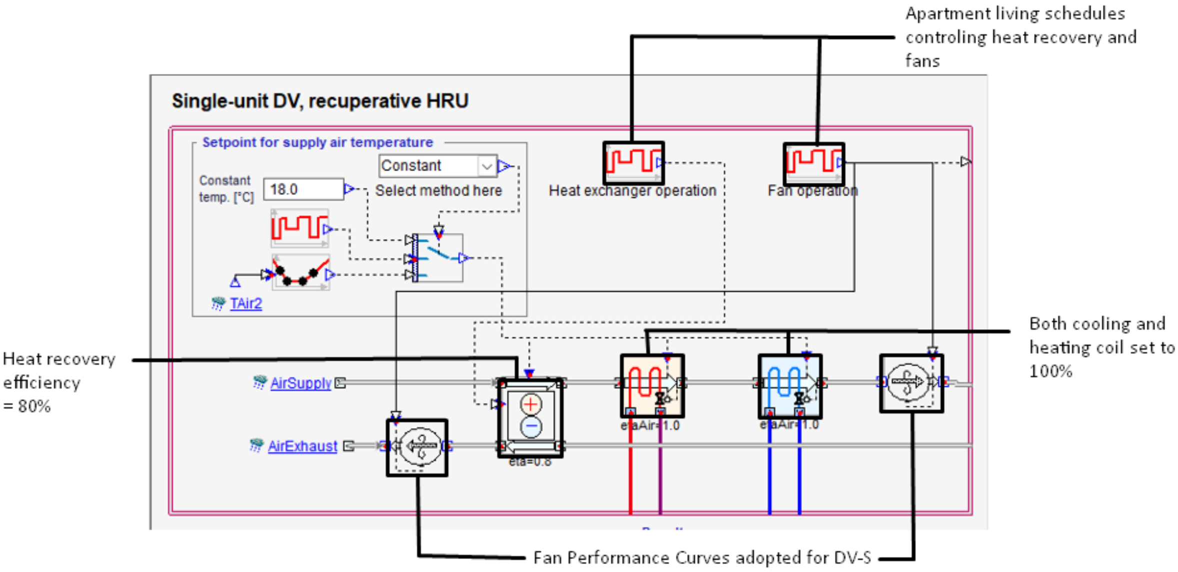


Figure 32: Modelling of DV-S in IDA-ICE.

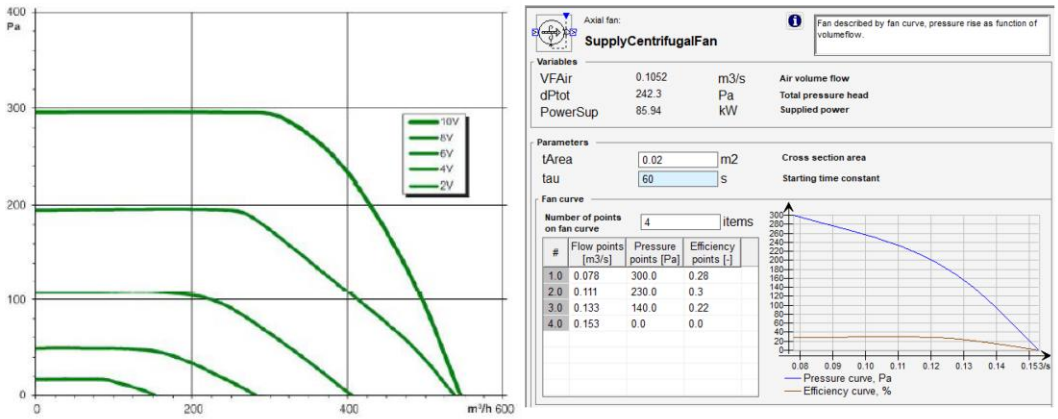


Figure 33: Fan performance curve for DV-S (on the left) and Fan-Curve macro (on the right) in IDA-ICE. Supply and Return Centrifugal Fans use the same Fan Performance curve.

For airflow strategy DV-S, see also *Table 15*.

Problem with energy meters after implementing of FanCurve-Fans in IDA-ICE

During the implementation and debugging phase of above-mentioned functionalities, an error in simulation occurred. When replacing the default "Fixed head" fans with the ones with custom Fan Performance curve, a link for logging the power consumption breaks. In order to re-establish it, the user needs to manually enter the *Outline* of energy meters and re-connect them with both supply and extract fans. For further instructions, please see *Appendix H*.

SFP, HRU

Based on research CV systems tend to use more energy and therefore have comparatively higher SFPs then DV systems, while performing better in terms of HRU efficiencies (K.M. Smith, 2016). Worse SFP value is due to higher pressure drop (longer ducts) and better efficiency of HRU is due to higher airflow rates. (Murray et al., 2015) That has been reflected in this thesis, as shown in *Table 14*. Moreover, HRU function is controlled simply by either activating it (setting to either 0.6 for DV-P or 0.8 for CV and DV-S) or deactivating it (setting to 0). This is illustrated in *Figure 75* in appendices section.

Heating and cooling coils for DV-P

Lastly, to differentiate between Pair-Wise and Single-Unit DV, former is not supplied with either heating or cooling coil and has no technical possibility to incorporate one. The latter, on the other hand, comes with both heating and cooling elements. DV-S can be connected to heating and cooling piping within the building or apartment through 2-pipe or 4-pipe system. Based on research it is the 2-pipe option that is far more energy efficient as the pressure drop for fans is lower. (J. Zemitis, 2020)

Appendix I shows summary of the parameters for DV-P and DV-S. This distinction has been achieved by setting both heating and cooling coils' efficiencies in the ventilation system diagram in IDA-ICE to 0. In effect Pair-Wise DV relies only on Zone Heating and Cooling.

UNITS PLACEMENT AND DIMENSIONING							
		CV		DV-P		DV-S	
Zone	Area	Chosen airflow	Chosen airflow	Chosen airflow	Chosen airflow	Chosen airflow	Chosen airflow
[-]	[m2]	[m3/h]	[l/s/m2]	[m3/h]	[l/s/m2]	[m3/h]	[l/s/m2]
0_LivRoom/Bedroom	15,78	52,00	0,92	75	1,32	75	1,32
0_Entrance	4,82	10,00	0,58	0	-	0	-
0_Kitchen	9,114	36,00	1,10	0	-	0	-
0_Bath	6,093	54,00	2,46	75	3,42	75	3,42
TOTAL 0_BOT	**35,807**	**152,00**	**5,05**	**150,00**	**4,74**	**150,00**	**4,74**
2_Bath	6,133	90,00	4,08	75	3,40	75	3,40
2_Kitchen	10,78	50,00	1,29	0	-	0	-
2_Entrance	5,564	18,00	0,90	0	-	0	-
2_Bedroom	12,12	52,00	1,19	0	-	0	-
2_LivingRoom	17,71	90,00	1,41	75	1,18	75	1,18
TOTAL 2_MID	**52,307**	**300,00**	**8,87**	**150,00**	**4,57**	**150,00**	**4,57**
3_Bedroom	17,94	90,00	1,39	75	1,16	75	1,16
3_LivingRoom	17,94	52,00	0,81	0	-	0	-
3_Bath	3,225	90,00	7,75	75	6,46	75	6,46
3_Entrance	3,227	18,00	1,55	0	-	0	-
3_Kitchen	12,45	50,00	1,12	0	-	0	-
TOTAL 3_TOP	**54,782**	**300,00**	**12,62**	**150,00**	**7,62**	**150,00**	**7,62**

Table 15: Dimensioning, chosen airflows for CV, DV-P and DV-S together with placement of DV units.

Lastly, to show a comparison between requirements and chosen airflows together with number of units for DV-P, taking into account that max capacity of one DV-P and DV-S units is 50 m³/h and 150 m³/h respectively, see Table 16

Requirements vs. Chosen Airflows						Number of DV units	
Zone	Area	Requirement normal ventilation	CV, chosen	DV-P, chosen	DV-S, chosen	DV-P, units	DV-S, units
[-]	[m2]	[m3/h]	[m3/h]	[m3/h]	[m3/h]	[units]	[units]
0_LivRoom/Bedroom	15,78	52,00	52,00	75,00	75,00	2,00	1,00
0_Entrance	4,82	6,94	10,00	-	-	-	-
0_Kitchen	9,114	36,00	36,00	-	-	-	-
0_Bath	6,093	54,00	54,00	75,00	75,00	2,00	1,00
TOTAL 0_BOT	**35,807**	**148,94**	**152,00**	**150,00**	**150,00**	**4,00**	**2,00**
2_Bath	6,133	54,00	90,00	75,00	75,00	2,00	1,00
2_Kitchen	10,78	36,00	50,00	-	-	-	-
2_Entrance	5,564	8,01	18,00	-	-	-	-
2_Bedroom	12,12	52,00	52,00	-	-	-	-
2_LivingRoom	17,71	25,50	90,00	75,00	75,00	2,00	1,00
TOTAL 2_MID	**52,307**	**175,51**	**300,00**	**150,00**	**150,00**	**4,00**	**2,00**
3_Bedroom	17,94	52,00	90,00	75,00	75,00	2,00	1,00
3_LivingRoom	17,94	25,83	52,00	-	-	-	-
3_Bath	3,225	54,00	90,00	75,00	75,00	2,00	1,00
3_Entrance	3,227	4,65	18,00	-	-	-	-
3_Kitchen	12,45	36,00	50,00	-	-	-	-
TOTAL 3_TOP	**54,782**	**172,48**	**300,00**	**150,00**	**150,00**	**4,00**	**2,00**

Table 16: Requirements vs. Chosen Airflows, CV, DV-P, DV-S + number of DV units.

CAV, VAV and DCV

Variable Air Volume (VAV) is preferable setting for DV systems because it enables controlling amount of air to a given zone by affecting the speed of fans and opening of air dampers. In that sense it elevates the advantages of decentralised systems by giving even more control to the user. Demand Controlled Ventilation (DCV) is a further step towards control and energy savings, and it should also be considered in the context of DV solutions. DCV is a term used to describe ventilation systems equipped with automation units that control indoor climate, take input from user and steer functioning of fans and dampers in order to meet given setpoints. (Mads Mysen, 2014).

In this thesis it was decided to use Constant Air Volume (CAV) for the simulation of both CV, DV-P and DV-S systems. It was because of the fact that zero-air-flows, as it was specified in airflows strategy (**Error! Reference source not found.**) resulted in simulation error in IDA-ICE while trying to use VAV and in course of writing this thesis no workaround for this problem has been found. It should be therefore noted that substantial energy saving potential lies in simulating VAV and DCV solutions when it comes to decentralised ventilation solutions in residential setting.

3.7 Modelling the effects of buoyancy and wind-stack on DV performance

It was decided to further detail the physics around DV-P and DV-S using advanced modelling functions in IDA-ICE. Buoyancy and wind-stack effect in IDA-ICE are a built-in functionality that don't need additional action to implement and activate in of it themselves.

The way that buoyancy and wind-stack effect are calculated in IDA-ICE has been briefly described in *Chapter 2.2*. In practice, after the user defines wind profile for the given simulation, a set of pressure coefficients is generated for each of the faces (walls) of the building. See *Appendix K* for full table with pressure coefficients generated by Autofill-function in IDA-ICE.

The step that was undertaken in this study to further detail effects of these phenomena was to introduce differential pressure across the external wall as a proportional controller for supply and exhaust. It was achieved by using a special input from LEAK function, that is a bidirectional transport of energy, humidity, and mass fraction between internal and external zone's space. See *Figure 34* that illustrates how the modelling was done in IDA-ICE graphical programming window.

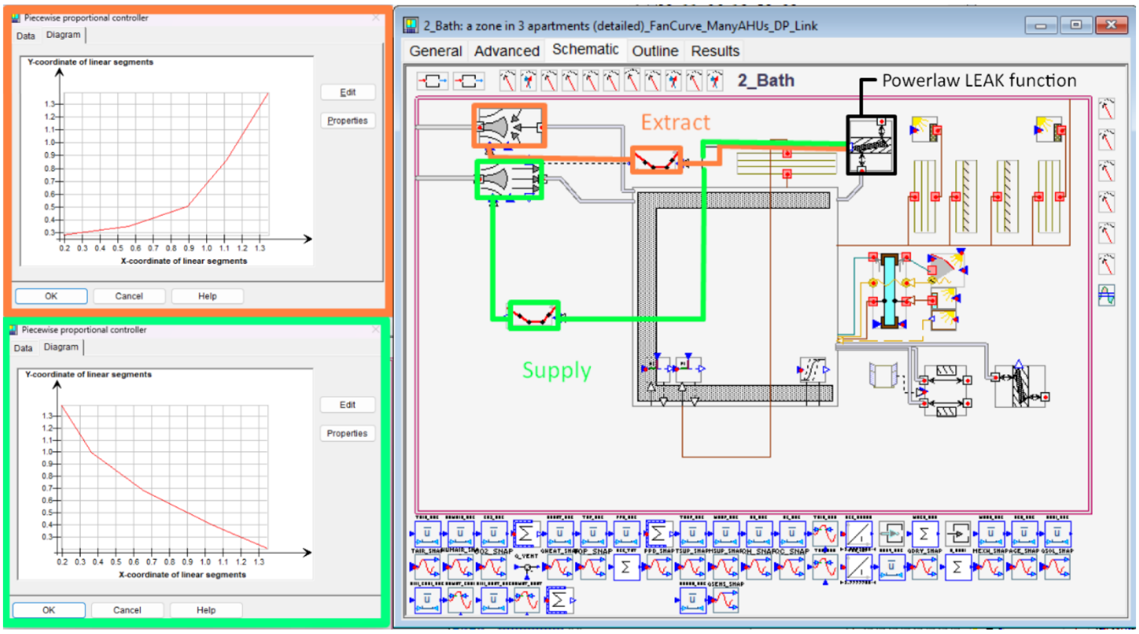


Figure 34: Implementation of DP_Link macro in IDA-ICE. Here, schematic of exemplary zone (bathroom). On the left: extract and supply Linear-Segments (P-controllers)

Linear segments shown in *Figure 34* come from a study on impact of air pressure conditions decentralised units (Mikola et al., 2019). The excerpt taken from this study that linear segments for supply and extract were based on are shown in *Figure 35*. Please note that the results obtained by Mikola et. al focused on regenerative HRU while this study uses also recuperative HRU for Single-Unit. A simplification is made to use the same approach for both recuperative and regenerative DV.

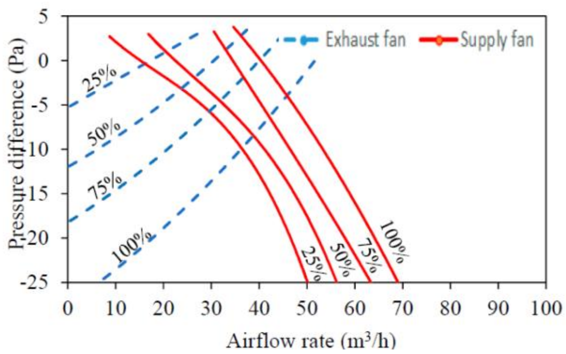


Figure 35: Measured based fan performance curves of room-based ventilation units with ceramic regenerative HRU. (Mikola et al., 2019)

3.8 Placement of DV units

DV-P and DV-S systems were distinguished by differing airflows and values for parameters of SFP and HRU efficiency. Another aspect that is also important to underline here is the question of placement of these systems. This section focuses on showing how, based on research, DV-P and DV-S units can be placed within an apartment to utilize potential of these distinct types of decentralised ventilation systems.

For clarity and comparison purposes, NoAHU and Centralised Ventilation will be shown first, see *Figure 36* and *Figure 37* respectively.

NoAHU

As can be observed from *Figure 36*, for this set-up without any Air Handling Units only fresh air intakes in facades (external walls) are drawn. Additionally, grey arrows indicate internal doors through which air can flow between zones. Windows can be opened according to the schedule and PI-controlled temperature macro, as described earlier.

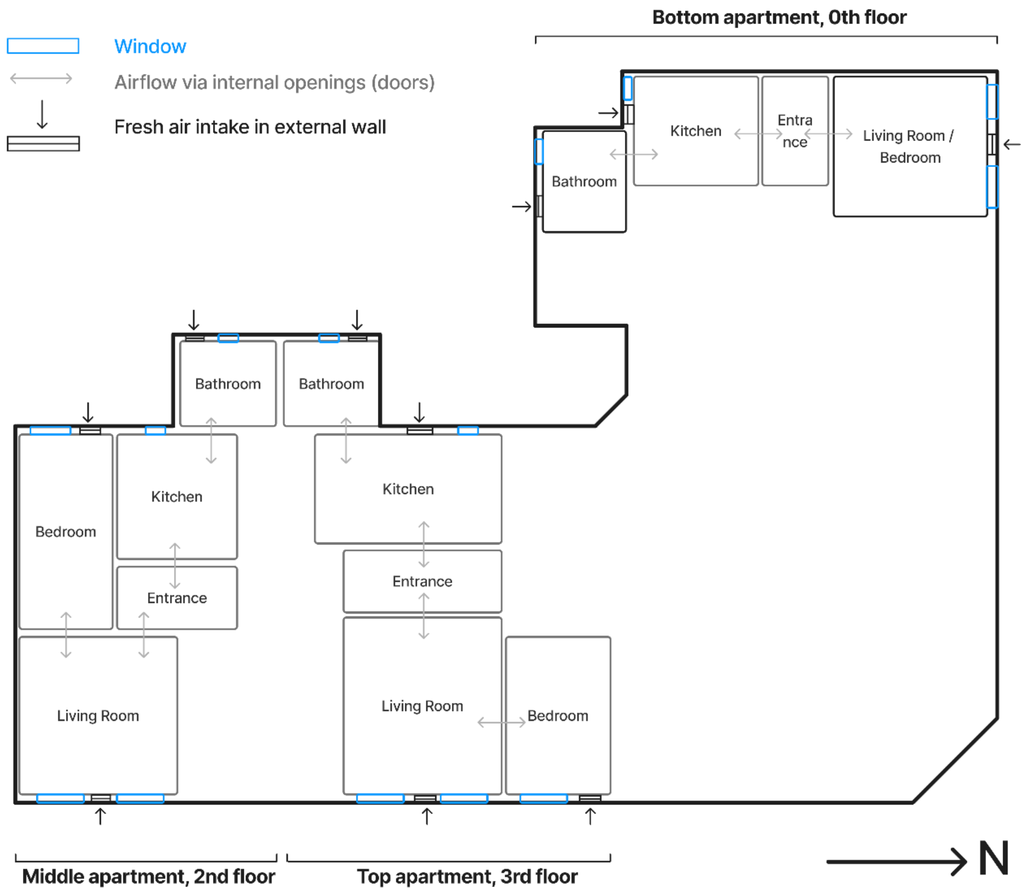


Figure 36: NoAHU (natural ventilation only) - proposed placement of fresh air intakes in facades.

CV

According to the simulation, a proposed set up for both supply and extract air terminals and, together with ventilation ducts has been proposed. *Figure 37* shows supply and extract in each room, with one AHU connected to all zones. Technical shafts can be seen placed in the Entrance. Further dimensioning of the shafts or detailed 3D design of ventilation ducts have not been performed to check validity of proposed solution.

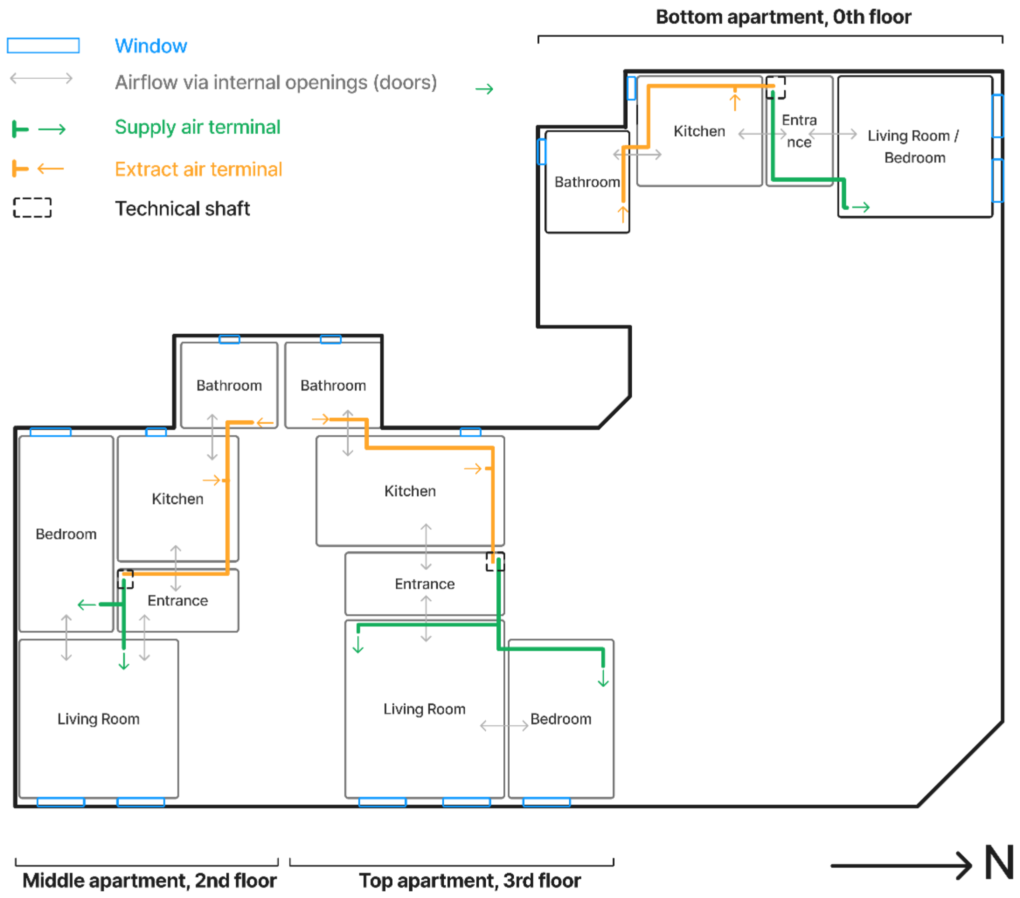


Figure 37: CV ventilation system. Proposed placement if airflow terminals, supply, and extract ducts.

Pair-Wise

DV-P have been placed on two far ends of the apartment. As we can see in *Figure 38*. Pair-Wise units are represented by red elements placed in facades.

