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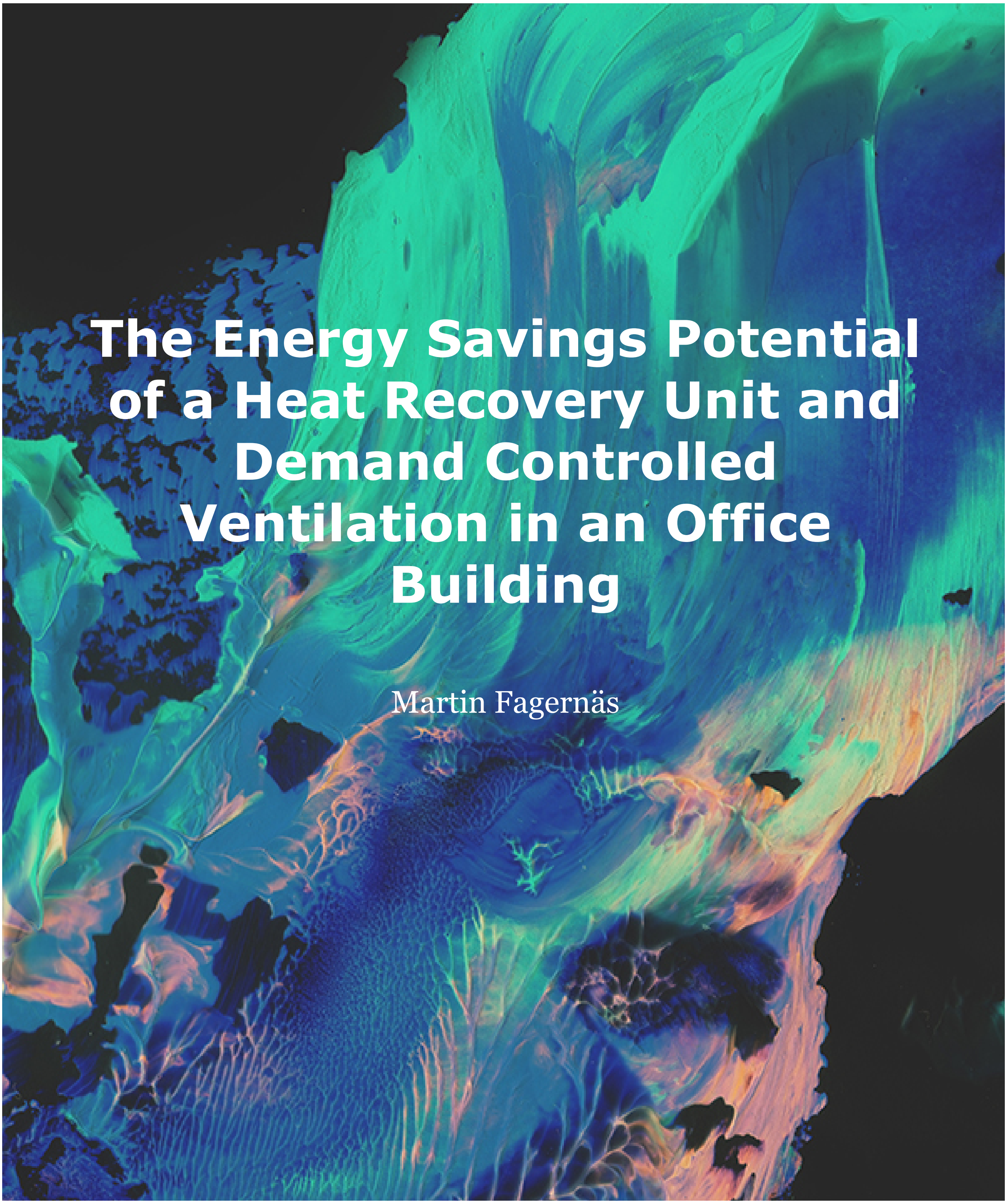

The Energy Savings Potential of a Heat Recovery Unit and Demand Controlled Ventilation in an Office Building

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Master thesis, 30.0 hp
M.Sc. in Energy Engineering, 300.0 hp
Department of Applied Physics and Electronics. Spring term 2021

Abstract

The building sector is responsible for approximately 40 % of the total energy usage in Sweden. In office buildings the heating, ventilation and air conditioning system can account for up to 55 % of the energy usage. In order to reduce the energy usage of the heating, ventilation and air conditioning system different control methods are often used. One of these control methods is demand controlled ventilation, where the ventilation system is controlled with regard to occupancy with the help of motion and/or CO_2 sensors.