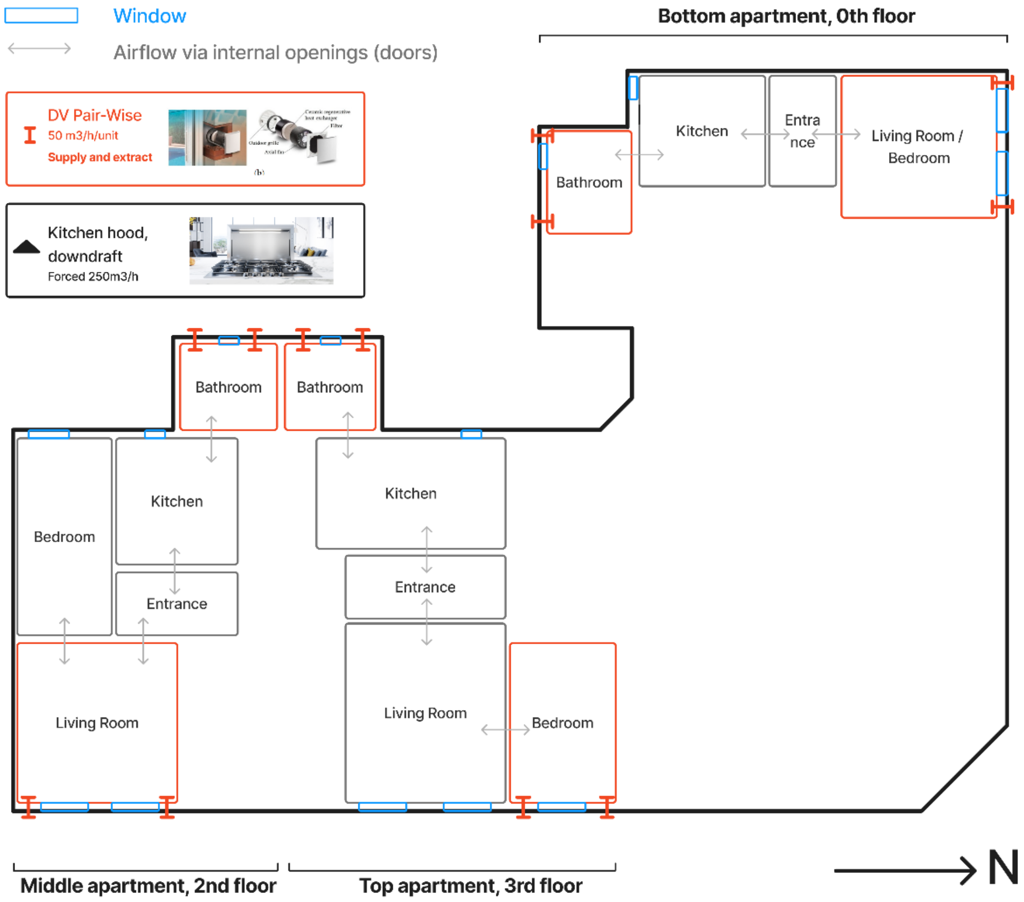


Figure 38: Proposed placement of DV Pair-Wise within 3 different apartments.

Single-Unit
DV-S units are placed in far ends of apartments, in a similar way as DV-P are. We can see in *Figure 39* that these are visualized as purple rectangular boxes placed on the inner side of east façade. Dimensioning airflow capacity of DV-S is 150 m^3/h, and because of that there are 2 units per apartment, 1 per given zone.

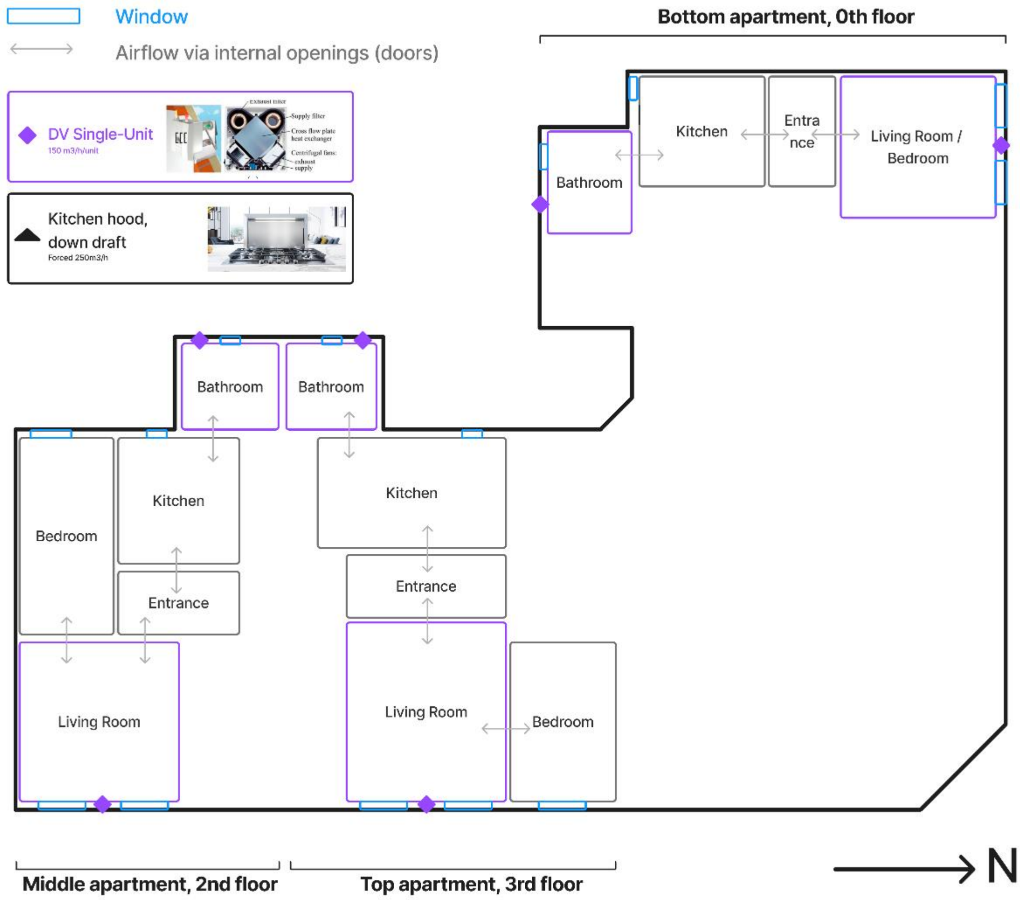


Figure 39: Proposed placement of DV Single-Unit within 3 different apartments.

Proposed placement and deviation from TEK 17 §13-2
Placement of DV units presented above has been chosen for simplicity purposes of the simulation. It shall be noted that even though overall airflows meet the requirements, situation around bedrooms, kitchens and bathrooms do not agree with what's stated in TEK 17 §13-2. Firstly, TEK 17 §13-2(2) requires that bedrooms are ventilated with minimum 26 m^3/h of fresh air per planned bed space when the room is occupied. This, due to the chosen placement of both DV-P and DV-S units is not met for zones 2_Bedroom and 3_Bedroom.

Secondly, as it stands in TEK 17 §13-2(4), DV-P and DV-S do not provide continuous extract from kitchens and bathrooms. While using downdraft kitchen hoods would partly solve the problem, when it comes to continuously ventilating these spaces, DV systems, in particular DV Pair-Wise becomes a problem, especially due it's oscillating function, as it will be further discussed in next chapter.

Suggested placement and the fact that is has not been rectified are chosen to be accounted for as an error during the work on the thesis and overall structural approach to the task. Time-constraints and consequences of the vast changes the rectifying would imply, weighed in on leaving the issue unresolved and remarking this as a comment only.

Possible quick solution that in the end was not realized, would be to move one DV-P unit from Living Rooms to bedrooms of apartments 2_MID and 3_TOP. In the case of DV-S, similarly, moving the units to bedrooms would solve the first problem, according to TEK 17 §13-2(2). The second problem though is not so easy solvable and needs a potential dispensation or additional investigation.

3.9 Forced exhaust from bathroom and kitchen

Both CV, DV-P and DV-S have been dimensioned to cover normal ventilation demand, as shown in *Table 13*. Forced exhaust from bathrooms are within capacity of both Pair-Wise and Single-Unit, but when it comes to what is required for kitchen forced extract, this is well above dimensioned capacity of the systems. As described briefly in *Chapter 3.5* downdraft kitchen hoods are to be introduced, with capacity up to 250 m^3/h. This, in theory, should solve the problem with forced ventilation in terms of bare airflow amounts.

A challenge that arises with forced exhaust for bathroom and kitchens, especially in a case of DV-P and DV-S is transport of humidity and pollutants around the apartments. As stated in Building detail 552.301 by Byggforskserien SINTEF, Chapter 33, Principle for removing pollutants through the means of ventilation system states that it should be done nearest the source of pollution (and humidity). Another important factor is a way the pollutants move. In the same publication we read that air movement should follow the principle "from clean to polluted" rooms to prevent spreading humid air and/or odour from bathroom and kitchen to living room and bedrooms.

With the suggested placement and design of DV-P and DV-S, as described in *Chapter 3.8* there can be real challenges with upholding this principle. DV-P, as described earlier, functions in practice by oscillating between supply and extract modes in constant time-intervals. In the case when bathroom is a source of pollutants at a given moment and two DV-P units installed in bathroom switch to supply mode while another DV-P in the other end of apartment switch to extract, for a duration of an interval (say, 90 seconds) polluted air with flow through the whole apartment reaching bedroom. This could potentially be fixed through sophisticated controls based on occupancy in the bathroom and kitchen in a way that moisture and VOC sensor-control wouldn't allow DV-P to switch modes while pollutants in bathroom/kitchen are present. After these polluting zones would be free of contaminating agents, DV-P would get back to normal functioning.

This is not so readily problematic for DV-S because these units, by design, allow for extracting and supplying the air at the same time. It would be needed though, to investigate further how it would work in practice and whether the pollutants would be removed nearest bathroom and kitchen.

3.10 Defining scenarios and boundary conditions

In *Chapter 3.1* an overall structure of files and types of simulation were described. To sum up, one simulation was done using SIMIEN, for TEK17 compliance test purposes on a simulation file consisting of only one zone for the whole building. Another one was done for the same purpose in IDA-ICE using a simulation file made up of 4 zones, 1 per floor. After that, an IDA-ICE simulation file for three apartments connected to one AHU was created, serving both as model for CV simulations, and a BASE FILE for creating 3 separate Apartment files.

TEK17 compliance for SIMIEN and IDA-ICE went through several iterations and after the TEK17 energy requirements were met, no further work on these files were performed. BASE FILE and 3 files for apartments on the other hand went through more simulations in IDA-ICE.

Results are to be viewed through scenarios. An overview of these can be found in *Table 17*. There are three apartments and four systems run for each: NoAHU, CV, DV-P and DV-S. It results in 12 scenarios. In Figure 40 a numbering system reflecting the scenarios' structure is shown. The first number indicates system number, and the second apartment number.

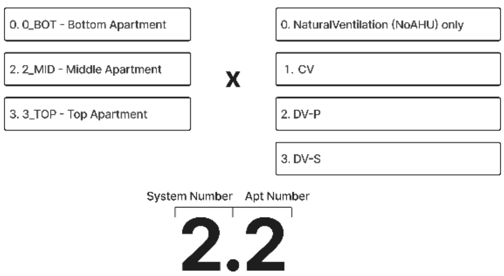


Figure 40: Conceptual break-down of scenarios with numbering system.

Simulation Workflow
There were done 4 separate, whole-year, advanced IDA-ICE simulations. Firstly, the overall overview on different scenarios has been planned out and put in the overview table in Excel. Before approaching each individual system, overall check of boundary conditions such us window control, zone setpoints and airflows has been double checked. Next, in IDA-ICE, correct ventilation setup has been done by choosing the correct ventilation system (NoAHU/CV/DV-P/DV-S) with corresponding airflow setup. Lastly the simulations were run and numerical results transferred back to Excel for evaluation and data presentation. Flow-charts presenting details of the workflows, including one for changes handling can be seen in *Appendix L.*

No	Apartment	Ap_area	System
[-]	[-]	[m2]	[-]
0.0	0_BOT	35,81	No_AHU
0.2	2_MID	52,31	No_AHU
0.3	3_TOP	64,13	No_AHU
1.0	0_BOT	35,81	CV
1.2	2_MID	52,31	CV
1.3	3_TOP	64,13	CV
2.0	0_BOT	35,81	DV-P
2.2	2_MID	52,31	DV-P
2.3	3_TOP	64,13	DV-P
3.0	0_BOT	35,81	DV-S
3.2	2_MID	52,31	DV-S
3.3	3_TOP	64,13	DV-S

Table 17: Overview of all simulation scenarios with their corresponding numbers.

3.11 TEK17 §14 compliance test in IDA-ICE

As previously mentioned, SIMIEN has a built-in, specifically programmed module for TEK17 § 14-2 compliance testing which checks whether the building meets the requirements stated by Norwegian Building Code. It uses standardized values picked from NS3031 standard. IDA-ICE needs adjustments to produce results that could resemble those from SIMIEN. Even still, the base physics model will not be exactly reflected as IDA-ICE uses different modelling approaches and different resolution.

In this section, a method for bringing IDA-ICE closer to SIMIEN in terms of compliancy test for TEK17 § 14-2 will be presented in step-by-step matter. Please see *Appendix N* for screenshots of the IDA-ICE UI (versions 6.017 and 7.012 if there will be differences) where details on the instructions presented here are shown. There are many different elements of a building energy simulation: thermal physics model, infiltration and window controls, heat loss through ground, climate model, technical systems (heating, cooling, ventilation), daylight, indoor climate models and more. In this chapter, the elements that will be discussed are only those that were affected in practice when running simulation in IDA-ICE for purposes in this study.

Climate is the first parameter that must be focused on. TEK17 compliance test requires using Oslo climate. In *Appendix O,* screenshots of what climate SIMIEN uses for its compliancy simulation are shown, for both 7.012 and 6.017 versions. We can see that SIMIEN uses climate data from Oslo Blindern. This can be done also in IDA-ICE, using before mentioned EPW file. For comparison between climate files, please see *Chapter 3.2 (section Climate)* and *Appendix E.*

Energy supply system (plant) is the second section in SIMIEN and a big subject to dive in, which has not been explored and developed in IDA-ICE during this study, as default IDA-ICE plant has been used throughout the whole work. Requirement TEK17 § 14-4. Krav til løsninger for energiforsyning (*Requirement for solutions to energy supply)* is especially important to consider as it regards the type and ratio of so-called “flexible heating systems” that must be reflected in TEK17 compliance test.

Building envelope, default constructions must be within what is stated in TEK17 § 14-3, as described in theoretical section in *Chapter 3.2.*

Airflows must be calculated according to TEK17 (table A6 in NS3031 or and/or building standard by SINTEF (for residential 552.301).

When it comes to **schedules for ventilation and internal gains**, these must be standardized according to Table A.3 in NS3031, which implies 24/7/52 for occupants and ventilation (constant, whole year) and 16/7/52 for heating, lighting, and equipment. This has to be implemented in IDA-ICE, that is a custom schedules with constant values through the year have to be created for ventilation, occupancy and internal gains.

Values for internal gains must be set according to Table A.1 from NS3031, for example for block of flats, residential (*Boligblokk*) it must be 1,95 W/m2 for lighting and 3,00 W/m2 for equipment. See *Figure 24* for how the schedules between NS3031 and SN-NSPEK 3031 compare.

Result of energy simulation required by TEK17 has to be expressed in net energy, while default way for IDA-ICE is to express it in delivered energy. A workaround to that is to set all extra energy and losses to 0 in IDA-ICE. This is done in *General* tab, under *Extra energy and losses*. Additionally, under *Building defaults* (still *General* tab), in section *Generator Efficiencies*… Heating has to also be set to 1 in order to remove any sources of inefficiencies.

Regarding **SFP** and **heat recovery rate**, it is suspected that there are differences in how IDA-ICE these parameters comparing to SIMIEN, but no definite study has been done during working on this thesis. SIMIEN ver. 6.017 lets user define HRU efficiency in terms of %-temperature efficiency (yearly averaged value), hygroscopic efficiency (in case heat recovery unit transports humidity from extract air) and frost protection temperature. Ver. 7.012 on the other hand adds option for defining HRU efficiency for 20, 40, 60, 80 and 100% of dimensioning airflows. Similarly, SFP is treated in a simplified way (yearly averaged value, according to Appendix H in NS3031:2014) in ver. 6.017 of SIMIEN and gets and upgrade in version 7.012 (SFP given for 20/40/60/80/100 of airflow). Moreover, SIMIEN lets define the placement of supply and extract fans. SFP is defined as SFP under and outside the occupancy. Still, these are fixed values.

Based on underlying code, posts on EQUA Labs forums and documentation, heat recovery units in IDA-ICE are affected by varying airflows, as effect of pressure differences across external walls, occupancy, outdoor temperature, leaks and more. According to the code in IDA-ICE for "*Simplified air-to-air latent heat exchanger with Control*", it operates in two modes: dry and wet. For dry operation "*ETA [Effectiveness parameter] is defined as the supply side temperature effectiveness (…)*". For wet operation it is assumed that "*apparatus dewpoint (…) equals the entering temperature of the opposite medium*".

SFP, in its simplest form, that is by using FixedHead Fan in IDA-ICE, is treated as "*Fan with on/off control (low flow when off). Performance at rating, VAV PLR [Partial Load Ratio] coefficients, air temp rise and efficiency given*" (quote from code). SFP value can be given as constant here, and according to code it is used as a constant parameter, next to other parameters like: temperature rise over fan, max and min pressure head and motor in air efficiency.

In conclusion, while treatment of SFP can be assumed as relatively similar between SIMIEN and IDA-ICE, heat recovery efficiency must be approached with care, as IDA-ICE uses more advanced methods to calculate it. Analysis of year-averaged heat recovery should be undertaken to evaluate potential differences.

3.12 Assumptions and uncertainties

Assumptions

Until this point in the thesis there were made several assumptions about various parts of simulations performed in IDA-ICE. This section will summarize those already mentioned and outline other important premises set as basis for the simulation.

- Uniform distribution of zone temperature assuming ideal mixing of air in and in between zones
- Ducting and pressure work due to distribution of air is not investigated in this study. Applies to both CV and DV systems.
  - The same applies to fan loads.
- Ideal heat exchange between airflows within apartments.
- No air exchange between floors. No air exchange between apartments and staircases. Important when investigating problems related to differential pressures across external walls.
- Heat recovery unit efficiency in case of Centralised Ventilation (HRU) is independent of location
  - In case of DV, heat recovery efficiency varies due to air pressure variations (buoyancy, wind-stack effect). It is thanks to use DP_Link macro in IDA-ICE. (A. Merzkirch, 2015; Mikola et al., 2019; Zender – Świercz, 2020)
- Constant heat capacity of air equal 1006 J/kg*K.
- Constant air density equal 1,263 kg/m3.
- Constant supply air temperature through the year of 18 °C.
- Ideal efficiency of heating and cooling coils in AHU when present, 100% efficiency. (AB, 2018)
- Temperature rise of the fan in CV equal 0,5 °C (Sturla Ingebritsen, 2019b) while in DV-P and DV-S equal 0 °C (Merzkirch et al., 2017)
- Walls not connected to other adjacent zones are modelled as adiabatic, i.e., there is no heat exchange there outside of the apartment.
- "Typical", according to IDA-ICE, thermal bridges, and overall thermal bridge value.
  - Swedish definition on thermal bridges has been used for all simulations. The one that was supposed to be used is a Norwegian one, "Overall internal" thermal bridges. This is an error. 552.305
  - The same applies to ground properties as they were chosen as defaults from IDA-ICE database.

Uncertainties

Uncertainties, in engineering and physics, are defined as an interval about measured value such that "any repetition of the measurement will produce a new result that lies within this interval"(College, 2014). This definition, by applying to simulation instead of measuring, can be applied in this study. Several sources of uncertainties have been found, namely:

- **Building envelope, U-values and modelled geometry in IDA-ICE.** Construction types used for the modelled apartment can vary a lot, depending on building standard. Key factor here is also the fact that TEK17 does not state requirements to all building elements that IDA-ICE lists in *Default* constructions. Therefore, there has been made decisions in this study as to, for example, treat internal floor as slabs or basement wall towards ground modelled as external wall.
- **Differentiating between AHU and Zone cooling / heating.** The way IDA-ICE meets the heating and cooling demands as default. Without proper control strategy implemented the results can be skewed towards Zone-based heating and cooling even though AHU-based perform better energy-wise and have enough capacity. It has not been further investigated in this study whether this can be alleviated. No other control strategy than default
- **Air-coupling between zones.** It is important to consider airborne heat exchange between rooms when there are zones with supply-only and return-only DV units. In the case of this thesis entrance room is an

example of zone that has neither supply nor exhaust and relies only on the airflow from and to other zones. It has not been investigated how in detail IDA-ICE treats air-coupling in its physical model.

- **Weather data.** In this study, EPW climate file for Oslo, has been used. ASHRAE database climate for Oslo and SIMIEN climate file has been compared.
- **Occupancy.** It has not been investigated how IDA-ICE models occupancy in each time for a given zone. The only parameters that can be set within the application are number of occupants per zone and a corresponding occupancy schedule. It has been observed that fractional values of occupancy show up in the results and this is quite important to note as that leads to underestimation of internal gains.
- **PPD, percentage of people dissatisfied.** It is connected to previously mentioned occupancy aspect. PPD, according to IDA-ICE manual, is calculated only if there are occupants present in each zone, for a given time. There are therefore situations when PPD cannot be evaluated since no one occupies the zone according to IDA-ICE model.

3.13 Global simulation settings, IDA-ICE

Under simulation tab in IDA-ICE there are some global settings that needs to be defined before simulations can be run. In appendices' section in *Figure 66* and *Figure 67* there are shown parameters with their corresponding values used for all scenarios. Days of dynamic start-up were set to 14, while all the advanced settings concerning tolerances, maximal time-step, maximum number of periods, tolerance for periodicity and time-step for output were kept as defaults. Time-split parallelization has been enabled in case of for some complicated, time-consuming simulation. For more, see *Appendix B*.

3.14 Gathering data from simulations

Process of collecting numerical data from simulation reports of IDA-ICE consisted of three steps. Firstly, the simulation was run, and corresponding report was automatically made available in each tab in simulation software. Then, data from the report was copied into previously prepared Excel file that contained all scenarios divided into multiple spreadsheets, each named after scenario number from 0.0 to 3.3, as shown in *Table 17*. Last step was to link each individual scenario table, i.e., raw output data from IDA-ICE, with summarizing table shown below in appendices section as *Table 21*.

Comment on optimalisation of overall method in IDA-ICE

A substantial portion of time has been dedicated for debugging and optimising of the whole simulation structure and IDA-ICE models. In *Appendix L* a workflow for changes handling and obtaining results is presented. These procedures are effects of effort towards minimising systemic noise and time-efficiency of the whole process. Despite that, it has been observed, that the framework used in this thesis is not flexible enough for rapid changes and adjustments in the simulation. Advanced techniques such as *parameter runs* that, according to IDA-ICE manual and EQUA Labs forums, should be used in similar, future works. Integration with programming environment (MATLAB, Python) is another possibility that would improve the process.

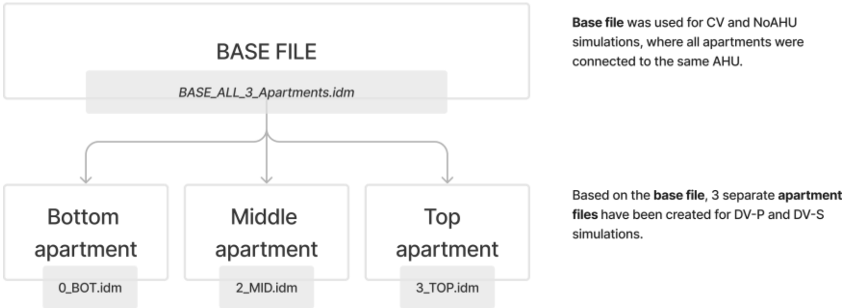


Figure 41: Summary of the file structure for IDA-ICE.

4 Results and discussions

4.1 Presentation of the results

Some results are presented in two parts: firstly, as indoor climate indicators and then energy. It is done to be able to present that even though certain set-ups (scenarios) produce very satisfactory results in terms of energy used, they cannot be accepted due to poor indoor climate they produce. Therefore, when additional data is available, the results shall be looked upon as a combination of energy and indoor climate aspect.

NoAHU, CV, DV and AHU-Heating, AHU-Cooling

NoAHU-scenarios represent set-up where no Air Handling Unit is present in the apartment. That is one of defaults functions in IDA-ICE one can choose for simulation. It involves only natural ventilation and movement of airflows between zones, through leaks, air intakes in facades and windows. No heating or cooling is then being produced by AHU; only room-based units are used to meet zone setpoints in terms of temperature. The same applies to DV Pair-Wise unit due to its design i.e., having both cooling and heating coil deactivated. Therefore, both NoAHU and DV-P won't produce any results for airborne heating or cooling. In other words, those columns marked with AHU-Heating and AHU-Cooling will be non-present for these scenarios.

Worth explaining is so called PDH Indoor Climate indicator which indicates the integral of the PPD (percentage of people dissatisfied) multiplied by the total number of present occupants in actual zone/apartment. This can be used to compare overall comfort between design alternatives. PDH stands for *Percentage Dissatisfied Hours,* which means hours during the year when occupants were in a state of discomfort caused by indoor climate.

In general, Indoor Climate results have been transferred directly from IDA-ICE, without alteration. According to IDA-ICE manual, signals are filtered by a 15 minute sliding average (by default)

- **CO_2** is given in IDA-ICE as maximum value of the concentration in a zone. Results presented here are then averaged across systems and apartments.
- **PPD** is given as maximal value of percantage of people dissatisfied. Equal zero for a given zone when there are no occupants present.
- **Operative temperature over 25 °C** is given as the total time when the zone is in use (occupied).

Total delivered energy, electric cooling, electric heating and HVAC aux

Energy results are obtained in a following matter:

- total delivered energy for a given building, apartment, or zone,
- electric cooling (consisting of both AHU and Zone based cooling),
- electric heating (consisting of both AHU and Zone based heating).

All of these are expressed in areal specific energy unit [kWh/m2/year] for better comparison between apartments of different areas.

AHU based cooling or heating represents heat produced or removed by, respectively heating and cooling coil inside the air handling unit. **Zone-based cooling and heating** comes from the plant through room units, as described in *Chapter 3.3, Table 10: Specification of room units in zones.*

Auxiliary energy, here called HVAC aux, stands for:

- Energy used by any central humidification equipment.
- Energy used by fans.
- Energy used by pumps.

General structure

First, in *Chapter 4.2,* a summary of the compliance test according to TEK17 for SIMIEN and IDA-ICE will be presented. Next, in *Chapter 4.3*, comparison between NoAHU and other systems is made, in terms of energy and Indoor Climate, which is important since NoAHU system does not qualify for further analysis because of very unsatisfactory Indoor Climate results. After that, in *Chapter 4.4* detailed indoor climate results between CV, DV-P and DV-P will be outlined and discussed.

Energy results will be presented in *Chapter 4.5* (total energy), *4.6* (systems breakdown), *4.7* (peak power), *4.8* (cooling), *4.9* (heating), *4.10* (HVAC aux), and *4.11* (summary of the results).

Color coding

For easier comparing of the results, on each chart the worst system within a given apartment has been overlayed with red and the worst with red color. If the chart presents data broken down by system, the apartment with worst score is highlighted in red, and the best in green.

4.2 Compliance test TEK17 in IDA-ICE vs SIMIEN

Both SIMIEN and IDA-ICE whole building simulation obtained results that are within what is required for total calculated net energy demand of 95 kWh/m2/year. Overview on simulation files can be found in *Appendix F* and in *Appendix N*. Detailed SIMIEN results can be found in *Appendix O*.

In *Table 18,* summary of the results obtained in SIMIEN for the whole building are shown. Analogically, in *Table 19* summary results from IDA-ICE are presented. As we can see, both simulations met the requirements. A difference of 6.9 kWh/m2/year in favour of SIMIEN energy consumption can be explained by differences in heat recovery calculations between programs. Further investigation of this difference has not been performed.

Energiramme (§14-2 (1), samlet netto energibehov)	
Beskrivelse	Verdi
1a Beregnet energibehov romoppvarming	17,1 kWh/m²
1b Beregnet energibehov ventilasjonsvarme (varmebatterier)	6,2 kWh/m²
2 Beregnet energibehov varmtvann (tappevann)	29,8 kWh/m²
3a Beregnet energibehov vifter	4,1 kWh/m²
3b Beregnet energibehov pumper	1,1 kWh/m²
4 Beregnet energibehov belysning	11,4 kWh/m²
5 Beregnet energibehov teknisk utstyr	17,5 kWh/m²
6a Beregnet energibehov romkjøling	0,0 kWh/m²
6b Beregnet energibehov ventilasjonskjøling (kjølebatterier)	0,7 kWh/m²
Totalt beregnet energibehov	88,0 kWh/m²
Forskriftskrav netto energibehov	95,0 kWh/m²

Table 18: Energiramme (Energy frame). Energy simulation results in SIMIEN according to § 14-2. TEK17.

Delivered Energy Overview

	Purchased energy		Peak demand
	kWh	kWh/m²	kW
Lighting, facility	14834	10.3	1.69
Electric cooling	964	0.7	8.84
HVAC aux	39798	27.6	6.32
Electric heating	67724	46.9	75.67
Total, Facility electric	123320	85.4	
Domestic hot water	0	0.0	0.0
Total, Facility fuel*	0	0.0	
Total	123320	85.4	
Equipment, tenant	13624	9.4	1.56
Total, Tenant electric	13624	9.4	
Grand total	136944	94.9	

*heating value

Table 19: Summary of the results from IDA-ICE for the whole building.

4.3 NoAHU vs CV and DV in terms of indoor climate and energy

In this section, only a small comment on the results of NoAHU scenarios are made. Further details on energy consumption of decentralised systems are done under the *Chapter 4.4* when comparing CV and DV systems. Here, only a short comparison between NoAHU and other systems is outlined.

Indoor Climate: NoAHU vs other systems

As we can see in *Figure 42*(please note the logarithmic scale on y-axis) NoAHU system in all apartments is characterized by substantially higher CO_2 concentration. *Figure 43* is also showing very high number of hours when operative temperature was above 25 °C for both with and without cooling.

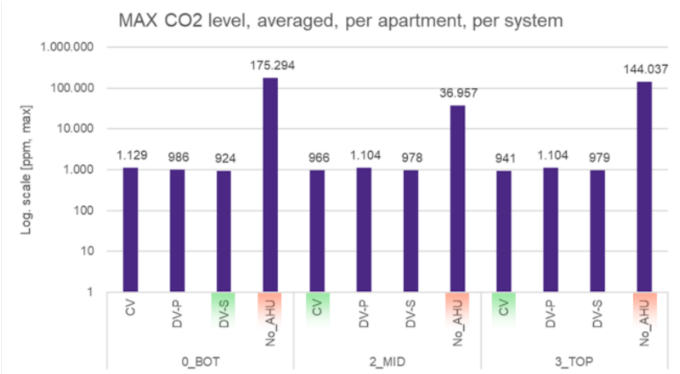


Figure 42: Results for Indoor Climate: NoAHU vs CV, DV-P and DV-S.

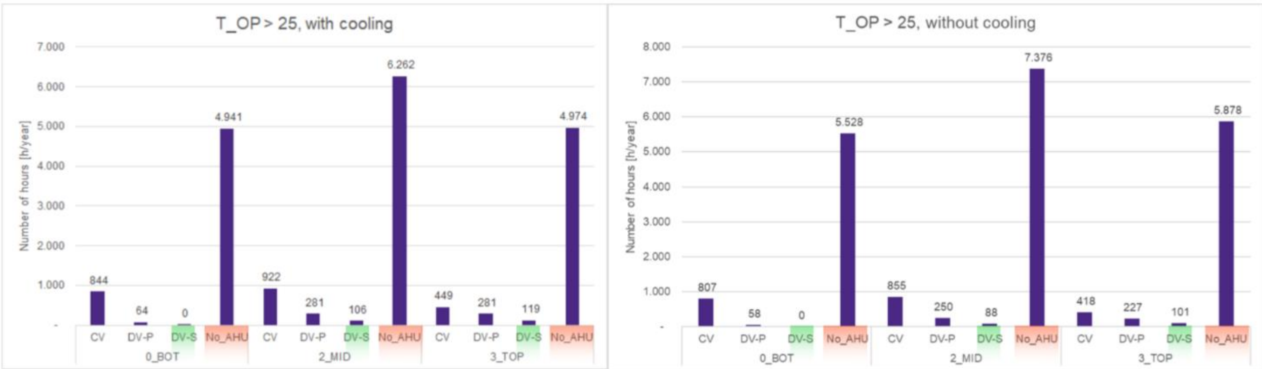


Figure 43: Results for Indoor Climate: T_OP>25 with (on the left) and without cooling (on the right), number of hours in the year. No AHU vs CV, DV-P and DV-S.

Energy: NoAHU vs other systems

From *Figure 44* we see that NoAHU performs best energy-wise among other systems, scoring around 29 kWh/m2/year in terms of areal specific energy across all apartments. Considering unsatisfactory Indoor Climate results, NoAHU will not be analysed further.

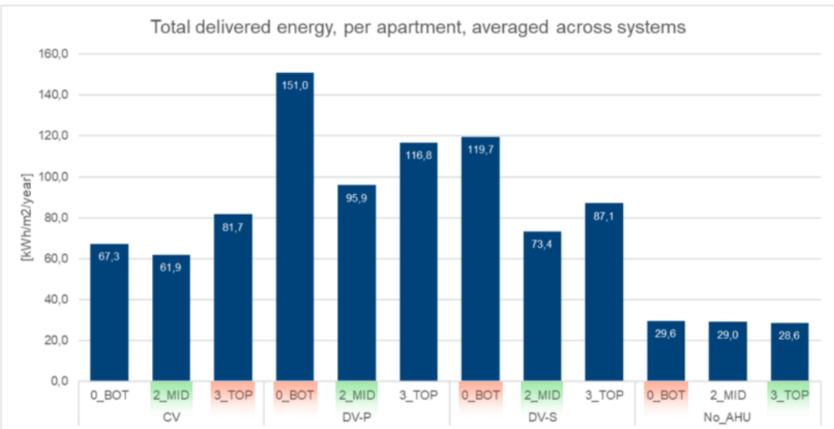


Figure 44: Total delivered energy, NoAHU vs other systems.

4.4 Indoor Climate: CV vs DV-P vs DV-S

When looking at comparison of Indoor Climate in terms of CO_2 concentrations between CV, DV-P and DV-S from *Figure 45,* we can see that in the Bottom apartment, CV scores above requirement of 1000 PPM of CO_2 indoors, while DV-P and DV-S are below that limit. In Middle apartment it is DV-P that has the highest concentration above 1100 PPM while CV and DV-S lay not far from each other, with results around 970 PPM. In the Top apartment we observe similar situation as in case of 2_MID with DV-P having the worst Indoor Climate results, followed by DV-S and CV.

Results shown below are averaged values of maximal CO_2 concentration a given zone, averaged for a whole apartment and system. Detailed maximal values that occurred in zones can be seen in *Appendix M.*

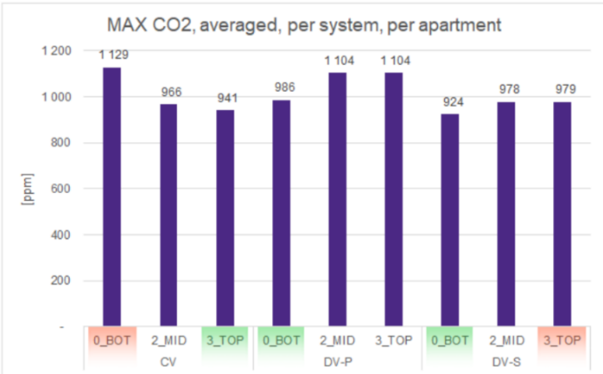


Figure 45: Results for Indoor Climate: CO_2 levels, CV vs DV-S vs DV-P

Figure 46 shows that centralised ventilation system has the highest number of hours when the operative temperature is above 25 °C, across all apartments. It is followed by DV-P and DV-S.

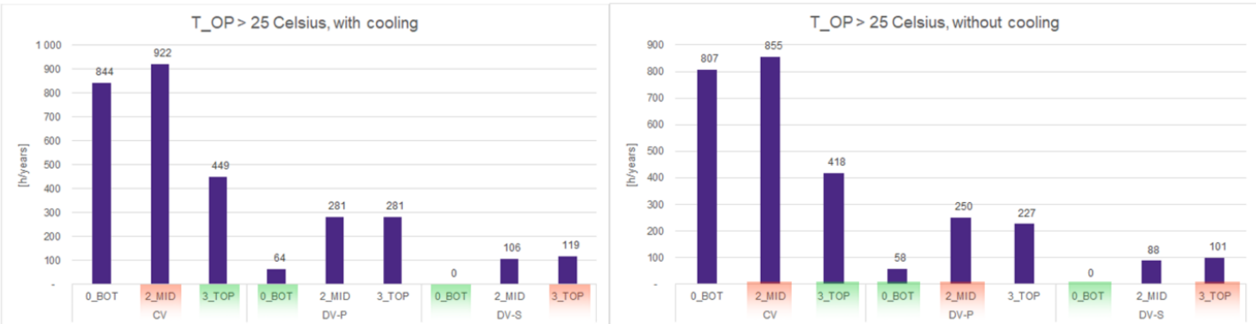


Figure 46: Results for Indoor Climate: Number of hours when T_OP > 25, with (on the left) and without cooling (on the right).

From *Figure 47* we can see a pattern where CV scores consistently lowest on hours of people dissatisfied, followed by DV-P with around 100 hours/year more than CV and DV-S last across all apartments.

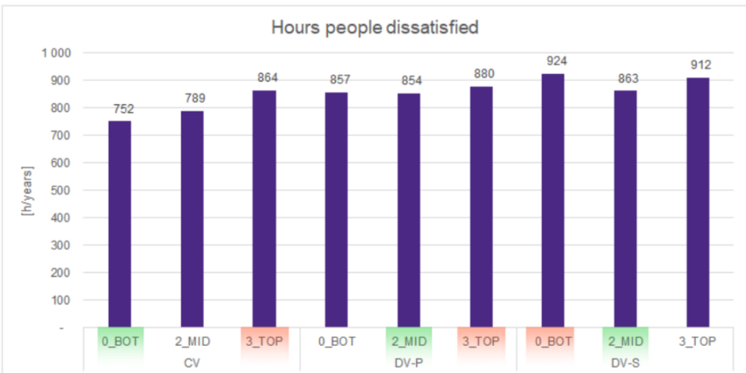


Figure 47: Results for Indoor Climate: Hours people dissatisfied, averaged.

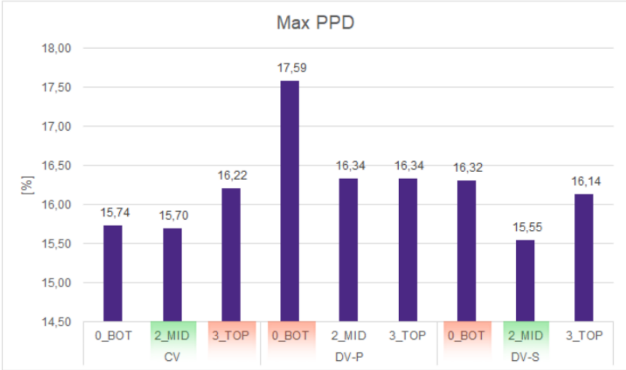


Figure 48: Results for Indoor Climate: Max PPD, averaged.

Lastly, chart in *Figure 48* for averaged percentage of people dissatisfied shows that even though differences are small, it is CV that scores best with 15,7% in Bottom and Middle apartments with DV-S achieving lowest percentage in Top apartment. DV-P on the other hand has the highest percentage of dissatisfied across all apartments.

To sum up the Indoor Climate results, in terms of CO_2 concentration DV-S performs the best, followed by DV-P and CV with highest CO_2 being the only system exceeding 1000 PPM across all apartments. DV systems keep CO_2 under 1000PPM. After analysing thermal comfort, we can see that CV has the highest number of hours during the year when the operative temperature exceeds 25 °C, both with and without cooling. Results for DV are substantially better with DV-P having up to 8-10 times less hours when T_OP > 25 in Bottom apartment and DV-S about 50% less then DV-P.

Lastly, when looking at results for percentage of people dissatisfied and hours when occupants were dissatisfied, CV scores best with DV-P and DV-S not far behind. The last finding can be explained by considering that PMV, and effectively PPD indicators take into account more indoor climate parameters then just CO_2 and operative temperature. High air velocity and therefore discomfort caused by air drafts can be a real cause of that.

The fact that CV results are worse than DV has been investigated but no definite cause has been found in the simulation files. One idea as to what could cause worse performance of centralised system in terms of carbon dioxide concentration and thermal comfort is airflow strategy. DV systems supply and extract much more area specific air into zones with occupants. This should be investigated more to optimise the simulation so the results would be more realistic.

4.5 Energy: CV vs DV-P vs DV-S

In this section, areal specific delivered energy to the apartments will be presented, broken down to different systems. Firstly, as shown in *Figure 49* overall analysis of which apartment has the highest energy consumption, averaged across analysed systems. We can see that from this perspective, all of them meet the base criterium of 95 kWh/m2/year. Middle apartment is the one with lowest yearly energy consumption of 65,1 kWh/m2/year, Top apartment is the next with 67,1 kWh/m2/year and Bottom apartment has the highest score of 91,9 kWh/m2/year.

The results differ because the flats are located facing different facades with different solar exposition, are located on different heights, which in turn leads to distinct way they are affected by wind and pressure variances

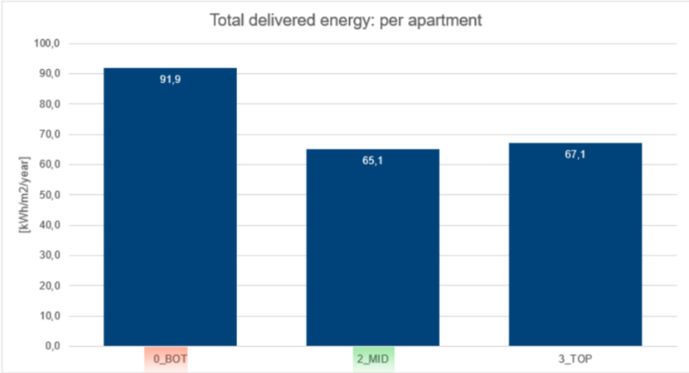


Figure 49: Energy results: per apartment.

Figure 50 shows energy breakdown by system for a whole year energy simulation, averaged across apartments. We see that averaged score for DV-P is the worst with 115,6 kWh/m2/year, with DV-S on the second place with 89,1 kWh/m2 and CV on top with the lowest 66,3 kWh/m2.

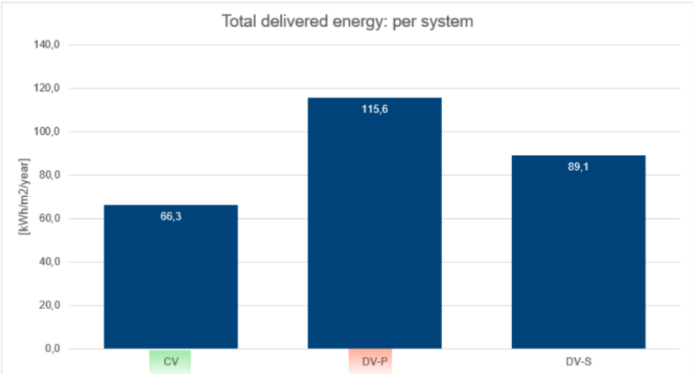


Figure 50: Energy results: per system.

Combined results of two before mentioned figures is presented on *Figure 51* where energy results are broken down by systems and then by apartments. To start off with apartment CV, we see that it is in the apartment 2_MID that this system achieved the best result with 61,9 kWh/m2/year. The differences to other apartments are not high and, all the results for CV lie under the line that indicates TEK17 § 14-2 energy requirement. For DV-P, the 2_MID apartment is on the verge of meeting the requirement scoring 95,9 kWh/m2/year while 3_TOP and 0_BOT are above the requirement with the latter scoring the worst of all analysed scenarios with score 151,0 kWh/m2/year. Lastly, DV-S results show that, once again, 2_MID is the apartment when this precise system has the lowest energy consumption of 73,4 kWh/m2/year, with 3_TOP on the second place, also below the TEK17 § 14-2 energy requirement. 0_BOT with score 119,7 kWh/m2/year is the only one for this system that does not meet the requirement.

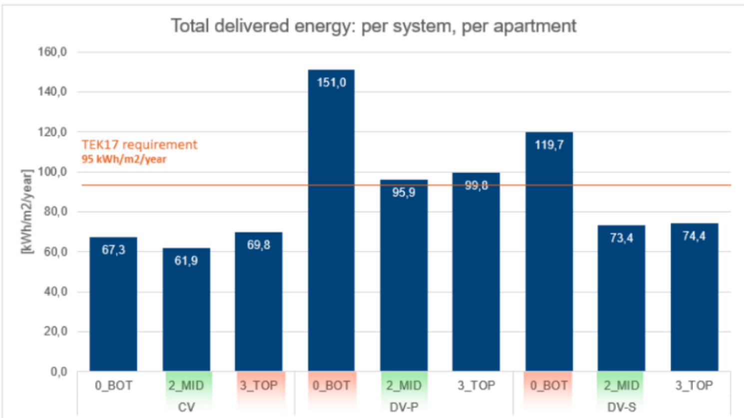


Figure 51: Energy results, per system and per apartment.

4.6 Energy usage breakdown

In this section, a breakdown to energy systems will be done. Three categories will be outlined: electrical cooling (consisting of AHU cooling and Zone cooling), Electrical heating (AHU- and Zone based heating) and HVAC aux (fans, pumps and humidity transport).

Starting with *Figure 52* showing the cooling results per system and per apartment, we see that in case of CV it is apartment 3_TOP that uses least amount of energy for cooling with result of 1,7 kWh/m2/year, and 0_BOT, with slightly higher score of 2,1 0_BOT is on the top for this system. Pair-Wise DV is a system that comparatively used the least among all systems with 2_MID scoring the highest 0,7 kWh/m2/year for cooling and 0_BOT with the lowest result of only 0,3 kWh/m2/year. Lastly, DV-S has very similar results to CV. From 2,1 for 0_BOT to 1,6kWh/m2/year for 3_TOP. By design, Pair-Wise system has to rely solely on zone-based cooling and thus loses on flexibility front comparing to centralised and Single-Unit DV.

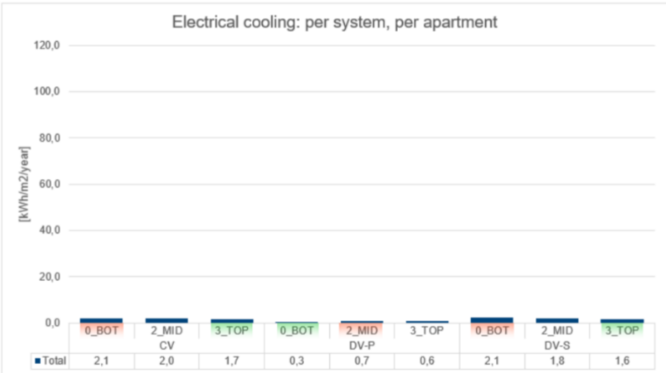


Figure 52: Energy results: electrical cooling, per system, per apartment.