The aim of this thesis is to determine the energy savings potential of a heat recovery unit as well as demand controlled ventilation in an office building. The effect of longer intervals between sensor control signals to the ventilation system is also investigated. This is done by creating schedules, gathered from actual building occupancy, that are being used to control the occupancy and ventilation in a building model in the building performance simulation software IDA ICE. As a reference building, the fifth floor of the LU1 section of the natural science building at Umeå University is used. The reference building consists of 40 offices for which the occupancies are known.

The average occupancy for all the offices combined throughout the investigated time period is determined to be 34.8 %. The results from the simulations indicate that an energy savings potential of 52.98 % can be achieved by a heat recovery unit with an efficiency of 80 % or 95 %, when compared to not having an heat recovery unit. When implementing demand controlled ventilation an energy savings potential of 2.76-10.98 % can be achieved, with the energy savings potential decreasing when the efficiency of the heat recovery unit increases. Finally it is shown that longer intervals between sensor control signals to the ventilation system leads to a small increase in energy usage and poorer indoor air quality.

Sammanfattning

Bostads- och servicesektorn står för ungefär 40 % av den totala energianvändningen i Sverige. I kontorsbyggnader kan värme, ventilation och luftkonditionering bidra med upp till 55 % av byggnadens energianvändning. För att reducera värme, ventilation och luftkonditioneringens energianvändning används ofta olika slags kontrollmetoder. En av dessa kontrollmetoder är behovsstyrd ventilation, var man använder rörelse- och/eller CO_2-sensorer för att kontrollera ventilationen.

Målet för detta examensarbete är att bestämma energibesparingspotentialen av en värmeåtervinningsenhet samt ifall man använder sig av behovsstyrd ventilation. Utöver detta undersöks även vilken inverkan längre tidsintervaller mellan sensorernas kontrollsignaler till ventilationssystemet har på energianvändningen och luftkvalitén. Genom att nyttja uppsamlade sensordata av närvaro från en kontorsbyggnad gjordes scheman som används för att kontrollera närvaro och ventilation i en modell av en kontorsbyggnad i byggprestationsimuleringsmjukvaran IDA ICE. Som referensbyggnad används femte våningen av LU1 sektionen av naturvetarhuset vid Umeå Universitet. Referensbyggnaden består av 40 kontor vars närvaro är givet.

Medelnärvaron för alla kontoren kombinerat under den undersökta tidsperioden bestämdes till 34,8 %. Resultaten från simuleringarna visar att en energibesparingspotential på 52,98 % kan uppnås ifall en värmeåtervinningsenhet med en effektivitet på 80 % eller 95 % inkluderas, jämfört med att inte ha en värmeåtervinningsenhet. Ifall man använder sig av behovsstyrd ventilation kan en energibesparingspotential på 2,76-10,98 % uppnås, där energibesparingspotentialen minskar desto högre effektivitet värmeåtervinningsenheten har. Slutligen visades att förlängning av tiden mellan kontrollsignalerna från sensorerna till ventilationssystemet medför en liten ökning i energianvändningen samt sämre luftkvalité.

Acknowledgements

First and foremost, I would like to thank the Horizon 2020 project "RUGGEDISED" for providing me with occupancy information from their sensors. I would also like to thank my supervisor Gireesh Nair, associate professor at the Department of Applied Physics and Electronics at Umeå University, for helping me throughout this master thesis. A huge thanks to Mark Murphy as well for answering my seemingly endless stream of questions.

Finally, I would like to thank my friends and family for keeping me company throughout the last few months.

Umeå, June 2021
Martin Fagernäs

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Appendix

A Building parameters **i**

1 Introduction

In 2018 the building sector was responsible for 40 % of the total energy usage in Sweden [1]. Of the aforementioned 40 % residential and non-residential buildings contributed with approximately 90 %, with residential buildings accounting for 59 % and non-residential buildings for the remaining part [1].

Pérez-Lombard et al. [2] estimates that 48-55 % of the energy consumption in office buildings goes towards the buildings heating, ventilation and air conditioning (HVAC) system. This can vary with regard to the geographic location of the building. However, studies have shown that the energy usage of a building could be reduced by optimizing the HVAC system control with regard to the occupancy of the building [3–10].

The energy usage for ventilation in non-residential buildings is approximately 10 % of the energy usage of the building [11]. There are different methods that can be used in order to reduce this percentage; two methods investigated in this thesis are the implementation of an heat recovery unit (HRU) to the ventilation system and demand controlled ventilation (DCV). With the help of an HRU one can preheat the air going in to the ventilation system by exchanging the heat from the warm air going out of the building. Studies have shown that up to 60 % of the otherwise wasted energy could be recovered [12]. With DCV the ventilation in rooms is controlled by sensors, most often CO_2 or motion sensors. The sensors are used to determine if a room is occupied or unoccupied. If a room is deemed unoccupied the ventilation to the room is adjusted to a lower level [8]. Studies have shown that the energy savings potential for DCV can be up to 64 % in school and office buildings [8, 13]. In residential buildings studies have shown that the energy savings potential can reach 35 % [9, 14]. However, when investigating the energy savings potential for DCV it is important to have an accurate reading of the occupancy in the building as a lower occupancy can yield a higher energy savings potential. There are standards from sources like American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) that can be used to approximate the occupancy, see figure 1, however the actual occupancy is specific to the building.

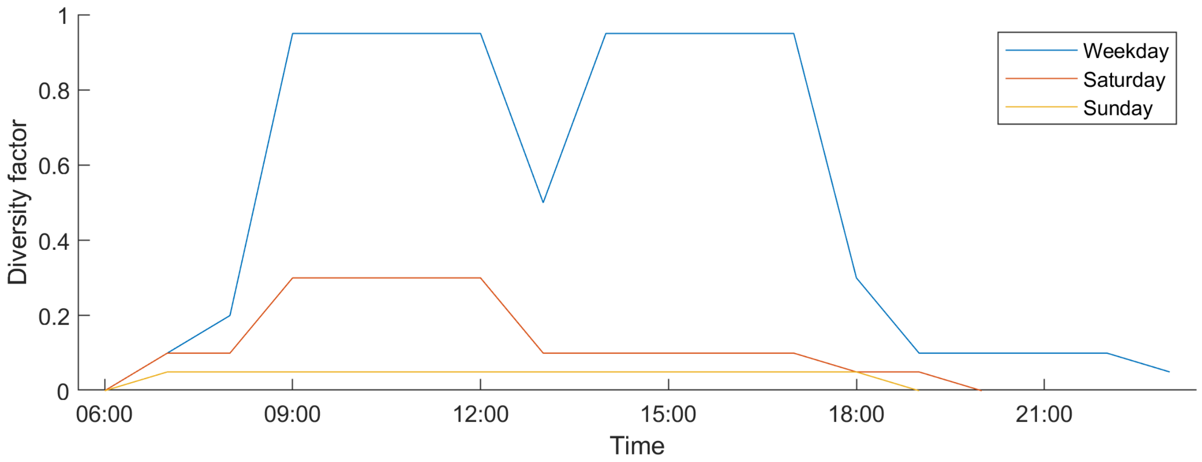


Figure 1 – ASHRAE recommendations for diversity factor for office buildings.

In order to determine the energy savings potential of different measures building performance simulation software like *IDA ICE*, *EnergyPlus* or *TRNSYS* are often used [15]. These softwares can run simulations of how the energy systems in a building will react to different weather conditions, to the occupancy changes in the building and much more. However, in order to get an accurate representation of the building performance, it is important to have accurate measurements of the current state of the building [16].

1.1 Aims and objectives

The aim of this thesis is threefold. The first and second aims are to determine the energy savings potential of an HRU and DCV respectively in an office building. The third and final aim is to investigate the effect on energy usage and indoor air quality (IAQ), with regard to the CO_2 level in the air, of lengthening the interval between control signals sent from the sensors to the ventilation system.

The objective is to create schedules from sensor data gathered from an office building. The schedules will then be used to control the occupancy and ventilation in a model of an office building in a building performance simulation software. With the scheduled occupancy and ventilation different scenarios will be simulated with and without an HRU and the energy savings potential will be determined.

The natural science building at Umeå University is used as a reference building. The building in its current state is very energy efficient, but the structure can be used as a reference for other, not so energy efficient buildings. The main reason why the natural science building is used as a reference building is the fact that the occupancy of the building is very well documented.

The thesis is structured as follows: in section 2 literature regarding sensors, HVAC control and heat recovery efficiencies will be presented. In section 3 the theory used will be presented. Section 4 introduces the method used for creating occupancy profiles and energy simulations. In section 5 the results will be presented and in section 6 the results will be discussed. Finally, section 7 concludes the thesis.