Electrical heating breakdown, shown in *Figure 53* presents quite a different view. CV system shows similar results for all apartments with results from 19,2 for 2_MID to 28,9 kWh/m2/year for 3_TOP. DV-S comes out on the second place with the lowest score for 2_MID with 31,9 kWh/m2/year and highest for 0_BOT with 67,6 kWh/m2/year. DV-P, again, sticks out significantly, especially in 0_BOT apartment, where 117,2 kWh/m2/year goes for Electrical heating. This shows that there is a potential for improvement of heating system in this apartment in order to qualify it under TEK17 energy requirements. 2_MID is the apartment with lowest energy usage for Pair-Wise system. Overall, 2_MID apartment showed the lowest demand for electrical cooling across all systems. On the other hand 0_BOT scored highest for DV systems, while for CV it was 3_TOP apartment.

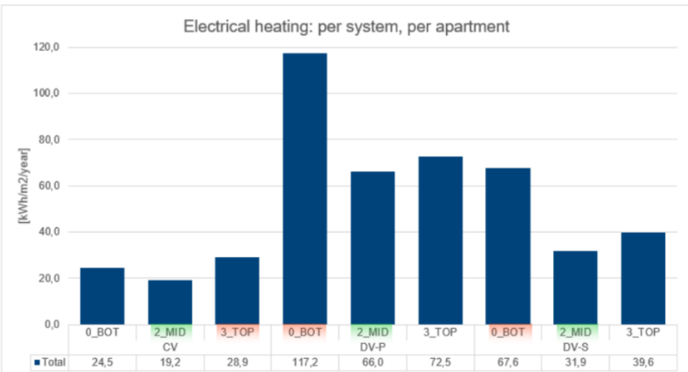


Figure 53: Energy results: electrical heating, per system, per apartment.

Figure *54* shows results of energy usage for HVAC aux, per system and per apartment. CV's score of 23,4 kWh/m2/year is the same across apartments due to the fact that it is one AHU serving three groups of zones, and that is why energy used for fans and pumps is distributed evenly. DV systems show a pattern of energy usage. 0_BOT apartment uses the most energy for HVAC aux, 16,0 in case of Pair-Wise and 32,4 kWh/m2/year for Single-Unit. 2_MID apartment sits in between with 3_TOP using the least amount of energy, 10,7 for DV-P and 17,2 for DV-S.

The breakdown of HVAC aux is one of the most interesting as the results are not what was hypothesized in the beginning of the study. Including DP_LINK into advanced IDA_ICE physics model, and by that influence of buoyancy and wind-stack effect was thought to bring the most instabilities to the apartment 3_TOP located highest. What results presented in Figure 54 show is the opposite, 0_BOT apartment is influenced the most. No further breakdown of HVAC aux was done, to find out what part of energy was dedicated to pumps, and what to fans. Despite that, we know that DV-P is only equipped with fans so HVAC aux result indicate decline in fans effectiveness. What is also surprising is the fact that it is DV-S which has been affected the most. One of the suspected reasons to that could be fan performance curve used for this system and the way that differential pressure affected supply and exhaust.

In conclusion, further work needs to be done on the matter of modelling DV units in IDA-ICE with a focus on different heights, different DP_LINK settings and Fan Performance curves in order to investigate dependence between these parameters. Choices taken in this study led to a situation when only a limited part of the problem has been highlighted.

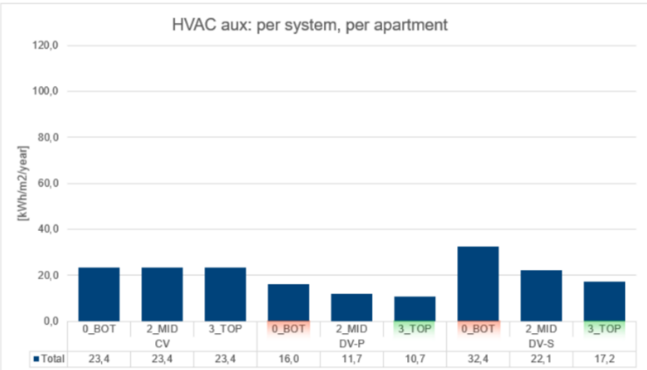


Figure 54: Energy results: HVAC aux, per system, per apartment.

To sum up, a combined electricity consumption for electrical heating, cooling and HVAC aux is presented in *Figure 55*. Please note that energy for lighting and equipment are not shown here so the results do not sum up to what was shown for total delivered energy in *Figure 51*. Since areal specific energy consumption for lighting and equipment is the safe across all apartments, and thus their part is equal, removing them from the total mix doesn't influence overall picture. 2_MID apartment is the apartment with overall lowest energy consumption across systems. For CV, it is 3_TOP with the highest, for DV-P it is the 0_BOT due to very high energy for electrical heating and in case of DV-S it is also 0_BOT for both high HVAC aux and heating.

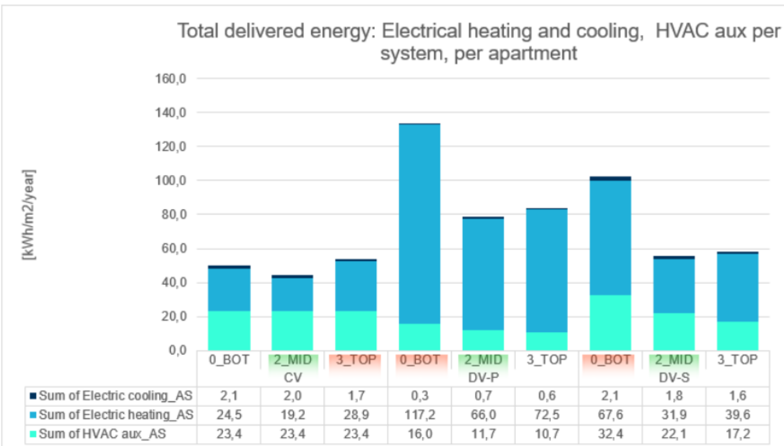


Figure 55: Energy results: Electrical cooling and heating, HVAC aux combined. Per system, per apartment.

4.7 Peak power demand

Figure 56 shows the maximal overall power demand per system, per apartment. Apartment-wise it is 0_BOT that has the lowest peak power of 2,1 kW for CV, 3,3 for DV-P and 3,9 for DV-S. System-wise CV scores the lowest with averaged 3,0 kW across apartments, and 0_BOT being the apartment with lowest result for this system. DV-P and DV-S are very similar, on average 4,0 kW peak demand for all apartments. For Pair-Wise it is 2_MID apartment that has the highest score of 4,4 kW, lowest 3,3 kW for 0_BOT. For single-Unit DV it also 0_BOT that has the lowest peak power of 3,8 kW, but this time it is 3_TOP with the highest, 4,3 kW.

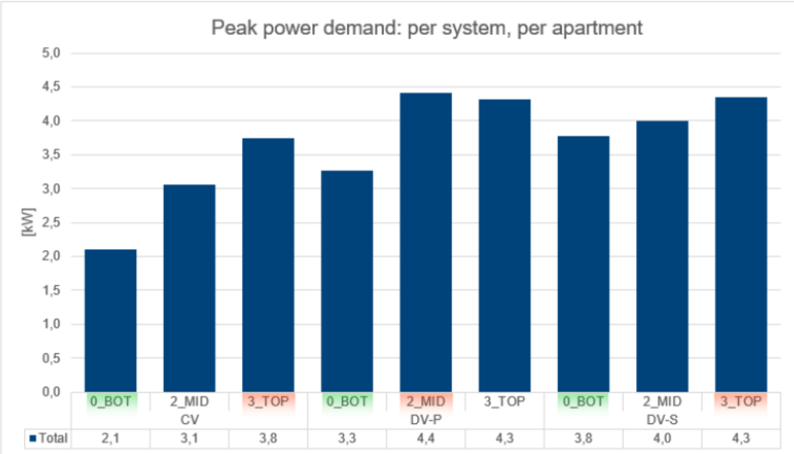


Figure 56: Energy results: 4477007Peak power demand: per system, per apartment.

4.8 Whole year analysis, cooling

Figure 57, Figure 58 and *Figure 59* show yearly variation of electrical energy spent for cooling for, respectively, CV, DV-P and DV-S. Overall, we see that cooling occurs from May to September with a peak in July for all systems. Comparatively, the highest nominal difference between June, August and July is present for CV, around 1300 W/m2 between the peak and June/August level.

Apartment-wise, again a clear trend: 3_TOP uses the most energy for cooling, followed by 2_MID and 0_BOT. Jumps in energy consumption are more readily visible for 3_TOP then other apartments like for example from June to July where initial 500 W/m2 in June raised to 1800 W/m2 for 3_TOP apartment.

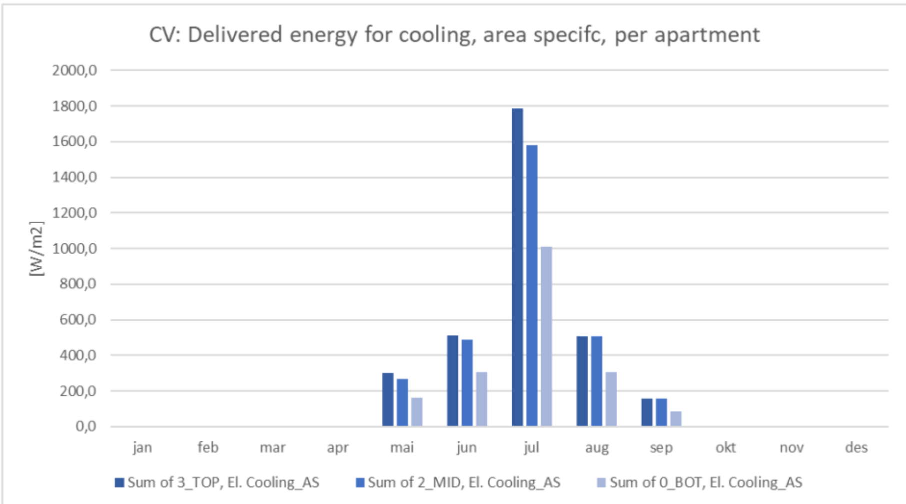


Figure 57: Energy results: Electrical cooling, variation through the year for CV.

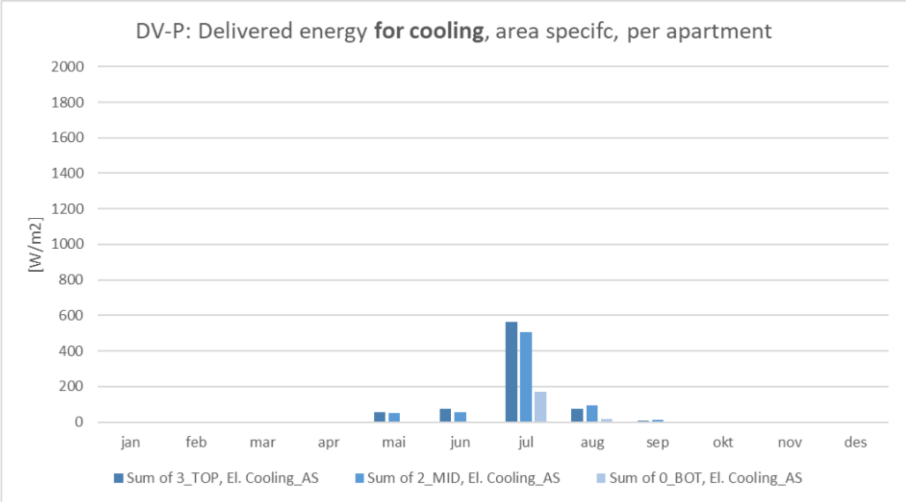


Figure 58: Energy results: Electrical cooling, variation through the year for DV-P.

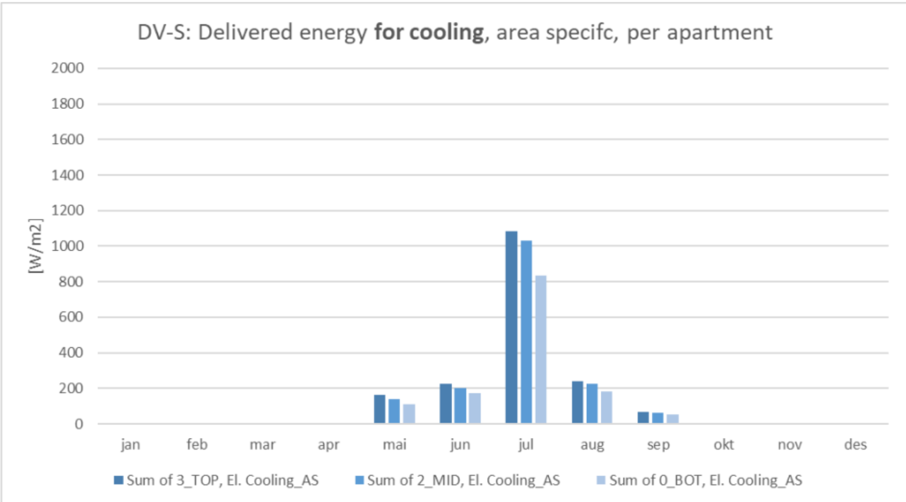


Figure 59: Energy results: Electrical cooling, variation through the year for DV-S.

4.9 Whole year analysis, heating

Figure 60, Figure 61 and *Figure 62* present electrical heating analysis in a similar fashion as it was done in previous section. Again, we observe that the overall trend during the year is similar for all systems. Heating occurs in all months with the heating season clearly starting in October and ending in Mai. The longest period of heating happens for DV-S for 0_BOT apartment, as we see that heating is active there throughout the year, even in July and August. The shortest on the other hand is in case of CV with almost no heating from June to August.

In case of CV, it is always 3_TOP that scores highest for areal specific heating, achieving also the highest spikes in energy from month to month (around 4 kW/m2 from December to January) and with highest differences comparing to other two apartments (7 kW/m2 more then 2_MID and 10 kW more then 0_BOT). Worth noting that already in September and especially in October 3_TOP uses substantially more energy on heating, around 2 kW/m2. 2_MID and 0_BOT are more similar to each other, both in pattern and size.

For Pair-Wise, it is also 3_TOP apartment with highest heating demand, peaking in January with value of 20 kW/m2. Second place is 0_BOT with highest around 16 kW/m2 in January and then 2_MID with 15,5 kW/m2 in the same month.

Similar trend to DV-P can be observed for DV-S, where 2_MID sits between 3_TOP and 0_BOT. Peaks are lower though, then in case of Pair-Wise reaching as high as 14 kW/m2 in January for 3_TOP, 12,5 kW/m2 for 0_BOT and 10 kW/m2 for 2_MID.

Apartment-wise, trends between CV and DV differ. While for centralised system we see an order from the highest heating demand represented by 3_TOP and ending with 0_BOT, for decentralised system, it is 2_MID that scores lowest. Relative difference between 3_TOP and other apartments is always the highest across all systems.

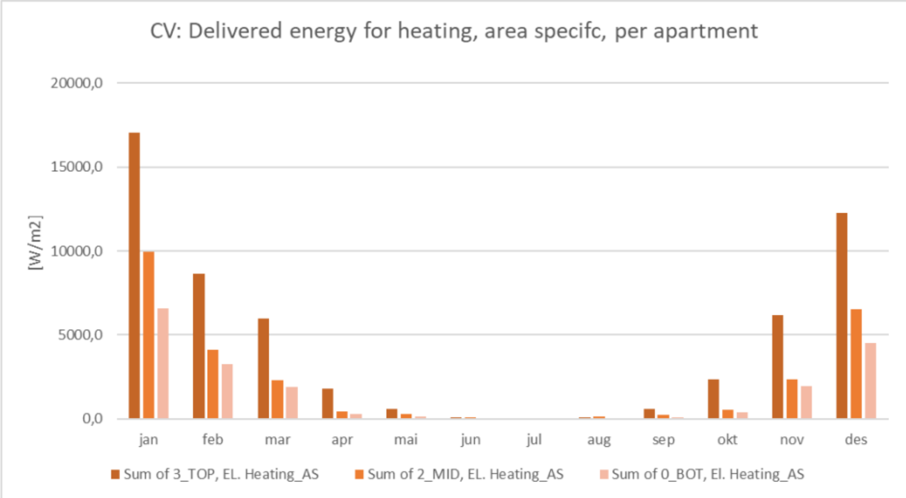


Figure 60: Energy results: Electrical heating, variation through the year for CV.

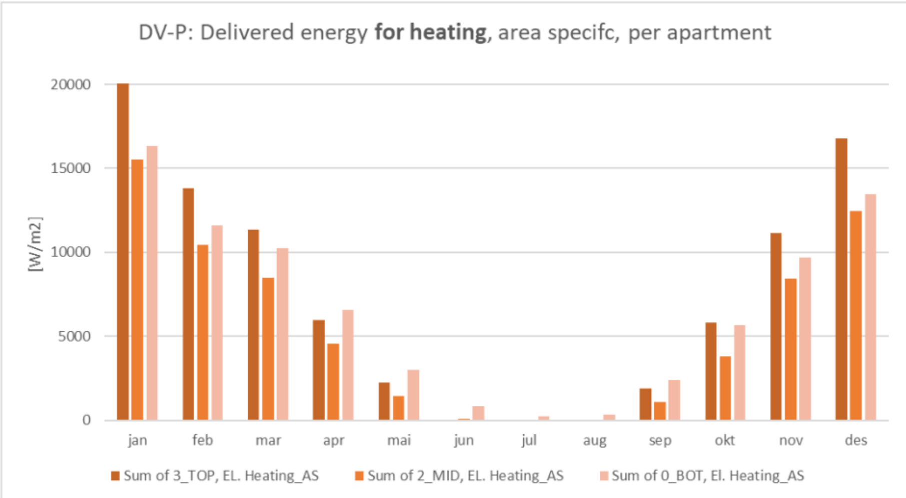


Figure 61: Energy results: Electrical heating, variation through the year for DV-P.

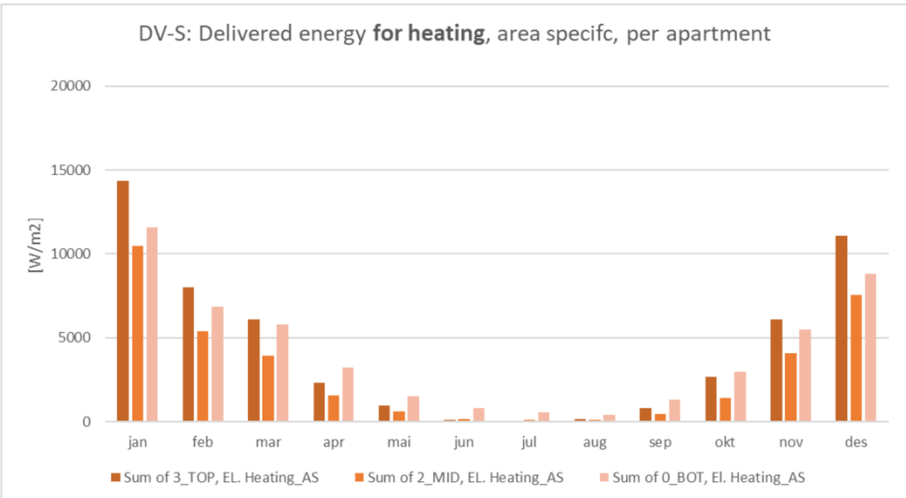


Figure 62: Energy results: Electrical heating, variation through the year for DV-S.

4.10 Whole year analysis, HVAC aux

Lastly, HVAC aux yearly variation during the year, presented in *Figure 63, Figure 64* and *Figure 65will* be discussed in this section. At first glance, we see differences between centralised and decentralised systems. CV's results are characterized by big differences between apartments. 3_TOP uses on average 20% more then 2_MID, and 60% then 0_BOT in all months of the year. In case of DV systems, differences between apartments are much smaller.

Differences in CV case can be explained in terms of a real scenario in which central AHU is placed on the lowest floor, thus nearest 0_BOT apartment. Then, the pressure loss in ducts rises with each floor leading to increased energy usage. Unfortunately, a description of placement of the AHU for centralized system could not be found in IDA-ICE and therefore this explanation cannot be scrutinized.

We see around 30% increase in energy usage between DV-P and DV-S across all apartments, during all months. The trend apartment-wise is also different. For DV-P it is always 3_TOP with 15% higher energy for fans then 2_MID and 25% higher than 0_BOT. This can be argued as a direct cause of DP_LINK for DV-P system. The higher the apartment is located, the lower the efficiency of fans and the higher the energy usage.

DV-S energy consumption pattern for pumps and fans is almost opposite, with 3_TOP scoring the lowest energy and 0_BOT highest. Again, this is opposite to the assumed behavior, described already under *Figure 54*.

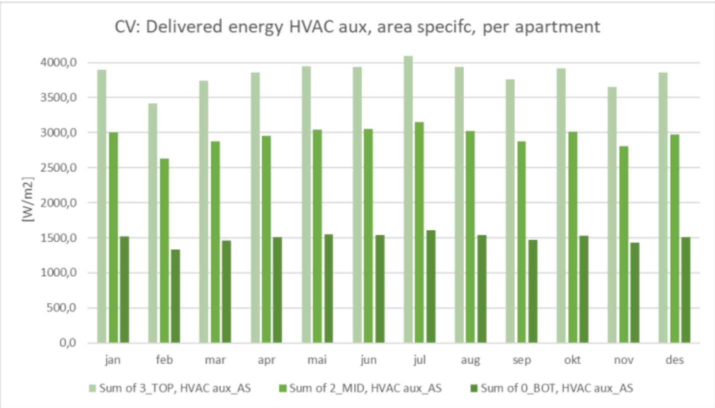


Figure 63: Energy results: HVAC aux, variation through the year for CV.

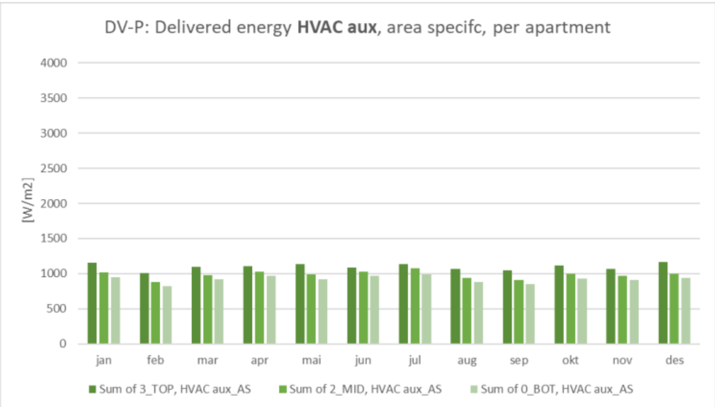


Figure 64: Energy results: HVAC aux, variation through the year for DV-P.

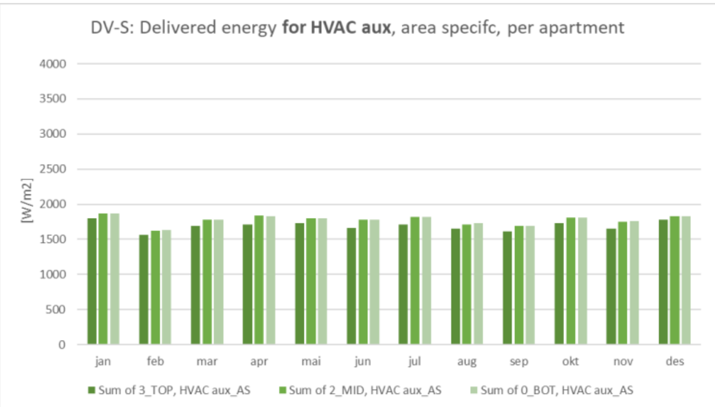


Figure 65: Energy results: HVAC aux, variation through the year for DV-S.

4.11 Summary of the results

For summary, a table presented below shows overall results divided in four categories: Indoor Climate, TEK 17 § 14-2 results, Energy (electrical) and technical parameters. It was decided to use semi-objective nomenclature and where it is not possible to express in numbers, words like "Good", "Poor' and "Medium" were used. Some disclaimers that serve as explanation to the tables:

(1): Acceptable results for CO_2 mean that the system is slightly above 1000 MAX PPM CO_2 on average

(2): Good results for CO_2 mean that the system is under 1000 MAX PPM CO_2 on average

(3): Poor results for T_OP mean that there is substantial number of hours with T_OP over 25 °C.

(4): Good results for T_OP mean that there are manageable number of hours with T_OP over 25 °C.

(5): DV-P has no cooling coil, thus with "Lowest" it's meant to express the overall energy spent for cooling in case of DV-P, not that cooling delivered by DV-P is most energy efficient.

(6): DV systems do not meet the requirement for the proposed placement of DV as described in Chapter 3.8

(7): Source: (Thorstensen, 2022)

"Good" means that two systems are equal in terms of a parameter, i.e., heating.

"Medium": is used mostly for DV-S. It means worse than CV, better DV-P and NoAHU.

System description	System	NoAHU Natural Ventilation	CV Centralised Ventilation	DV-P Decentralised Pair-Wise	DV-S Decentralised Single-Unit
	Description	Natural ventilation only	Centralised Ventilation	Decentralised Ventilation, Pair-Wise type	Decentralised Ventilation, Single-Unit type
	Openable windows	Yes	Yes	Yes	Yes
Indoor Climate	CO2 *Air quality*	Very poor	Acceptable (1)	Good (2)	Good (2)
	T_OP *Thermal comfort*	Very poor	Poor (3)	Good (4)	Good (4)
TEK17 §13 compliance	Transport of humidity, odour *TEK17 §13-1(1,3-6)*	Requirement not met	Meets requirement	Requirement not met (6)	Requirement not met (6)
	Filtering outside air *TEK17 §13-1(2)*	Requirement not met	Meets requirement	Potential problem due to poor filtering possibilities	Meets the requirement
	Bedroom ventilation *TEK17 §13-2(2)*	Requirement not met	Meets requirement	Requirement not met (6)	Requirement not met (6)
	Extract kitchen, bath *TEK17 §13-2(4)*	Requirement not met	Meets requirement	Requirement not met (6)	Requirement not met (6)
Energy, electrical	Heating *Comparative*	Not evaluated	Lowest	Highest	Medium
	Cooling *Comparative*	Not evaluated	Good	Lowest (5)	Medium
	HVAC aux *Comparative*	Not evaluated	Good	Lowest	Medium
	Total energy *TEK 17 §14-2*	Not evaluated	Best (<95 kWh/m2)	Worst (>95 kWh/m2)	Good (<95kWh/m2)
	Best apartment *Lowest energy consumption*	2_MID	2_MID	2_MID	2_MID
Technical parameters	Investments costs	Lowest	Highest (AHU and ducts) (7)	Lowest	Middle (7)
	Installation *Difficulty*	Very easy	Most difficult	Lowest	Middle
	Filter types available	Very poor	Wide range, from coarse to fine	Only coarse G3	From G3 to F7
	Cooling capacity	None	Best	None	Middle
	Heating capacity	None	Best	None	Middle
	Heat recovery	None	Best	Worst	Middle
	Control possibilities *Invidividual*	Limited (window opening)	Limited (with AHU/building)	Invidividual control is possible, per room.	Invidividual control is possible, per room.
	Required space	Very little	Big (AHU, ducts)	Smallest (unit in ext. Wall only)	Medium and can require ducts
	Maintenance *Per occupant*	Very easy	Easy	Can be demanding	Most demanding

Table 20: Summary of Indoor Climate, TEK § 13 compliance tests, energy, and technical parameters. Indoor Climate and Energy results are averaged across apartments. Energy results given as areal specific.

5 Conclusions

Based on the results obtained by performing a series of energy simulations in IDA-ICE and a set of chosen given boundary conditions together with settings within the used tools, there has been drawn conclusions that will be outlined in this section.

Main research question: energy efficiency of CV vs DV-P and DV-S

First analysed scenario, which is NoAHU, turned out to be the best energy-wise. Although, it was quickly disqualified from further investigation due to unacceptable levels of CO_2 and operative temperature with or without cooling (according to IDA-ICE nomenclature). Indoor climate indicators were exceeded greatly in the case of this system.

System-wise, centralised ventilation came out as the most energy efficient in a sense that net energy demand for this system was the lowest, based on the results, even despite high energy consumption for HVAC aux (pumps, fans). The results for CV are consistently within the TEK17 § 14-2 energy requirement and lower than those of DV-P and DV-S. Considering acceptable indoor climate indicators, centralised solution is an overall best system based on the obtained results.

DV Pair-Wise consumed the biggest amount of energy, especially on the heating part. None of the results of DV-P met the TEK17 § 14-2 requirement with the Middle apartment being the closest. In general, poor heat recovery and relying solely on room-based heating render this solution as the worst in relation to competitors. Indoor climate is acceptable or in some respects better then CV. It is also worth noting that DV-P has low (up to 50 m^3/h) airflow capacity and at least two units per room are required which can be technical challenge. Moreover, Pair-Wise units have no possibility for integrating with building's piping system.

DV Single-Unit sits right in between CV and DV-P, both energy-wise and in terms of indoor climate. Besides Bottom apartment, it met TEK17 § 14-2 energy requirement. Versatile design with both heating and cooling coils, and heat recovery comparable to CV makes this solution a potential alternative to centralised ventilation.

Apartment-wise, Middle apartment (2_MID) turned out to be the one with the least energy consumption across all systems. Hypothesis about differential pressure being a deciding factor for overall energy consumption of decentralised ventilation couldn't be confirmed by the simulations. In some cases, for the DV Single-Unit, the effect was opposite to expected.

Side research question 1: placement of DV units

As described in *Chapter 3.8*, placement of DV-P and DV-S units within 3 different apartments has been proposed. In presented approach, decentralised units are placed on each far end of apartments (living rooms and bathrooms). While it serves its purpose in terms of leading air masses through all the zones, it comes with challenges. Question of transporting the humidity, pollutants and odour through apartments has been raised. Principles of air movement from clean towards polluted zones and removing pollutants nearest their source, as described in SINTEF's building detail 552.301, are not followed. This forms a risk for occupants' health and comfort and should be addressed. It was proposed to investigate control strategies that using humidity, CO_2 and VOC sensors would adjust amount and direction of airflows to account for the risks.

Side research question 2: impact of air pressure differences on DV function

Advanced macro in IDA-ICE has been implemented in order to simulate and investigate effects of air pressure on efficiency of small fans installed in decentralised units. Additionally a realistic fan performance curve has been implemented in DV AHU based on one axial and one centrifugal fans. Unfortunately, no conclusion could be made as of the effect are important in measurable.

As mentioned earlier, the expected decline in effectiveness only partly occurred. More extensive research on this part should be performed. As written in *Chapter 3.12*, it has been assumed that there is no air exchange (infiltration) between floors, between apartment and between apartments and staircases (and other external spaces). Complete air-tightness, despite advanced treatment of differential pressure, may have resulted in negligible or opposite results.

Other conclusions

Process of modelling decentralised ventilation in IDA-ICE turned out to be challenging which led to uncertainties further ahead in the work on the thesis. The DV solution is not pre-programmed in the software itself. Due to time constraints, it was chosen to use CV as a template combining with various airflows strategies as described in methodology chapter.

Forced ventilation in kitchen has been shortly discussed by pointing out use of downdraft hoods to take care of forced extract due to its amount of 250 m^3/h.

A step-by-step workaround for IDA-ICE has been proposed, that could bring it closer SIMIEN built-in function for TEK17 § 14-2 evaluation, energy-wise. Detailed instructions are documented in appendix section.

Summary of findings:

- Centralised ventilation system is most energy efficient according to the obtained results. Single-Unit DV takes second place, while Pair-Wise DV turned out to be the least efficient of analysed systems.
- Indoor Air Quality is not greatly affected by either of the analysed systems. To some degree, DV-S and DV-P systems can perform better in this regard than CV.
- Impact of air pressure differences on energy consumption couldn't be fully investigated but the results suggest that it isn't very significant.
- There is still immense potential in further development of control strategies for DV. VAV and DCV present opportunities for greatly improved energy performance for decentralised systems by fully utilize their possibilities.
- Building Software Simulation tools shall be equipped with pre-programmed ways to model DV ventilation to allow more accurate representations of specific physical phenomena related to that technology that differentiate it from centralised systems. In turn it would contribute to wide-spreading these solutions among professionals.

6 Further research

Scope of this study was limited to energy performance and comparison of one centralised and two decentralised ventilation systems. Another restricting factor was of course the time spent to write this thesis, perform the simulations, and describe them. These constraints led to an array of problems and questions that still can be deepened and explored. In this section some areas of further research will be outlined in this fascinating field of decentralised ventilation for residential buildings as the author of this thesis honestly believes in its unfulfilled potential and room for significant improvement and more widespread application.

Firstly, a study on impact of climate for decentralised systems should be performed. Challenges with pressure differences, stack-effect, and frosting protection are among the topics that depend on outdoor temperature and location. A "heat-map" showing applicable areas within, let us say, Scandinavia where DV systems could be applied to the advantage over centralised systems are just one of examples of such climate-based study.

Additionally, to answer the second research question in better way, a physical model of internal air leakages between floors could be made. In case of DV Pair-Wise, it would be also interesting to investigate how these devices influence each other in terms of fan efficiency and heat recovery, that is working as a connected system, especially in oscillating mode.

Secondly, diving deeper into plant and energy supply system should be done. Advanced, dynamic ways of modelling heat pumps would bring the simulation to another level. This study used a standard "Plant" built-in in IDA-ICE, while there is a whole advanced module called ESBO Plant worth investigating.

Another important aspect is including VAV, preferably in form of DCV in the energy simulation of decentralised ventilation systems. There is considerable potential to be used when it comes to controlling smaller, separated parts of a ventilation system for both comfort and energy consumption. The decentralised paradigm calls for more advanced methods involving smart meters and self-learning to meet constantly changing occupancy variations and user needs.

An economic study on different specific decentralised ventilation products and systems should be done. A LCC or LCA analysis together with technical costs of rebuilding existing building mass would be an interesting further take on the problem of adapting rehab apartments to newcoming standards.

Furthermore, using other tools than the one utilized in this study, which is IDA-ICE is a practical way to go. Not only to exchange this application for another one, but to perform a comparative analysis between them. As previously mentioned, there are other leading examples of building simulation software such as TRNSYS or EnergyPlus or SIMIEN. Additionally, this dynamic simulation tools can be accompanied by Computer Fluid Dynamics, numerical studies and other. It all could broaden understanding of DV systems as the demand for it is real. Just to mention the need for a representative template within IDA-ICE itself that would stand for decentralised system more properly.

Lastly, modelling the DV-P and DV-S systems needs refinement and more detailed approach in further studies using Building Simulation Software such as IDA-ICE. Overall physical model should be adjusted in a way that it resembles decentralised ventilation system in more correct way. An important part of it is modelling heat recovery unit. An independent system template should be derived in IDA-ICE that can reproduce more proper physics concerning DV-P and DV-S solutions. This study, as previously mentioned, used a default starting system in IDA-ICE for centralised ventilation. Problem of scale, among other issues, such us heat recovery and efficiency of heating and cooling coils, should be addressed in future.

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8 Appendices

Appendix A: DV units overview on Norwegian market – November 2022, detailed table

Overview: manufacturer and product, Airflow capacity, Fan type, SFP, Power usage, HRU type, HRU efficiency, filter type, cooling, and heating capacities.

Manufacturer	Product	Airflow capacity, max	Fan type	SFP	Power usage, max	HRU type	HRU eff, max	Filter	Cooling capacity	Heating capacity
[-]	[-]	[m3/h]	[-]	[kWh/m3/s]	[W]	[-]	[%]	[-]	[W]	[W]
DV-P, Regenerative HRU										
Lunos	e2 60	60	Axial	0,37 (40 m3/h) 0,43 (60 m3/h)	0,3 - 3,3	Regenerative	88% (40 m3/h) 83% (60 m3/h)	G3	-	-
Lunos	eGO	20	Axial	Not specified	Not specified	Regenerative	Not specified	Not specified	-	-
Lunos	Silvento	90	Axial	Not specified	Not specified	Regenerative	Not specified	Not specified	-	-
Helios	EcoVent Verso	45	Axial	Not specified	1,6 - 4,5	Regenerative	88%	G3	-	-
Flexit	Roomie Dual	30	Axial	Not specified	2,9 - 6,8	Regenerative	70 - 80%	G3	-	-
DV-S, Recuperative HRU										
Airmaster	AM series, example 150	147	Not specified	Around 1,2	38	Recuperative	Not specified	50% ePM_10	700	500-1000
TROX	FSL B ZAB SEK	150	Centrifugal	1	23	Recuperative	Not specified	Extract: G3 Supply: F7	400	1000
SWEGON	Freeair-100	100	Not specified	0,22 - 0,24	38	Recuperative	94% at 50% RH	Supply: ePM10 or ePM1 (pollen filter) Extract:	-	-

…continuation of the table above: manufacturer and product (…) frost protection, installation notes, controls, and comments.

Manufacturer	Product	Frost protection	Installation	Controls	Comments
[-]	[-]	[-]	[-]	[-]	[-]
DV-P, Regenerative HRU					
Lunos	e2 60	Not specified	Outer walls from 280mm, ø160.	Possible.	
Lunos	eGO	Not specified	Outer walls from 280mm, ø160.	Possible.	Can be used as forced extract, up to 45 m3/h but then without HR.
Lunos	Silvento	Not specified	To be installed in a recessed cabinet in the wall	Humidity, temp sensors, schedules, VOC, occupancy.	
Helios	EcoVent Verso	Not specified	Outer walls from 280mm, ø160.	Software from Helios for advanced controls from PC	
Flexit	Roomie Dual	Down to -15 Celsius	Outer walls from 280mm, ø160.	Flexit software for synchronising pairs of DV-P units	
DV-S, Recuperative HRU					
Airmaster	AM series, example 150	Not specified	Ceiling mounted, condense water extract needed	Not specified	
TROX	FSL B ZAB SEK	Not specified	Under ceiling, under sill, wall mounted	Modular control system FSL-CONTROL II, specially for decentralised ventilation systems	
SWEGON	Freeair-100	Automatic bypass-control at about -5°C outside	In the external wall, from 320mm wall thickness	CO2, temperature control + 5 levels	

Appendix B: Global simulation settings

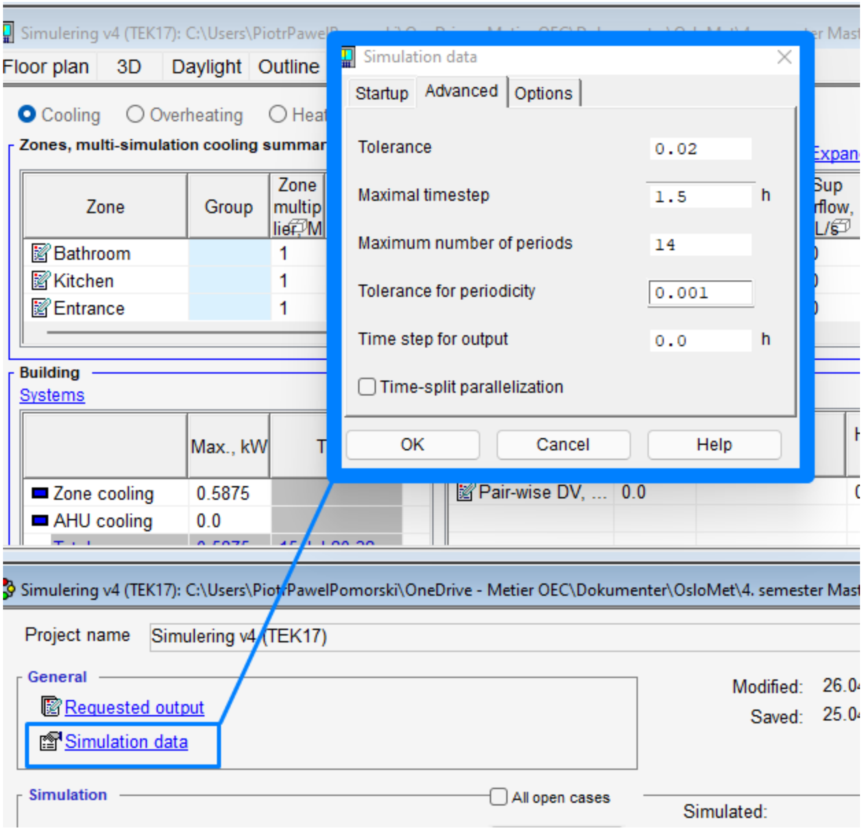


Figure 66: Advanced simulation settings in IDA-ICE. Tolerance, maximal timestep, periodicity.

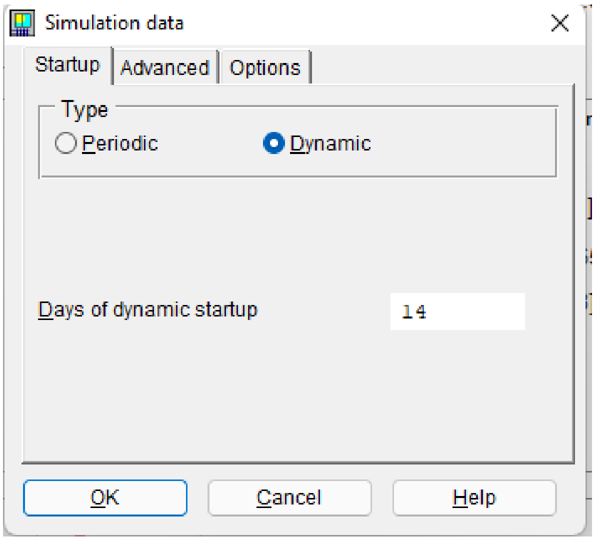


Figure 67: Start-up simulation settings. IDA-ICE

Appendix C: Advanced settings for adiabatic external walls

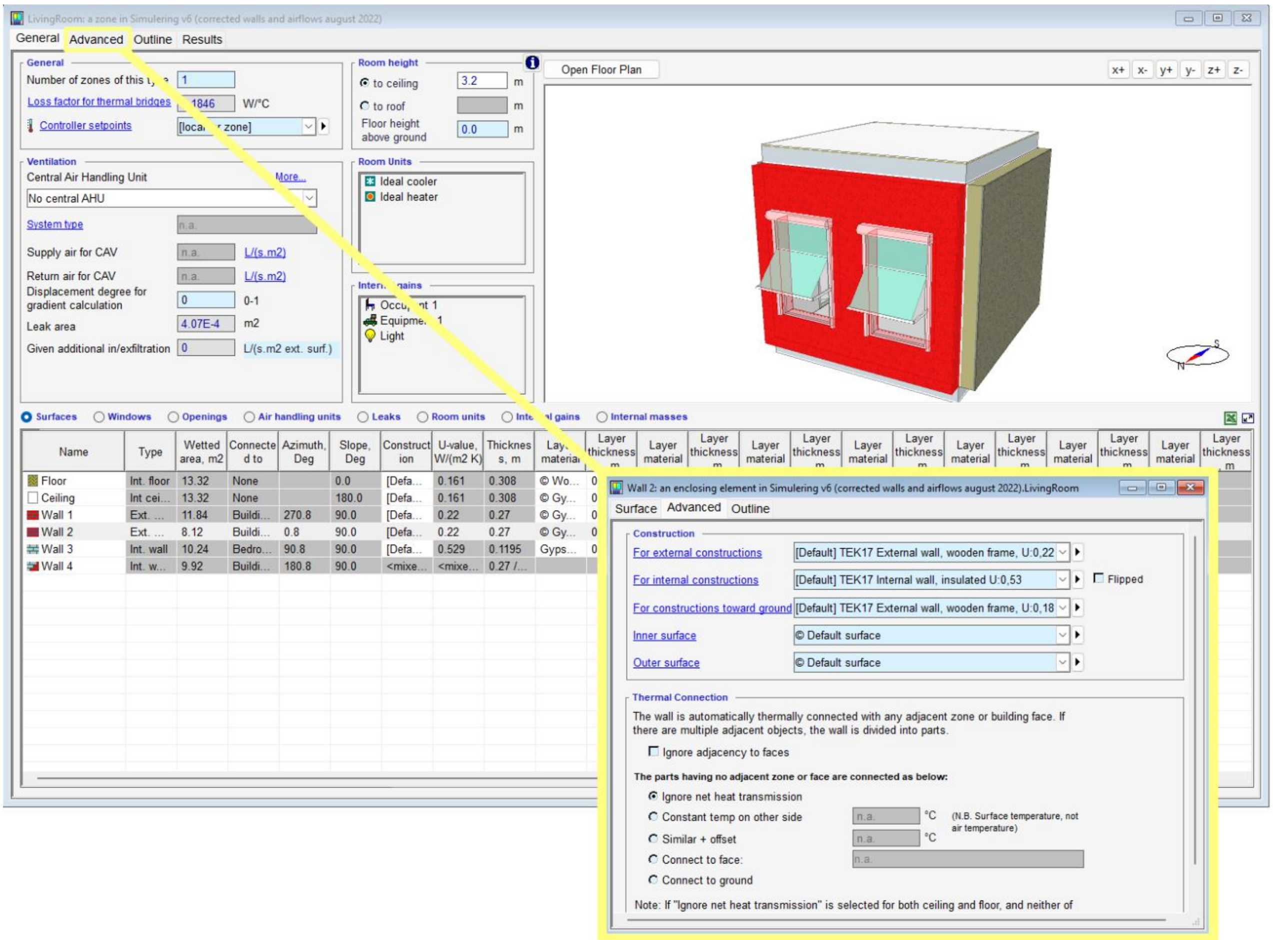


Figure 68: Treatment of external surfaces having no adjacent zones. Advanced wall settings in IDA-ICE.