2 Literature study

The literature study is divided into four parts; sensors, HVAC, DCV and HRU. In the first part the strengths and the weaknesses of sensors commonly used in office buildings are discussed. In part two and three different HVAC system control methods are reviewed. In the final part the impact of the efficiency of the HRU is discussed.

2.1 Sensors

There are many different types of sensors that can be used to estimate occupancy in an office and therefore be used for automated control systems. Passive infrared (PIR) sensors are a type of motion sensors that sense the infrared radiation emitted from an object and compare the temperature of the object to the background temperature in order to detect movement [17]. The output from a PIR sensor is binary, which means that they are only capable of detecting occupancy and not occupancy count [18]. PIR sensors are also prone to false negatives, i.e. registering the space as unoccupied when it is in fact occupied, during periods when the object is motionless [13,17]. PIR sensors can also be subject to false positives, i.e. registering the space as occupied when it is in fact unoccupied. This can be caused by heat currents from HVAC systems or a failure to detect short intermediate breaks [17,19]. PIR sensors are most commonly used for automated lighting control [20]. Another type of sensor for estimating occupancy is a CO_2 sensor. A CO_2 sensor measures the concentration of CO_2 in a space and since humans generate CO_2 it can be used to estimate both occupancy and the occupancy count [18]. A downside to CO_2 sensors is that they have a significant reaction time due to the slow build up of CO_2 in a space [13,17,18,20]. CO_2 sensors are also affected by intermittent opening and closing of doors and windows which makes it hard to measure the CO_2 concentration [18,20].

Using vision based sensors, i.e. video cameras, would provide information such as occupancy count, activity and location and would therefore be a prime candidate for automated system control. The drawback of using vision based sensors is that it would be in violation of occupants' privacy [13,18,20].

2.2 Heating, ventilation and air conditioning

HVAC systems in office buildings are often operating on a fixed time schedule. This means that they turn on at a certain time in the morning and are running all day at a set-point assuming maximal occupancy until they turn off at a specified time in the evening [21]. In these cases there are often potential energy savings to be made by implementing occupant-centric control strategies (OCC). According to Naylor et al. [22] there are four categories of OCC:

1. reactive response to occupancy in real-time
2. control to individual occupant preference
3. control catered to individual behaviours or activities
4. control based on the prediction of future occupancy/behaviour.

In this thesis the focus will be on reactive response to occupancy in real-time. This means that if a sensor senses an occupant the HVAC system reacts to it with appropriate measures, for example by changing the ventilation flow rate [22]. Furthermore, according to Haniff et al. [23] the methods for scheduling the HVAC system can be grouped into three classes; basic, conventional and advanced. The basic method consists of manipulating the "ON/OFF" state of the HVAC system while the conventional method is centered around manipulating the setpoint temperatures of the HVAC system. The advanced method is a combination of both the basic and the conventional methods [23]. The following sections display some HVAC control strategies that could be implemented in this study.

Agarwal et al. [3] deployed a combination of PIR sensors and magnetic reed switch door sensors in a wing of a building at University of California San Diego campus. The PIR sensors were set with a 30 minute timeout, meaning that after registering a movement the room was considered occupied for 30 minutes. The authors simulated the potential energy savings of a HVAC cooling control strategy where the temperature was changed from 22.9 °C to 26.1 °C when a room was considered unoccupied. A comparison was then made to a baseline case where the HVAC temperature was set to 22.9 °C at a fixed time schedule from 5:15 to 22:00. The study showed a potential HVAC energy reduction of 10-15 % depending on the outside temperature. In [4] the authors used the same sensor combination at the same university building where aggressive duty-cycling was implemented on the building HVAC system. For example, the HVAC system was turned off, or to standby mode, if a zone was considered empty and was turned on again if the temperature in the zone exceeded or subceeded a specified setpoint. The HVAC was also set to go to standby mode at 6:30 and turned off at 22:00. The study obtained a saving of 9.54-15.73 % in HVAC electrical energy usage and a saving of 7.59-12.85 % in HVAC thermal energy usage.

Gunay et al. [5] developed a self-adaptive occupancy-learning temperature setback algorithm which was found to reduce the annual cooling load of an office by 15 % and the heating load by 10 %. The algorithm was developed from a year's worth of motion sensor measurements collected from seven offices and was implemented in EnergyPlus in order to simulate the HVAC energy usage. The algorithm measured occupancy in each office in a thermal zone and applied heating and cooling setbacks if the thermal zone was deemed unoccupied. The algorithm chose the first arrival and last departure in each thermal zone and did not take intermediate breaks into account. An office was considered empty if the sensors did not register any movement in ten minutes.