Appendix D: Thermal bridges, ground properties, infiltration, pressure coefficients and system parameters, default values from IDA-ICE

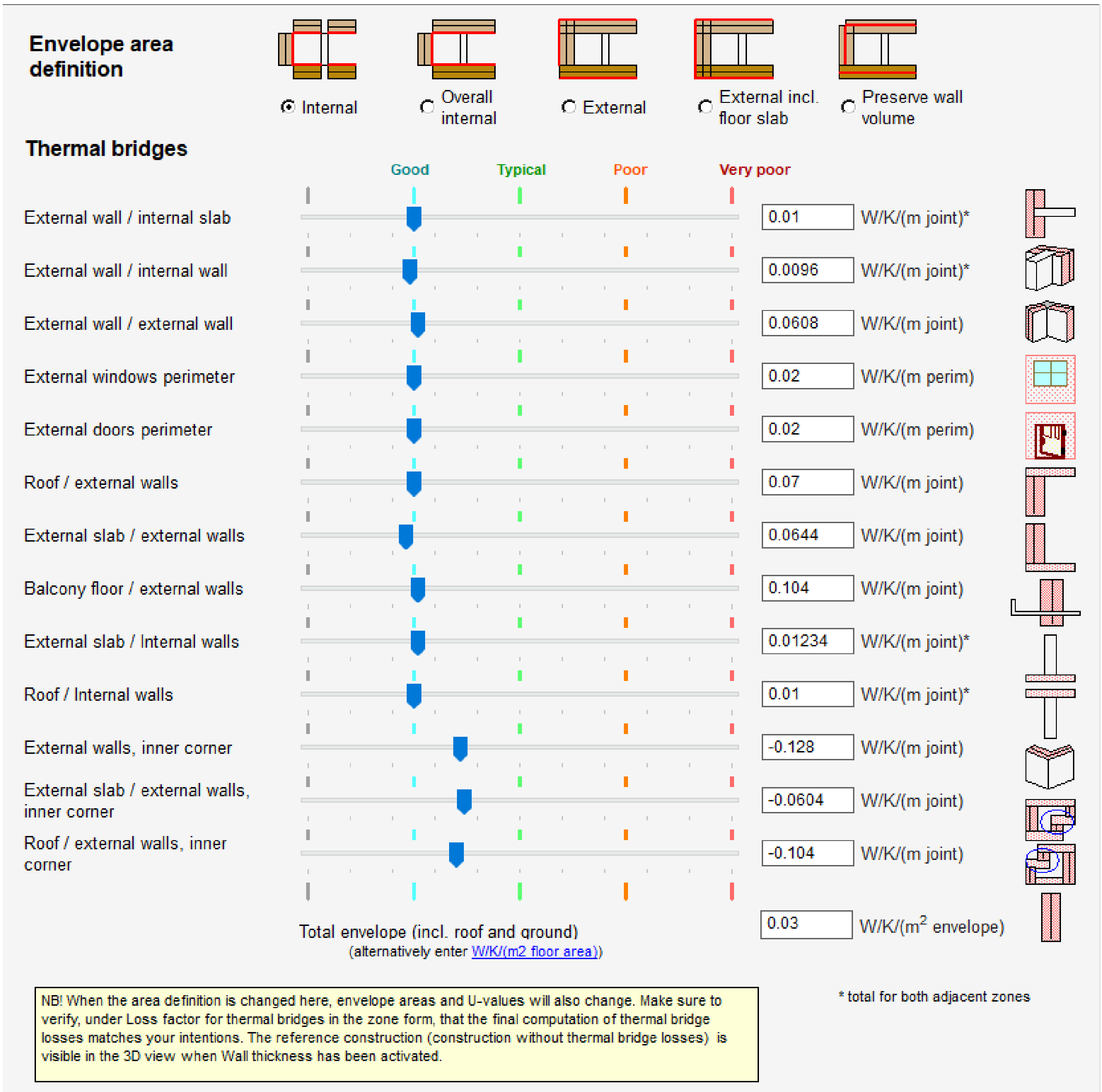


Figure 69: Thermal bridges used in simulations in IDA-ICE.

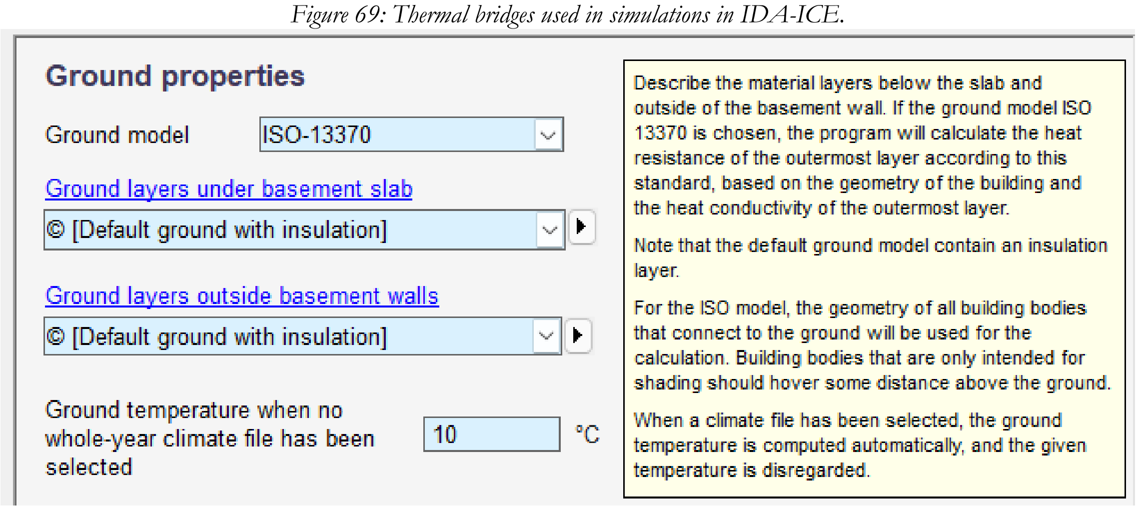


Figure 70: Settings of ground properties in IDA-ICE.

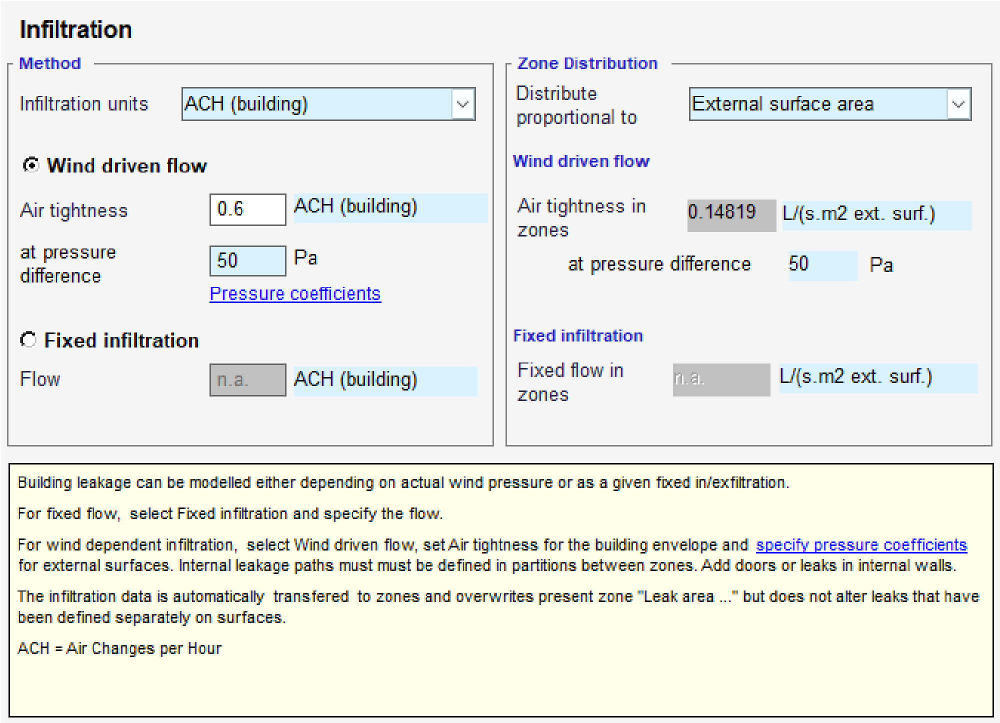


Figure 71: Infiltration settings in IDA-ICE.

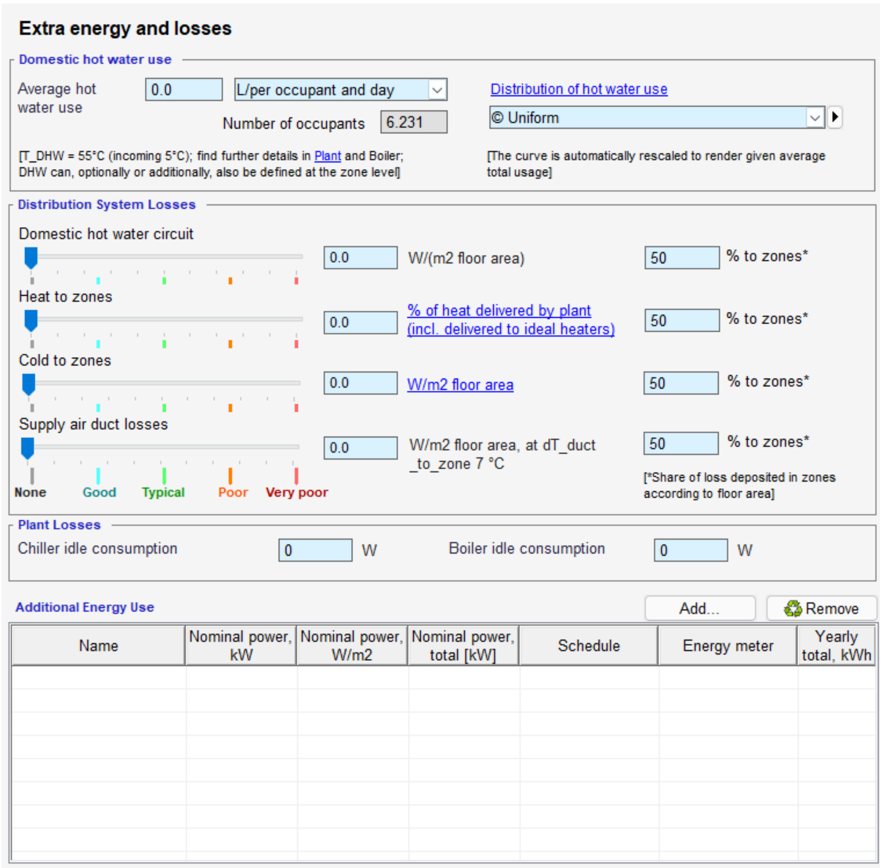


Figure 72: Extra energy and losses, kept default in IDA-ICE.

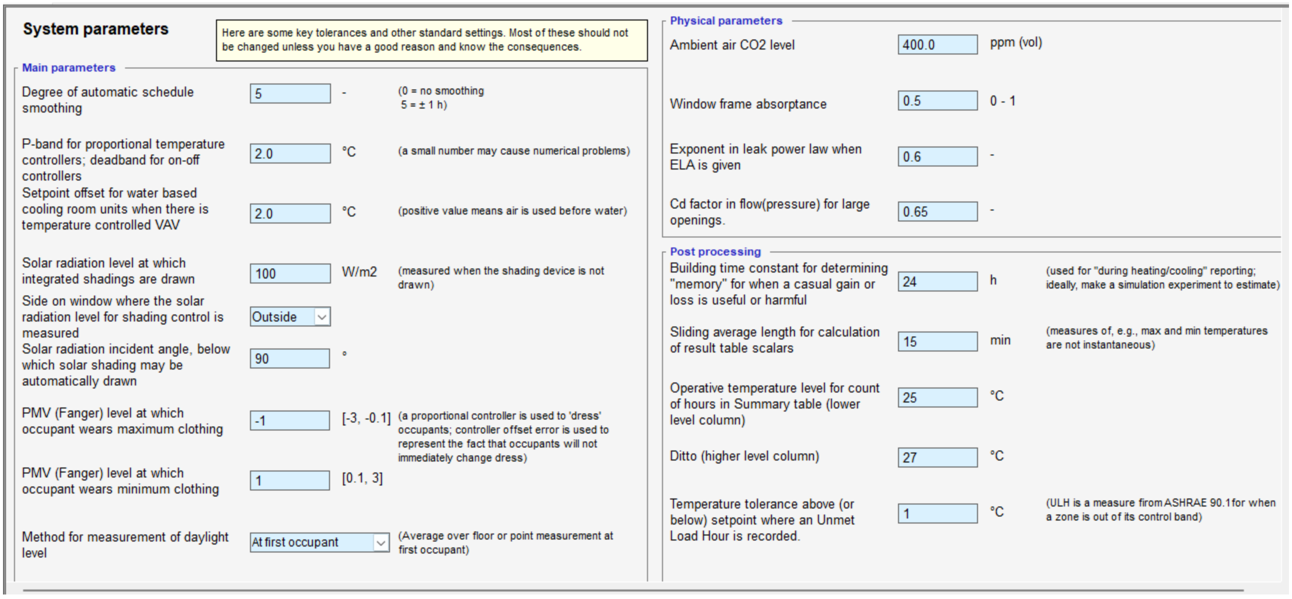
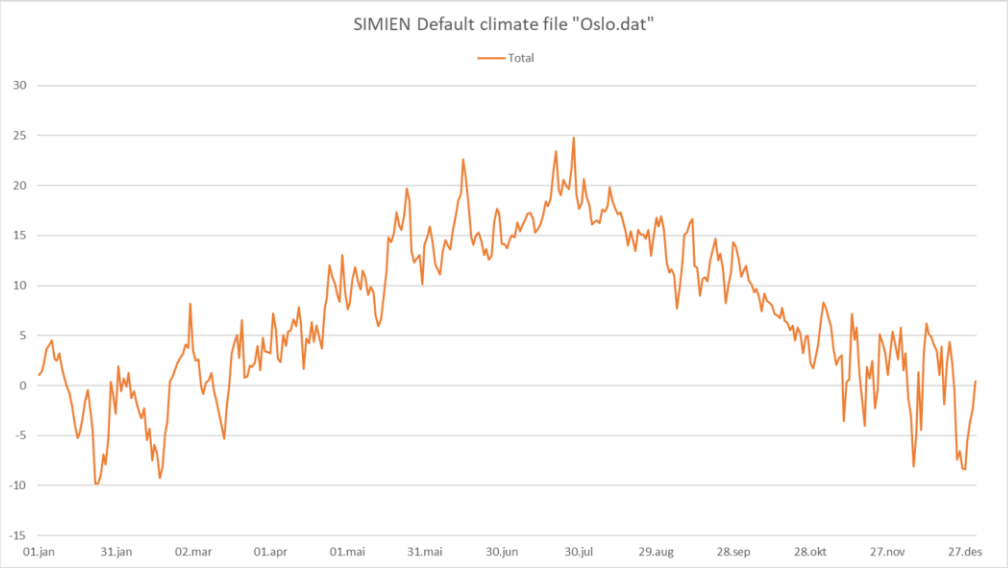
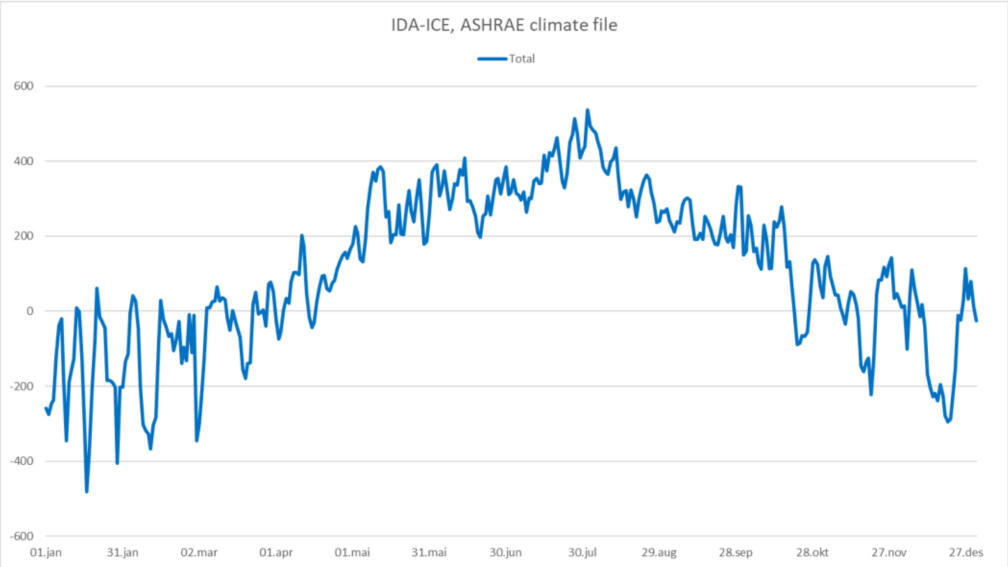
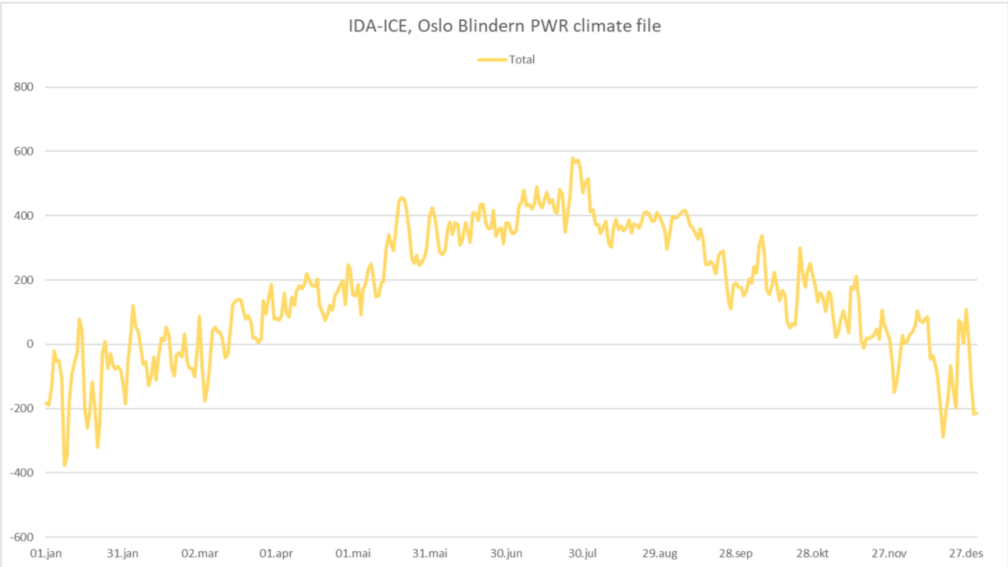


Figure 73: System parameters, kept default, in IDA-ICE.

Appendix E: Climate files, dry-bulb temperatures







Appendix F: Simulation files overview

Overview (part 1): Description, Energy, Climate file chosen, shading settings.

Overview simulation files						Climate	
	Simulation file / building code	Version	Status	Description	Energy [kWh/m2/yr]	Climate file chosen	Shading settings
TEK17	Requirement values from TEK17	-		Whole building	≤ 95	Oslo Climate, synthetic	No shading
SIMIEN	Whole_Building_SIMIEN.smi	1	👍	Whole volume of the building as a one zone	94,5	Oslo Climate, synthetic	No shading
IDA-ICE	Whole_Building_TEK17_EV.idm	1		Whole building, one zone per floor	102	Oslo/Gardermoen synthetic	No shading
	Whole_Building_TEK17_EV.idm	2		Whole building, one zone per floor	101,5	Oslo/Gardermoen synthetic	No shading
	Whole_Building_TEK17_EV.idm	3		Whole building, one zone per floor	101,5	Oslo/Gardermoen synthetic	No shading
	Whole_Building_TEK17_EV.idm	4		Whole building, one zone per floor	96,6	Oslo/Gardermoen synthetic	No shading
	Whole_Building_TEK17_EV.idm	5		Whole building, one zone per floor	96,38	Oslo/Gardermoen synthetic	No shading
	Whole_Building_TEK17_EV.idm	6	👍	Whole building, one zone per floor	94,86	Oslo/Gardermoen synthetic	No shading

Overview (part 2): U-values for building envelope

Overview simulation files				Building envelope								
	Simulation file	Version	Status	U-OutWalls [W/m2K]	U_BsmntWall [W/m2K]	U-InternWalls [W/m2K]	U-Roof [W/m2K]	U-GroundFloor [W/m2K]	U-InternFloor [W/m2K]	U-ExternFloor [W/m2K]	U-WindDoor [W/m2K]	U-ThBrdg [W/m2K]
SIMIEN	Whole_Building_SIMIEN.smi	1	👍	0,15	N/A	N/A	0,09	0,1	N/A	N/A	0,77	0,030
IDA-ICE	Whole_Building_TEK17_EV.idm	1		0,15	0,15	0,53	0,09	0,10	0,16	0,16	0,70	0,030
	Whole_Building_TEK17_EV.idm	2		0,15	0,15	0,53	0,09	0,10	0,10	0,10	0,70	0,030
	Whole_Building_TEK17_EV.idm	3		0,15	0,15	0,53	0,09	0,10	0,10	0,10	0,70	0,030
	Whole_Building_TEK17_EV.idm	4		0,12	0,12	0,53	0,08	0,08	0,08	0,08	0,60	0,025
	Whole_Building_TEK17_EV.idm	5		0,12	0,12	0,53	0,08	0,08	0,08	0,08	0,60	0,025
	Whole_Building_TEK17_EV.idm	6	👍	0,10	0,10	0,53	0,08	0,08	0,08	0,08	0,60	0,025

Overview (part 3): Leakage n50, efficiency of heat recovery, SFP, Natural ventilation, schedules.