Brooks et al. [6] implemented a Measured Occupancy-Based Setback (MOBS) algorithm to a HVAC system of a building located on the University of Florida campus. The building consisted of 12 zones and the occupancy was determined binary using PIR sensors. The algorithm determined the flow rate and amount of reheat for variable air volume (VAV) ventilation system terminals based on the occupancy and temperature in the zone. The results show a potential energy saving of 37 % over the baseline, where the primary savings were due to reduction of airflow rate during periods when the zones were unoccupied.

Yang et al. [7] conducted a study where one of the goals was to see if reassigning personnel with similar schedules to offices next to each other has an effect on the energy usage of the HVAC unit. The study was conducted in a three-story building at a university campus with approximately 50 permanent occupants. The authors created occupancy profiles based on actual data gathered using a binary detection model that indicated if an office was occupied or not. The authors then proceeded to investigate two different scenarios; controlling the HVAC system for each mechanical zone based on occupancy profiles and room reassignment coupled with profile based HVAC control. The HVAC system was set to start when the presence probability was positive for a zone and to stop at the last positive presence probability for the zone. The results indicated that by using occupancy profiles to control the HVAC system the energy usage could be reduced by up to 9 % compared to the control method, which was to have the HVAC turned on between 6:30 and 21:30. The authors also found that by clustering the personnel based on similarities in their occupancy profiles the HVAC system energy usage could be reduced by an additional 8 %.

2.3 Demand controlled ventilation

Merema et al. [8] conducted a case study on DCV for four buildings. The aim of the study was to evaluate the energy savings on heating and fans while maintaining good IAQ. Measurements of CO_2 concentration were made during two consecutive weeks for all four buildings during a heating demand period. The results of the case study show that by controlling the DCV system with measured CO_2 concentration the fan energy is reduced 25-55 % and the ventilation heat losses are reduced by 25-32 % compared to a constant air volume (CAV) system. Pavlovas [9] conducted a study where he implemented DCV to a multifamily building with respect to three different measurements: CO_2 level, relative humidity level and occupancy. The study focused on a single apartment which was simulated in IDA ICE. In the case of occupancy DCV the ventilation flow was set to a maximum value of 30 l/s when the apartment was occupied and lowered to 10 l/s when unoccupied and compared to a reference case where the ventilation airflow was kept at 30 l/s at all times. The results indicate that the annual heat demand for the ventilation system can be reduced by approximately 20 % by implementing an occupancy based ventilation control strategy.

Ahmed et al. [10] studied the indoor climate and energy performance of a Finnish low energy office building in order to determine the optimal control and operation solutions for the demand controlled room conditioning and ventilation system. Simulations were made in IDA ICE where the results show that by using a DCV system the total primary energy usage can decrease by 7-8 % compared to a CAV ventilation system, depending on the control and operation strategy used.

When a CAV ventilation system is converted to a DCV system there are a few costs that need to be considered. First, there is a need for sensors. PIR sensors are cheaper than CO_2 sensors and might also last longer due to the simplicity in their technological design [24]. Regarding the ventilation system, only the ductwork might be reusable [25]. The air inlets and outlets need replacement to adjustable ones and the AHU, including the ventilation ducts leading to the AHU need replacement due to the decrease in air flow in the ducts and therefore also their size [25].

When the energy savings potential for DCV systems are investigated, the length of the sampling intervals can affect the quality of the data; if the sample intervals are too short, it will lead to several data points without change. If the sampling intervals are too long, however, it can lead to changes not being reported [26]. Most commonly, data sampling intervals of up to ten minutes are used [8, 27]. In some cases, fifteen minute intervals are used [28]. However, no literature was found regarding the impact of longer intervals on the energy usage or IAQ.

2.4 Heat recovery unit efficiency

The efficiency of the heat exchangers in an HRU, i.e. how much of the heat can be transferred between the air streams, is dependent on the type of heat exchanger used, the mass flow rate of the cold air stream and the humidity. This was shown by Bonfiglio et al. [29] by conducting an experiment with a cross-flow heat exchanger in a test chamber. The mass flow rate for the cold air flow varied from 400 kg/h to 650 kg/h, and the humidity was set to 30, 45 and 60 %. The results indicate that the efficiency lies between 85-95 %, decreasing with a higher mass flow rate and lower humidity. A similar study was conducted by Gendebien et al. [30] where the efficiency of a cross-flow heat exchanger was determined for air volume flow rates of 30 m^3/h to 100 m^3/h. The results show that the efficiency lies between 76-92 %, decreasing as the volume flow rate increases. When heat exchangers are applied in cold climates it is also important to consider frosting. This was shown by Anisimov et al. [31] who determined that the efficiency of a cross-flow heat exchanger can decrease significantly, up to 37.5 %, due to frosting. Rafati Nasr et al. [32] describes a few different techniques to avoid frosting, including preheating the inlet air, reducing or closing the supply air side, recirculating warm exhaust air etc. However, all the techniques lead to a higher energy usage or poorer IAQ.

Michalak [33] conducted a study of the energy savings potential and the efficiency of an air handling unit with a cross-flow heat exchanger in an office building located in Poland. The results show that the average efficiency of the heat exchanger amounted to 65.2 % during heating periods and to 64.6 % during cooling periods, compared to the efficiency of 59.5 % declared by the manufacturer. The annual energy savings were 25.6 MWh during heating and 0.26 MWh during cooling. Zemitis et al. [34] conducted a study on a two-story-high residential building in Latvia that showed that the average efficiency of modern cross-flow heat exchangers is around 86 %. This was, however, dependent on the air flow volumes, with some manufacturers at lower air flow volumes reaching up to 92 % and at higher air flow volumes only reaching 73.4 %.

Efficiencies for cross-flow heat exchangers are often given to lie between 70-80 %. Examples of these are Mysen et al. [35] using an efficiency of 70 % according to a reference office building, Merema et al. [8] using a 78 % efficiency according to guidelines and Kostka et al. [36] assuming an 80 % efficiency in their study of a single-family building. According to Warfvinge et al. [37], it is reasonable to assume an 80 % efficiency. Efficiencies for rotary wheel heat exchangers are given to lie between 75-83 %. Examples include Luc et al. [38] using an efficiency of 75 %, Mardiana-Idayu et al. [39] specifying an efficiency of 80 % to be obtainable and Zemitis et al. [34] showing that an efficiency of 83 % could be reached.

3 Theory

In this section the theory and equations used in the methodology section are reviewed.

3.1 Demand controlled ventilation

DCV is an under category of variable air volume flow ventilation systems [40]. In DCV systems the air flow rates are most commonly controlled with respect to occupancy or CO_2 concentration. Therefore the ventilation air flow rates are lowered in cases where the space is vacant, which could lead to a decrease in thermal energy usage since there is a smaller volume of air for the AHU to heat up [8]. Furthermore, the lower air flow rates means that the fans in the ventilation system do not have to work as hard and therefore uses less electrical energy [8].

3.2 Ventilation air flow rate

The required ventilation air flow rate for a space, $\dot{V}$, is given by [37]

$$\dot{V} = \dot{V}_{base} + \dot{V}_{person}, \tag{1}$$

where $\dot{V}_{base}$ is the base flow rate given in the unit [l/(s·m^2)] and V_{person} is the flow rate per person with the unit [l/(s·person)]. The volume flow rate per person is often assumed to be 7 l/(s·person) [37]. To get the same unit for both terms, equation (1) can be written as

$$\dot{V} = \dot{V}_{base} + n \cdot \frac{\dot{V}_{person}}{A}, \tag{2}$$

where n is the number of persons and A is the area of the investigated space in [m^2]. This results in an air flow rate in the unit of [l/(s·m^2)].

3.3 Heat recovery

Ventilation HRU:s are designed to reduce the amount of energy needed for heating the air coming into the AHU by preheating the incoming air. This is done by transferring some of the waste heat from the exhaust air via a heat exchanger [41]. In most cases, however, the HRU is not capable of recovering all the heat from the outgoing air. In mechanical ventilation systems 80-90 % of the ventilation losses could be recovered [42]. The remaining heat that cannot be recovered by an HRU is then supplied by a heating coil. A schematic view of the function of an AHU with an HRU can be seen in figure 2.