Overview simulation files				Ventilation				Schedules		
	Simulation file	Version	Status	Leakage_n50 [ACH]	HRU_eff [%]	SFP [kW/m2/s]	Natural_ ventilation	Schedule_ Light	Schedule_ Equipment	Schedule_ Occupancy
SIMIEN	Whole_Building_SIMIEN.smi	1	👍	≤ 0,6	≥ 80%	≤ 1,5	Possible	Always on	Always on	Always present
IDA-ICE	Whole_Building_TEK17_EV.idm	1		0,5	75 %	1,25	• 68 pcs of 2sqm windows • opening controlled by temp from may to sept	Always on	Always on	Always present
	Whole_Building_TEK17_EV.idm	2		0,50	0,80	1,20	• 4 simplified windows per 2 facades • opening controlled by temperature	Always on	Always on	Always present
	Whole_Building_TEK17_EV.idm	3		0,50	0,80	1,20	• 4 simplified windows per 2 facades • opening controlled by temperature	Always on	Always on	Always present
	Whole_Building_TEK17_EV.idm	4		0,50	0,80	1,20	• Never opened	Always on	Always on	Always present
	Whole_Building_TEK17_EV.idm	5		0,50	0,80	1,20	• Never opened	Always on	Always on	Always present
	Whole_Building_TEK17_EV.idm	6	👍	0,40	0,80	1,20	• Never opened	Always on	Always on	Always present

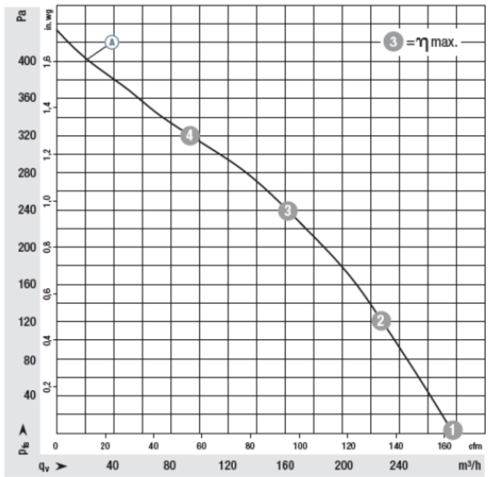
Appendix G: Fan Performance curves for DV-P and DV-S

DV-P, small axial fan.

backward curved, Ø 133

- **Material:** Housing: Plastic
  Impeller: Plastic
  Rotor: Thick-film passivated
  Electronics housing: Die-cast aluminium
- **Number of blades:** 7
- **Direction of rotation:** Clockwise viewed toward rotor
- **Degree of protection:** IP 54
- **Insulation class:** "B"
- **Installation position:** Any
- **Condensation drainage holes:** None, open rotor
- **Mode:** Continuous operation (S1)
- **Mounting:** Maintenance-free ball bearings

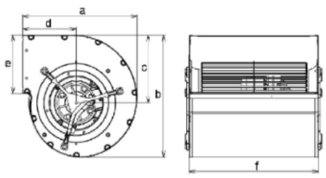
Curves:
Speed-controlled
0-10 V / PWM



		n rpm	P_{ed} W	I A	LwA dB(A)
A	1	3930	24	0,23	66
A	2	3800	26	0,26	63
A	3	3770	27	0,27	61
A	4	3850	25	0,25	66

Air performance measured according to: ISO 5801, installation category A, with ebm-papst inlet ring without contact protection. Intake-side sound level: L_{WA} according to ISO 13347, L_{pA} measured at 1 m distance from fan axis. The values given are only applicable under the specified measuring conditions and may differ depending on the installation conditions. In the event of deviation from the standard configuration, the parameters must be checked in installed condition. See Page 162 ff. for detailed information.

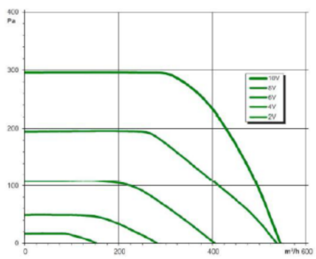
DV-S, small centrifugal fan

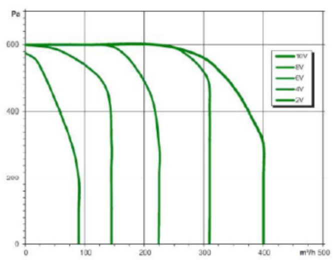


Dimensions (mm)	a	b	c	d	e	f
GDRD7 146x188R	205	218	121	96	104	232
GDSL4 160x242L	226	246	139	103	98	276

GDRD7 : Lead wires coming on the right-hand side looking at the discharge
GDSL4 : Lead wires coming out on the left-hand side looking at the discharge

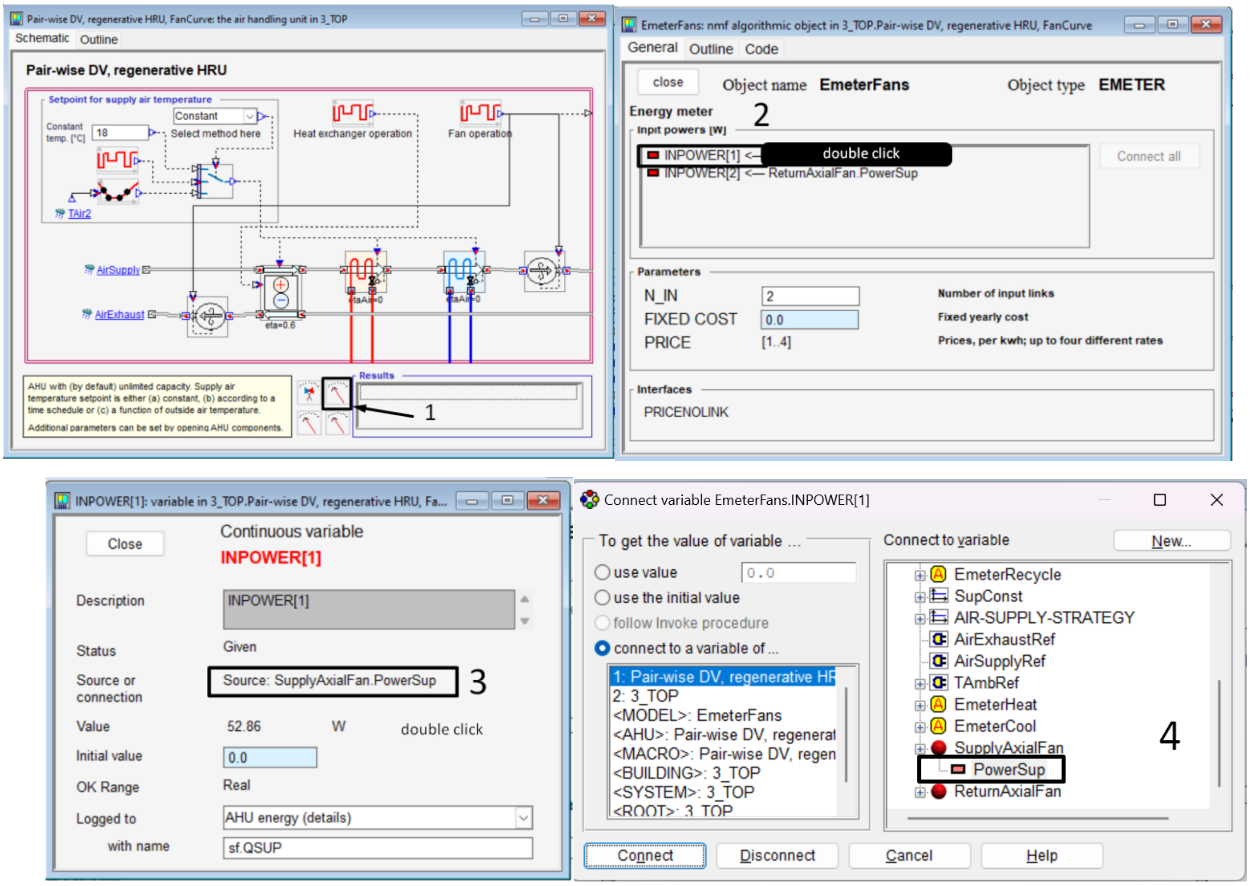
The graphs below show typical curves with either a constant pressure or a constant volume program for the GDRD7 version. The size and main characteristics of the fan remain the same, except for the software which is tailored to the customer's request. This kind of program is ideal for all HVAC applications, such as Central Exhaust Systems or Heat Recovery Units





Appendix H: Fix for "missing energy meters" after replacing Fixed Head fans

In order to re-establish the connection between newly placed fans and energy meter, the user needs to enter the meter options (1), in *General* tab click the *INPOWER[1] (2),* then double click on the *Source or connection (3),* and finally choose the variable for the power supply *PowerSup* from the FanCurve-Fan drop-down menu (4). In the case of this example, it is named "SupplyAxialFan". Repeat steps 2-4 for *INPOWER[2]* for the Extract fan.



Appendix I: Specification Pair-Wise and Single-Unit

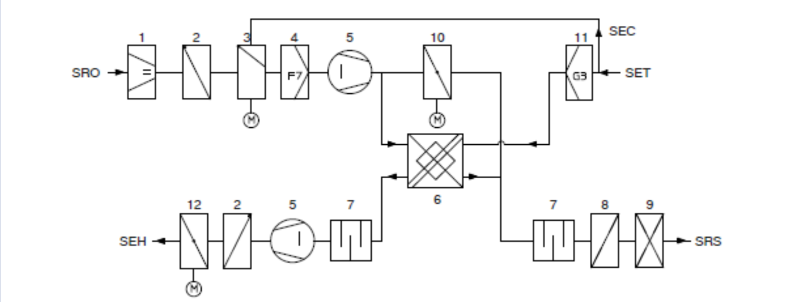
Pair-Wise DV

Parameter	Unit	Value
Wireless control	[-]	Yes
Airflow heat recovery modus	[m3/h[	15/30/50
Sound pressure Lp(A)	[dB]	19/28/37
Sound pressure Lw(A)	[dB]	36/45/54
Power usage	[W]	1,6/3,0/5,6
Filter	[-]	G3
Possibility for pollen filter	[-]	Yes
Tightness class	[-]	IP 24
Running temperatures	[Celsius]	-15 - 40
Wall thickness	[mm]	280 - 500
Whole in the wall, length	[mm]	160

Single Unit DV

Width	1085 mm
Height	630 mm
Depth	320 mm
Fresh air flow rate	Up to 150 m^3/h
Supply air flow rate	Up to 150 m^3/h
Cooling capacity	Up to 690 W
Heating capacity	Up to 2600 W
Room cooling capacity	Up to 400 W
Room heating capacity	Up to 1000 W
Max. operating pressure, water side	6 bar
Max. operating temperature	75 °C
Sound power level	31 – 43 dB(A)
Supply voltage	230 V AC ±10 %, 50/60 Hz

Supply air flow rate	m^3/h	80	100	120
Fresh air flow rate	m^3/h	80	100	120
Total cooling capacity	W	360	460	550
Room cooling capacity	W	216	271	329
Temperature of the air in the unit	°C	32.0	32.0	32.0
Relative humidity	%	40.0	40.0	40.0
Water content of the dry air	g/kg	11.9	11.9	11.9
Supply air temperature	°C	17.9	17.9	17.8
Condensation	g/h	0	0	0
Chilled water flow rate	l/h	100	130	170
Water temperature, inlet	°C	16	16	16
Water temperature, outlet	°C	19.1	19.0	18.8
Pressure drop – water side	kPa	<3	<3	<3
Total heating capacity	W	1500	1830	2140
Room heating capacity	W	446	521	573
Temperature of the air in the unit	°C	–12.0	–12.0	–12.0
Supply air temperature	°C	37.7	36.6	35.3
Hot water flow rate	l/h	90	130	170
Water temperature, inlet	°C	60	60	60
Water temperature, outlet	°C	45.4	47.7	49.0
Pressure drop – water side	kPa	<3	<3	<3
Sound power level L_{WA}	dB(A)	30	34	38
Sound pressure level with 8 dB system attenuation	dB(A)	22	26	30



SEH Single room exhaust air
SRS Single room supply air
SRO Single room fresh air
SET Single room extract air
SEC Secondary air cellular office
1 Volume flow limiter
2 Non-return damper
3 Shut-off damper
4 F7 fine dust filter
5 EC fan
6 Recuperative heat recovery
7 Sound attenuator
8 Heating coil
9 Cooling coil
10 Bypass damper
11 G3 extract air filter
12 Shut-off damper with actuator

Appendix J: Programming AHU system in IDA-ICE

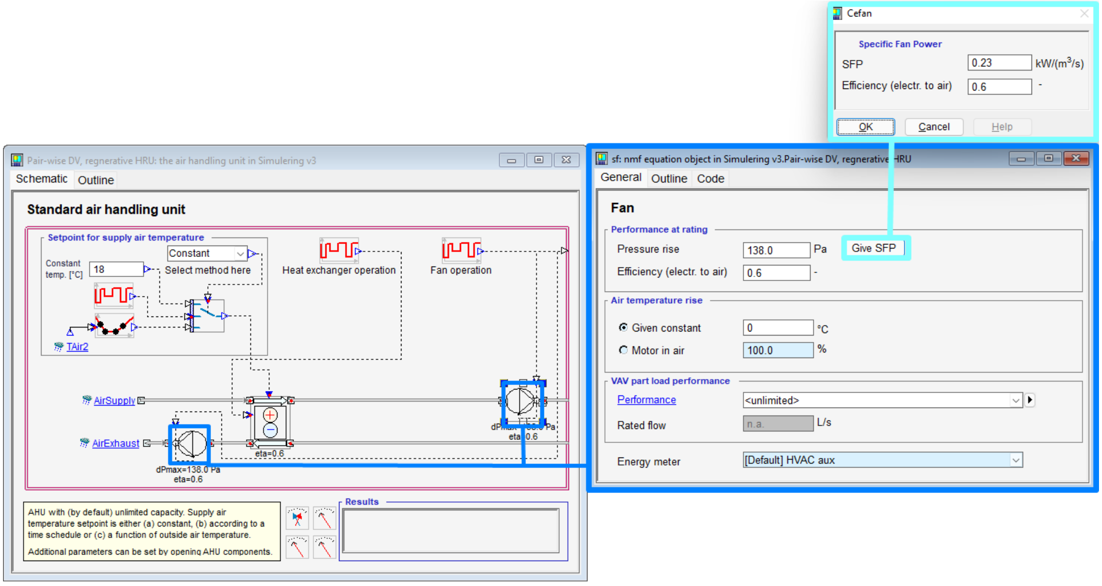


Figure 74: Principial diagram showing the settings for fans in IDA-ICE

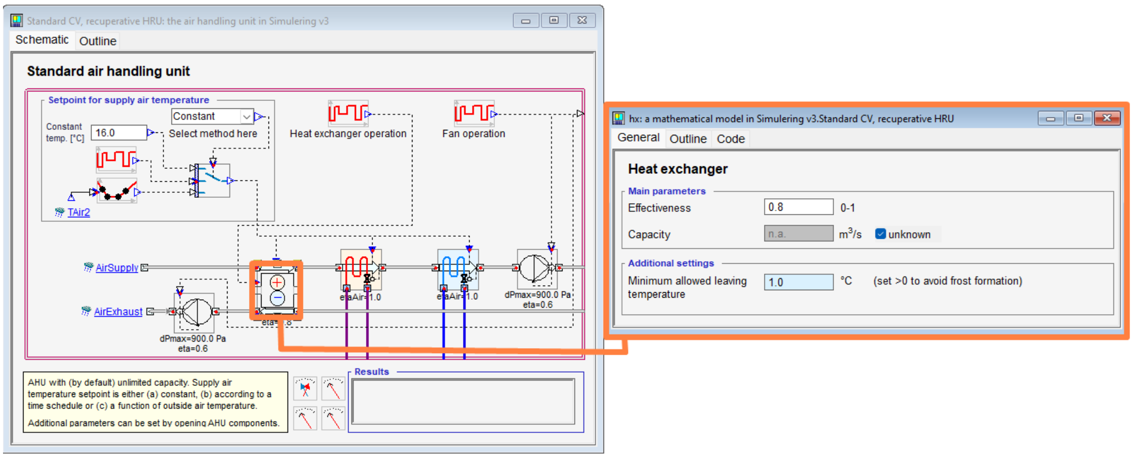


Figure 75: Principial diagram showing the settings for heat recovery in IDA-ICE

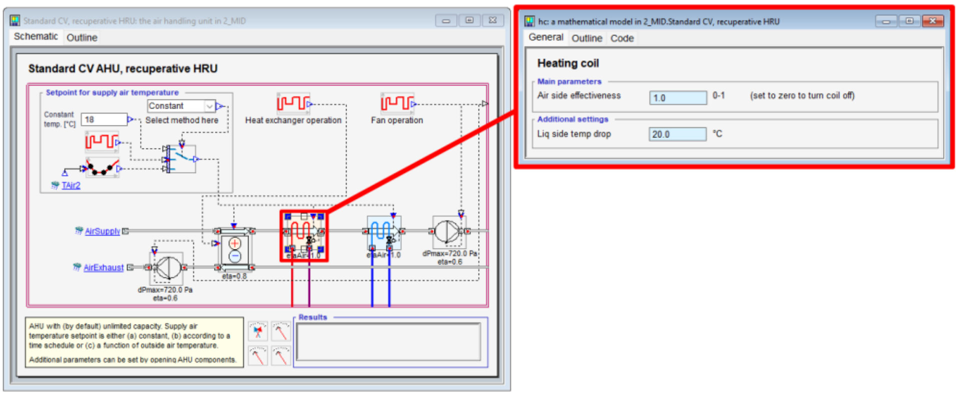


Figure 76: Principal diagram for heating coil, all values are IDA-ICE default.

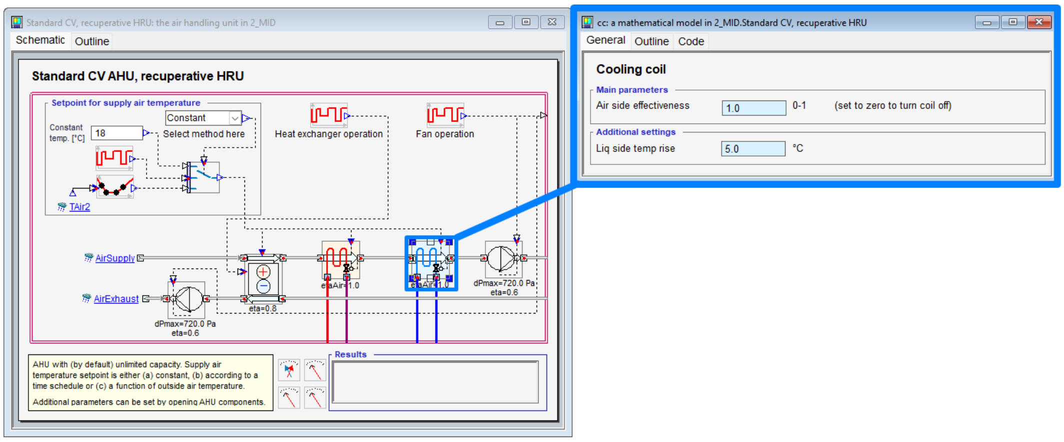
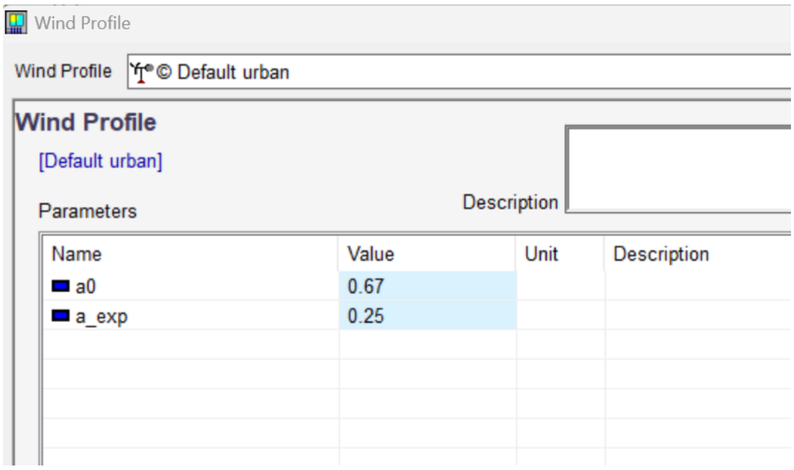


Figure 77: Principal diagram for cooling coil, all values are IDA-ICE default.

Appendix K: Wind profile and pressure coefficients, IDA-ICE

Wind profile for *Default urban* and corresponding coefficients (default).

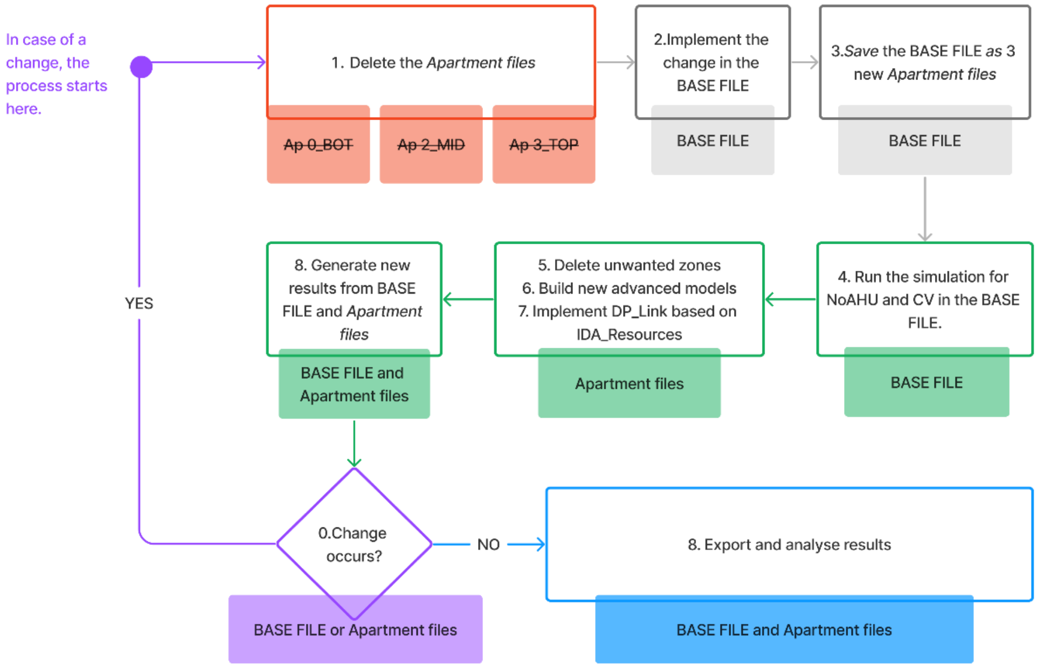


Set of pressure coefficients. Automatically generated thanks to “Autofill” function in IDA-ICE.

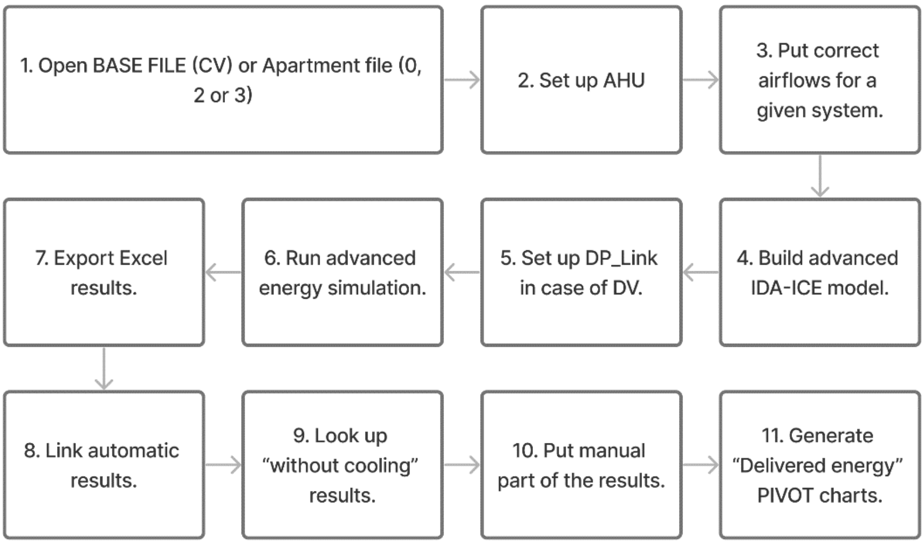
Pressure coefficients based on wind profile *Default urban*									
Face / angle	**0°**	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**	**Face azimuth [°]**
f1baaa	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	249,8
f1baab	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	180,8
f1bab	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	90,8
f1bdb	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	180,8
f1bea	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	270,8
f1beb	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	180,8
f1bi	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	270,8
f2a	0,2	0,05	-0,25	-0,3	-0,25	-0,3	-0,25	0,05	0,8
f2b	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	42,57
f3b	0,2	0,05	-0,25	-0,3	-0,25	-0,3	-0,25	0,05	90,8
f4aa	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	180,8
f4ab	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	270,8
f4ac	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	180,8
f4ba	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	270,8
f4bb	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	0,8
f4bca	0,18	0,15	-0,3	-0,32	-0,2	-0,32	-0,3	0,15	270,8
Crawl space	0	0	0	0	0	0	0	0	270,8
Roof	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	270,8

Appendix L: Handling changes and collecting results – workflows

When a change on the model occurred, due to new findings or corrections that had to be made, a following chart describes the process that were to be done to apply the changes in all models. In short, this workflow implied that the change had to be invoked in the BASE FILE, which led to creating new Apartment files. After the new BASE FILE was created, NoAHU and CV results were obtained. Next, the work on Apartment files started. In the end, export and analysis of the results could begin.



Running the simulation, applying variable parameters such us airflows and choosing the ventilation system and obtaining the results were performed in IDA-ICE and Excel as described in the flow-chart below. This procedure had to be repeated 4 times on each iteration or when a substantial change occurred in the BASE FILE. After a stable version of BASE FILE model was achieved, results for NoAHU, CV, DV-P and DV-S were extracted, saved in Excel file, and then copied over to Word file.



Appendix M: Scenarios matrix and results in summarizing table

ENERGY RESULTS					Energy				Energy (area specific)				Power
No	Apartment	Ap_area	System	Abbreviation	Total delivered	Electric heating	Electric cooling	HVAC aux	Total delivered_	Electric heating_AS	Electric cooling_AS	HVAC aux_AS	Peak demand
[-]	[-]	[m2]	[-]	[-]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[kW]
0.0	0_BOT	35,81	No_AHU	(0.0) 0_BOT [No_AHU]	1058,20	22,24	408,60	0,00	29,55	0,62	11,41	0,00	0,69
0.2	2_MID	52,31	No_AHU	(0.2) 2_MID [No_AHU]	1519,40	0,00	593,50	602,70	29,05	0,00	11,35	11,52	0,64
0.3	3_TOP	64,13	No_AHU	(0.3) 3_TOP [No_AHU]	1567,40	0,00	662,70	512,50	24,44	0,00	10,33	7,99	0,64
1.0	0_BOT	35,81	CV	(1.0) 0_BOT [CV]	2410,27	877,81	74,45	836,27	67,31	24,52	2,08	23,36	2,10
1.2	2_MID	52,31	CV	(1.2) 2_MID [CV]	3238,65	1003,31	105,42	1221,63	61,92	19,18	2,02	23,36	3,06
1.3	3_TOP	64,13	CV	(1.3) 3_TOP [CV]	4477,05	1853,81	111,23	1497,66	69,82	28,91	1,73	23,36	3,75
2.0	0_BOT	35,81	DV-P	(2.0) 0_BOT [DV-P]	5407,60	4198,20	10,01	571,90	151,02	117,25	0,28	15,97	3,26
2.2	2_MID	52,31	DV-P	(2.2) 2_MID [DV-P]	5018,20	3450,60	37,98	613,00	95,94	65,97	0,73	11,72	4,42
2.3	3_TOP	64,13	DV-P	(2.3) 3_TOP [DV-P]	6397,30	4649,20	40,84	683,60	99,76	72,50	0,64	10,66	4,31
3.0	0_BOT	35,81	DV-S	(3.0) 0_BOT [DV-S]	4284,50	2420,40	76,74	1160,00	119,66	67,60	2,14	32,40	3,78
3.2	2_MID	52,31	DV-S	(3.2) 2_MID [DV-S]	3836,90	1667,50	94,12	1158,60	73,35	31,88	1,80	22,15	3,99
3.3	3_TOP	64,13	DV-S	(3.3) 3_TOP [DV-S]	4769,20	2539,50	101,20	1104,80	74,37	39,60	1,58	17,23	4,34

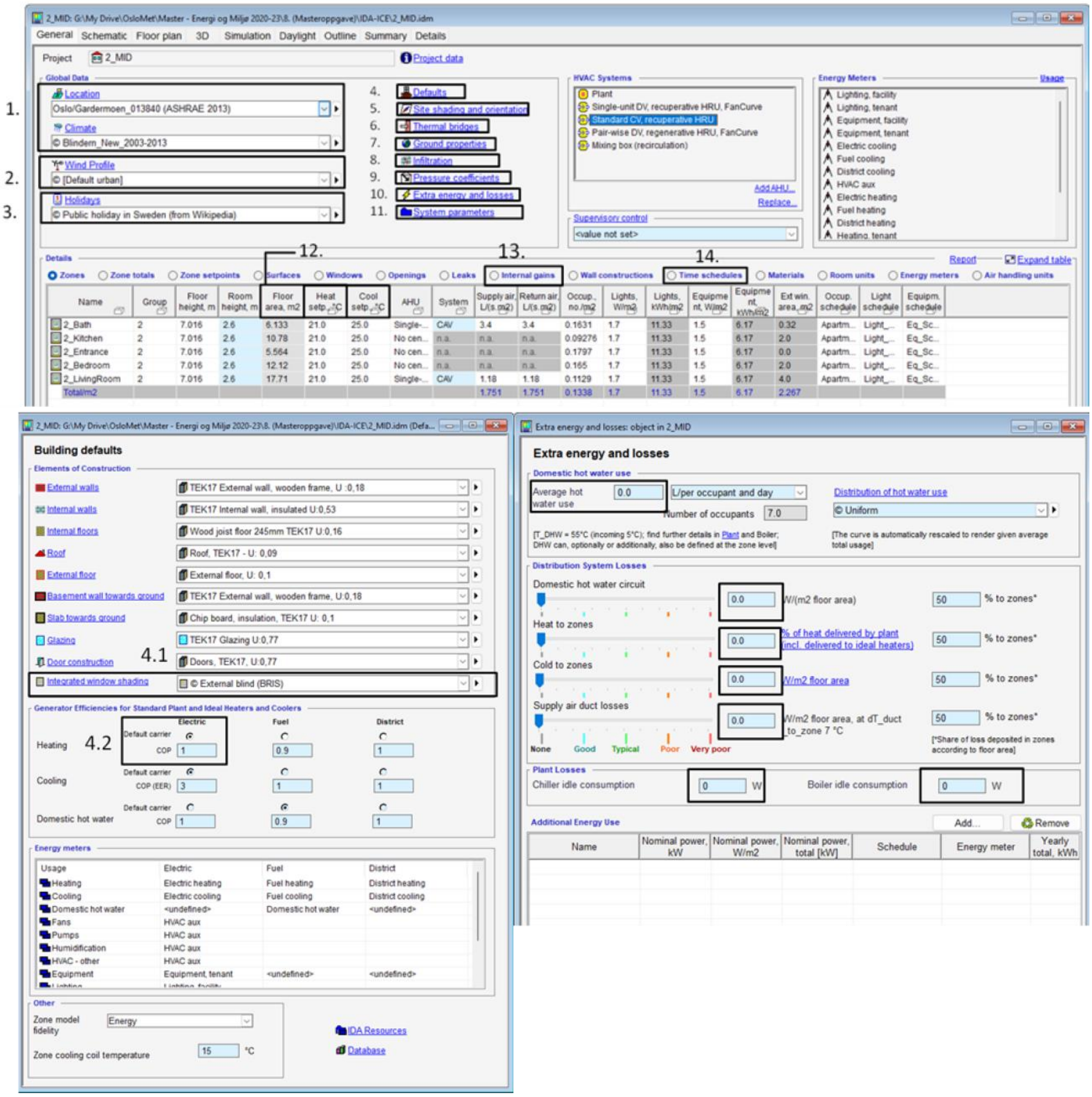
Table 21: Scenarios matrix and energy results. Summarizing table from Excel.

Indoor Climate RESULTS (Averaged values)						Fanger	EN-15251, thermal comfort					
No	Apartment	Ap_area	System	Abbreviation	CO2, avg	Max PPD	T_OP>25, with cooling	T_OP>27, with cooling	T_OP>25, without cooling	T_OP<18, without cooling	Hours people dissatisfied	Hours people dissatisfied % of all
[-]	[-]	[m2]	[-]	[-]	[ppm]	[%]	[h]	[h]	[h]	[h]	[h]	[%]
0.0	0_BOT	35,807	No_AHU	(0.0) 0_BOT [No_AHU]	175294,00	9,38	4940,88	0,00	5527,50	0,00	551,93	8 %
0.2	2_MID	52,307	No_AHU	(0.2) 2_MID [No_AHU]	36956,80	8,90	6262,00	0,00	7376,00	0,00	583,56	9 %
0.3	3_TOP	64,126	No_AHU	(0.3) 3_TOP [No_AHU]	144037,40	9,56	4974,28	0,00	5878,00	0,00	595,20	9 %
1.0	0_BOT	35,807	CV	(1.0) 0_BOT [CV]	1128,75	15,74	843,80	0,00	807,00	0,00	751,75	11 %
1.2	2_MID	52,307	CV	(1.2) 2_MID [CV]	966,48	15,70	922,06	0,00	854,80	0,00	788,50	12 %
1.3	3_TOP	64,126	CV	(1.3) 3_TOP [CV]	941,08	16,22	448,74	0,00	418,22	0,00	864,10	13 %
2.0	0_BOT	35,807	DV-P	(2.0) 0_BOT [DV-P]	986,13	17,59	64,23	0,00	58,35	0,00	857,48	13 %
2.2	2_MID	52,307	DV-P	(2.2) 2_MID [DV-P]	1103,96	16,34	281,12	0,00	250,42	0,00	854,16	13 %
2.3	3_TOP	64,126	DV-P	(2.3) 3_TOP [DV-P]	1103,96	16,34	281,12	0,00	226,88	0,00	879,72	13 %
3.0	0_BOT	35,807	DV-S	(3.0) 0_BOT [DV-S]	924,18	16,32	0,03	0,00	0,13	0,00	923,98	14 %
3.2	2_MID	52,307	DV-S	(3.2) 2_MID [DV-S]	978,18	15,55	105,84	0,00	88,10	0,00	862,86	13 %
3.3	3_TOP	64,126	DV-S	(3.3) 3_TOP [DV-S]	979,02	16,14	119,06	0,00	100,76	0,00	912,32	14 %

Table 22: Indoor Climate results. Excel table.

Appendix N: IDA-ICE and compliance testing for TEK17, step-by-step based on SIMIEN method

No	Parameter / setting	Target value/setting in IDA-ICE for TEK17 compliance check
1	Location, climate	Oslo, Blindern.
2	Wind profile	Default urban.
3	Holidays	Public holiday in Sweden.
4	Defaults	Building envelope according to TEK17.
4.1	U-values	Building envelope according to TEK17.
4.2	Window shading	For manual control, use values for sun flux from Appendix E in NS3031:2007.
5	Site shading, orientation	Both defined for an actual building.
6	Thermal bridges	Building envelope according to TEK17.
7	Ground properties	No specific requirements, define closes to reality.
8	Infiltration	Building envelope according to TEK17.
9	Pressure coefficients	No specific requirements, define closes to reality. Use AutoFill.
10	Extra energy and losses	All fields marked in black set to 0.
11	System parameters	Default values in IDA-ICE can be used.
12	Heating and cooling setpoints	According to NS3031, Appendix A, NS 3031.
13	Internal gains	According to NS3031, Appendix A, NS 3031.
14	Time schedules	According to NS3031, Appendix A, NS 3031.



Appendix O: SIMIEN detailed results, TEK17 evaluation

SIMIEN
Evaluering Energiregler 2016

Simuleringsnavn: Evaluering
Tid/dato simulering: 13:11 26/11-2022
Programversjon: 6.017
Simuleringsansvarlig: PPP
Firma: Undervisningslisens
Inndatafil: G:\...\Whole_Building_Divided_SIMIEN.smi
Prosjekt: Whole_Apartment_Block
Sone: 0_Bottom_floor; 1_Mid_floor; 2_Mid_floor; 3_Top_floor;

Resultater av evalueringen	
Evaluering av	Beskrivelse
Energitiltak	Bygningen tilfredsstiller ikke kravene til energitiltak i §14-2 (2)
Varmetapsramme	Bygningen tilfredsstiller omfordeling energitiltak (varmetapstall) ihht. §14-2 (2)
Energiramme	Bygningen tilfredsstiller energirammen ihht. §14-2 (1)
Minstekrav	Bygningen tilfredsstiller minstekravene i §14-3
Luftmengder ventilasjon	Luftmengdene tilfredsstiller minstekrav gitt i NS3031:2014 (tabell A.6)
Energiforsyning	Fossilt brensel benyttes ikke i oppvarmingsanlegget (§14-4)
Samlet evaluering	Bygningen tilfredsstiller byggeforskriftenes energikrav

Energitiltak (§14-2 (2))		
Beskrivelse	Verdi	Krav
Samlet glass-, vindus og dørareal delt på bruksarealet [%]	10,1	25,0
U-verdi yttervegger [W/m²K]	0,15	0,18
U-verdi tak [W/m²K]	0,10	0,13
U-verdi gulv mot grunn og mot det fri [W/m²K]	0,10	0,10
U-verdi glass/vinduer/dører [W/m²K]	0,79	0,80
Normalisert kuldebroverdi [W/m²K]	0,03	0,07
Lekkasjetall (lufttetthet ved 50 Pa trykkforskjell) [luftvekslinger pr time]	0,5	0,6
Årsmidlere temperaturvirkningsgrad varmegjenvinner ventilasjon [%]	80	80
Spesifikk vifteeffekt (SFP) [kW/m³/s]:	1,00	1,50

Omfordeling energitiltak (§14-2 (2), varmetapstall)		
Beskrivelse	Verdi	Krav
Varmetapstall yttervegger	0,11	0,11
Varmetapstall tak	0,04	0,05
Varmetapstall gulv på grunn/mot det fri	0,02	0,03
Varmetapstall glass/vinduer/dører	0,08	0,20
Varmetapstall kuldebroer	0,03	0,07
Varmetapstall infiltrasjon	0,04	0,04
Varmetapstall ventilasjon	0,11	0,11
Totalt varmetapstall	0,44	0,62

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Evaluering Energiregler 2016

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Energiramme (§14-2 (1), samlet netto energibehov)	
Beskrivelse	Verdi
1a Beregnet energibehov romoppvarming	17,1 kWh/m²
1b Beregnet energibehov ventilasjonsvarme (varmebatterier)	6,2 kWh/m²
2 Beregnet energibehov varmtvann (tappevann)	29,8 kWh/m²
3a Beregnet energibehov vifter	4,1 kWh/m²
3b Beregnet energibehov pumper	1,1 kWh/m²
4 Beregnet energibehov belysning	11,4 kWh/m²
5 Beregnet energibehov teknisk utstyr	17,5 kWh/m²
6a Beregnet energibehov romkjøling	0,0 kWh/m²
6b Beregnet energibehov ventilasjonskjøling (kjølebatterier)	0,7 kWh/m²
Totalt beregnet energibehov	88,0 kWh/m²
Forskriftskrav netto energibehov	95,0 kWh/m²

Minstekrav (§14-3)		
Beskrivelse	Verdi	Krav
U-verdi yttervegger [W/m²K]	0,15	0,22
U-verdi tak [W/m²K]	0,10	0,18
U-verdi gulv mot grunn og mot det fri [W/m²K]	0,10	0,18
U-verdi glass/vinduer/dører [W/m²K]	0,8	1,2
Lekkasjetall (lufttetthet ved 50 Pa trykkforskjell) [luftvekslinger pr time]	0,5	1,5

Energiforsyning (§14-4 (1))	
Beskrivelse	Verdi
Bruker fossilt brensel til oppvarming	Nei

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Krav til formålsdelte energimålere (§14-2 (6))
Boligblokker skal ha formålsdelte energimålere for oppvarming og tappevann når de har sentral produksjon av av varme til romovpparming. ventilasjonsvarme eller sentral varmtvannsproduksjon.
Dette er ikke en del av evaluering i SIMIEN og må derfor dokumenteres på annen måte.

Krav til isolering av rør, utstyr og kanaler (§14-3 (2))
Rør, utstyr og kanaler som er knyttet til bygningens varmesystem skal isoleres. Isolasjonstykkelsen skal være økonomisk optimal beregnet etter norsk standard eller en likeverdig europeisk standard.
Dette er ikke en del av evaluering i SIMIEN og må derfor dokumenteres på annen måte.

Krav til energifleksible varmeløsninger (§14-4 (2))
Bygning over 1000 m2 oppvarmet bruksareal skal ha energifleksible varmesystemer og tilrettelegges for bruk av lavtemperatur varmeløsninger.
Dette er ikke en del av evaluering i SIMIEN og må derfor dokumenteres på annen måte.

Energibudsjett reelle verdier (§14-2 (5)) Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	2411 kWh	1,7 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	5048 kWh	3,5 kWh/m²
2 Varmtvann (tappevann)	0 kWh	0,0 kWh/m²
3a Vifter	7159 kWh	5,0 kWh/m²
3b Pumper	511 kWh	0,4 kWh/m²
4 Belysning	29852 kWh	20,7 kWh/m²
5 Teknisk utstyr	31124 kWh	21,6 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	1114 kWh	0,8 kWh/m²
Totalt netto energibehov, sum 1-6	77218 kWh	53,5 kWh/m²

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Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	69791 kWh	48,3 kWh/m²
1b El. til varmepumpesystem	655 kWh	0,5 kWh/m²
1c El. til solfangersystem	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	5400 kWh	3,7 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-0 kWh	-0,0 kWh/m²
Totalt levert energi, sum 1-7	75846 kWh	52,5 kWh/m²
Solstrøm til eksport	-0 kWh	-0,0 kWh/m²
Netto levert energi	75846 kWh	52,5 kWh/m²

Dokumentasjon av sentrale inndata (1)		
Beskrivelse	Verdi	Dokumentasjon
Areal yttervegger [m²]:	1100	
Areal tak [m²]:	600	
Areal gulv [m²]:	361	
Areal vinduer og ytterdører [m²]:	145	
Oppvarmet bruksareal (BRA) [m²]:	1444	
Oppvarmet luftvolum [m³]:	4620	
U-verdi yttervegger [W/m²K]	0,15	
U-verdi tak [W/m²K]	0,10	
U-verdi gulv [W/m²K]	0,10	
U-verdi vinduer og ytterdører [W/m²K]	0,79	
Areal vinduer og dører delt på bruksareal [%]	10,1	
Normalisert kuldebroverdi [W/m²K]:	0,03	
Normalisert varmekapasitet [Wh/m²K]	150	
Lekkasjetall (n50) [1/h]:	0,50	
Temperaturvirkningsgr. varmegjenvinner [%]:	80	

SIMIEN

Evaluering Energiregler 2016

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Dokumentasjon av sentrale inndata (2)

Beskrivelse	Verdi	Dokumentasjon
Estimert virkningsgrad gjenvinner justert for frostsikring [%]:	79,9	
Spesifikk vifteeffekt (SFP) [kW/m³/s]:	1,00	
Luftmengde i driftstiden [m³/hm²]	1,70	
Luftmengde utenfor driftstiden [m³/hm²]	0,00	
Systemvirkningsgrad oppvarmingsanlegg:	1,18	
Installert effekt romoppv. og varmebatt. [W/m²]:	230	
Settpunkttemperatur for romoppvarming [°C]	20,3	
Systemeffektfaktor kjøling:	2,50	
Settpunkttemperatur for romkjøling [°C]	22,0	
Installert effekt romkjøling og kjølebatt. [W/m²]:	8	
Spesifikk pumpeeffekt romoppvarming [kW/(l/s)]:	0,50	
Spesifikk pumpeeffekt romkjøling [kW/(l/s)]:	0,00	
Spesifikk pumpeeffekt varmebatteri [kW/(l/s)]:	0,50	
Spesifikk pumpeeffekt kjølebatteri [kW/(l/s)]:	0,60	
Driftstid oppvarming (timer)	16,0	

Dokumentasjon av sentrale inndata (3)

Beskrivelse	Verdi	Dokumentasjon
Driftstid kjøling (timer)	24,0	
Driftstid ventilasjon (timer)	24,0	
Driftstid belysning (timer)	16,0	
Driftstid utstyr (timer)	16,0	
Oppholdstid personer (timer)	24,0	
Effektbehov belysning i driftstiden [W/m²]	1,95	
Varmetilskudd belysning i driftstiden [W/m²]	1,95	
Effektbehov utstyr i driftstiden [W/m²]	3,00	
Varmetilskudd utstyr i driftstiden [W/m²]	1,80	
Effektbehov varmtvann på driftsdager [W/m²]	3,40	
Varmetilskudd varmtvann i driftstiden [W/m²]	0,00	
Varmetilskudd personer i oppholdstiden [W/m²]	1,50	
Total solfaktor for vindu og solskjerming:	0,04	
Gjennomsnittlig karmfaktor vinduer:	0,06	
Solskjermingsfaktor horisont/utspring (N/Ø/S/V):	1,00/1,00/1,00/1,00	

SIMIEN

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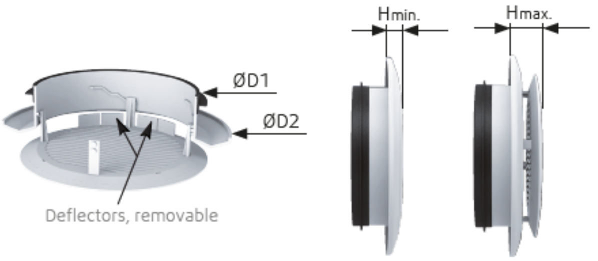
Firma: Undervisningslisens
Inndatafil: G:\...\Whole_Building_Divided_SIMIEN.smi
Prosjekt: Whole_Apartment_Block
Sone: 0_Bottom_floor; 1_Mid_floor; 2_Mid_floor; 3_Top_floor;

Inndata bygning	
Beskrivelse	Verdi
Bygningskategori	Boligblokker
Simuleringsansvarlig	PPP
Kommentar	6 boenheter per etasje, 4 etasjer.

Appendix P: Technical data for fresh air intake (wall grille)

Dimensions



BOREA	Art-no.	ØD1	ØD2	Hmin.	Hmax.
125	68872	119	165	12	24

Open (+) and closed (-) grid

Valve plate open (+) and closed (-)
Position: closed, 1 and 2

Technical data

Type	Air volume Qv[m^3/h]	Supply air								Extract air					
		Grid open, Plate closed wall mounting		without deflector				with deflector		Grid open, Plate open		Grid closed, Plate open			
				Grid closed, Plate open, ceiling mounting											
				Position 1		Position 2		Position 2		Position 2		Position 1		Position 2	
		dp (Pa)	Lw (dB(A))	dp (Pa)	Lw (dB(A))	dp (Pa)	Lw (dB(A))	dp (Pa)	Lw (dB(A))	dp (Pa)	Lw (dB(A))	dp (Pa)	Lw (dB(A))	dp (Pa)	Lw (dB(A))
BOREA 125	45	9	< 20	18	26	7	< 20	13	22	3	< 20	20	23	7	< 20
	60	17	< 20	30	31	13	21	20	27	5	< 20	37	33	13	21
	75	25	24	40	35	18	24	31	32	8	< 20	57	41	20	25
	90	36	31	56	39	25	28	43	36	11	20	80	46	27	29
	120	62	43	-	-	40	36	70	43	19	28	-	-	48	36
	150	-	-	-	-	62	41	-	-	28	34	-	-	74	43