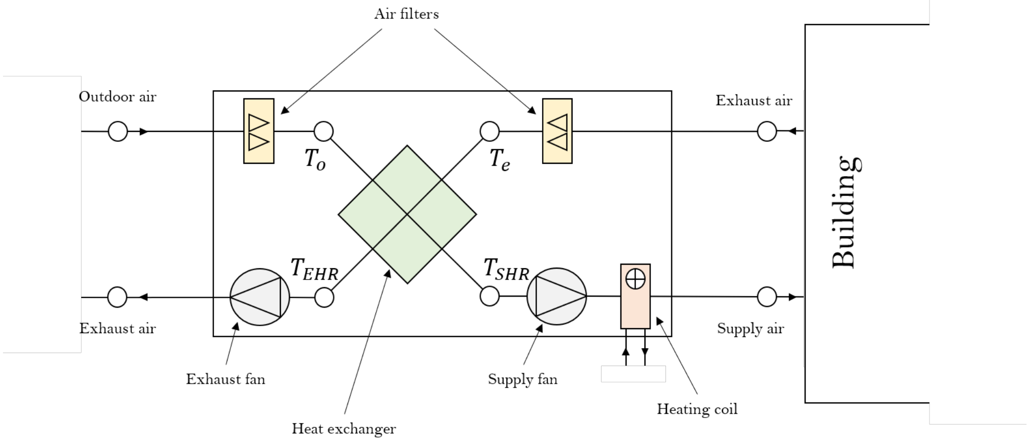


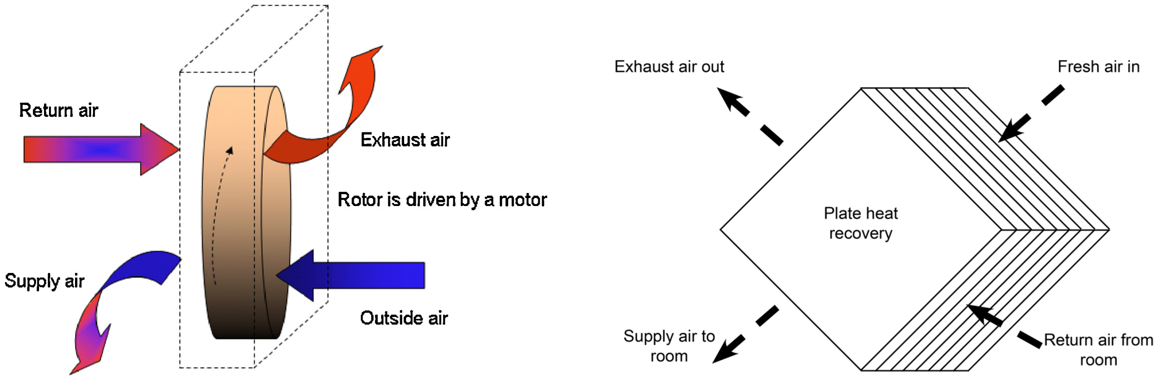
Figure 2 – Schematic view of the function of an AHU with an HRU, inspired by [33].

To evaluate the efficiency of a HRU temperature ratio, also known as temperature efficiency, can be used [33]. The temperature ratio for supply air, η_s, is given by

$$\eta_s = \frac{T_{SHR} - T_o}{T_e - T_o}, \tag{3}$$

where T_{SHR} is the supply air temperature after the HRU, T_o is the outdoor air temperature and T_e is the exhaust air temperature before the HRU [33].

Two of the most commonly used heat exchangers in HRU:s are plate heat exchangers, which in turn can be separated into cross-flow and counter-flow, and rotary wheel heat exchangers [34]. In plate heat exchangers the two air streams run through flow channels, separated by thin plates, where the heat is transferred from one stream through the plate to the other [41]. In rotary wheel heat exchangers the warm air stream heats up a motor-driven rotating porous wheel. The wheel then rotates and heats up the cold air stream [41]. Illustrations of a rotary wheel heat exchanger and a cross-flow heat exchanger can be seen in figure 3.



(a) Rotary wheel **(b)** Cross-flow

Figure 3 – Illustrations of a rotary wheel heat exchanger and a cross-flow heat exchanger [39].

The efficiency of a heat exchanger is not constant throughout the year. During colder seasons, a phenomenon called frosting can occur [32]. Frosting is caused by the warm exhaust air being cooled down to the dew point and starting to condensate. If the surface temperature then is below the freezing point this can cause the condensation water to freeze [43]. Frosting can lead to problems in heat exchangers through blockage of air flow passages and a decrease in heat transfer rate between the air streams, which can lead to an increase in the electric energy usage for the fans in the AHU [32]. Cross-flow heat exchangers can be preferable in cold climates, compared to rotary wheel heat exchangers, because they tend to have less problems with blockage caused by frosting [32].

3.4 Indoor air quality

IAQ in buildings is determined by the amount of particle and gas pollutants [40]. When subjected to poor IAQ a person's work performance may be impaired and health symptoms may increase [44]. One method that is often used to determine the IAQ in a room is measuring the level of CO_2 [40]. The level of CO_2 in outdoor air is approximately 400 ppm, which is also the base level in unoccupied buildings [37]. When a room is occupied the CO_2 level starts to increase. According to Swedish regulations, for the IAQ in a room to be considered good the CO_2 level should not exceed 1000 ppm [37, 40, 45].

4 Methodology

In this section the methodology of the thesis is explained. Section 4.1 gives a description of the reference building, sections 4.2 and 4.3 detail how occupancy schedules were created, section 4.4 goes through how the building model in IDA ICE was set up, section 4.5 explains the different scenarios that were simulated and in section 4.6 some limitations are presented.

4.1 Building description

The building that is used as a reference building in this thesis is the LU1 section of the natural science building at Umeå University, which can be seen in figure 4. The building has three wings, forming the letter "E" and the LU1 section is the middle wing. In the LU1 section of the building the part investigated is the fifth floor. The fifth floor consists of 40 offices and some other spaces, like a break room and conference rooms. In this thesis, however, the focus will be set mostly on the offices.

Figure 4 – A photo of Umeå University campus where the part marked in red is the LU1 section of the natural science building [46].

The natural science building was built in 1965, but has undergone some renovations since then. The windows on the fifth floor were replaced with more modern windows in 2007 alongside with a renovation that also improved the building envelope of the fifth floor [47]. In 2017 photovoltaic cells, covering up to 20 % of the buildings electricity needs, were installed on the roof [48]. These photovoltaic cells will not be included in the building model.

The offices are equipped with sensors by *Lindinvent*. The sensors collect information about occupancy, temperatures, CO_2 levels and ventilation air flow rate and are used to control the ventilation and lighting in the offices according to the occupancy [49].

4.2 Synchronization of the sensor data

The occupancy data gathered from the Lindinvent sensors consisted of an Excel-file with timestamps and occupancy, 0 if vacant and 1 if occupied, for all of the 40 offices. The data was gathered from the beginning of February 2019, with the date varying a bit from office to office, until the end of December 2019. To get the same investigation period for all the sensors it was decided to conduct the study for the time period of 10th of February until the 31st of December. In the Excel-file there were some missing data in the specified time period. In addition, the time intervals between the data points in the gathered sensor data were not constant. In order to address these issues the data was imported to *Matlab R2020b*.

In Matlab the tables with the sensor information for each sensor were converted to timetables with the function '*table2timetable*'. The timetables were then aligned with a central timestamp for the specified time period with ten minute intervals using the function '*synchronize*'. The function was set to include the first value in each time bin with 'firstvalue' and to include the right edge of each time bin with 'IncludedEdge' set to 'right'. These settings caused the function to go through the data for each ten minute interval and look for the sensor output closest to that timestamp, which was then assigned to that time step in the synchronized table. For example, if the sensor output was 1 at 03-Mar-2019 12:36 the synchronized data would show 1 at 03-Mar-2019 12:40. If data was missing for a time period the synchronized table would show 'NaN'. The missing data points were then found with the function '*ismissing*', summed together with the function '*sum*' and stored in a variable.

In order to determine what sensor output value should replace the missing values a Matlab code was written. The code went through all the time steps, t, and if the sensor output at the time step was 'NaN' one of two scenarios were set to happen. Scenario one was set to take place if the sensor output at time step $t-1$ is not equal to the sensor output at the time step $t+1$. In this case the value at time step t was set to 1, i.e. the office is occupied. According to Yang et al. [50], this method can lead to reduced energy savings but the occupant satisfaction is assured. The second scenario was set to take place if the sensor output at time step $t-1$ is equal to the sensor output at $t+1$ or if the sensor output at $t+1$ is 'NaN'. In these cases the value of the missing data points were set to be the same as the sensor output the time step $t-1$. This was done with the function '*fillmissing*' with the setting 'previous'.

The final steps of the synchronization phase were to store the synchronized data from all sensors in one timetable, 'AlignedTable', and to calculate the percentage of the data that was missing per sensor as well as the average occupancies during working hours for the offices throughout the investigated time period. The missing data for all the sensors and the average occupancies were then plotted in graphs.

4.3 Creating profiles from the sensor data

Since there is no direct way to import occupancy schedules to *IDA ICE 4.8* a few simplifications were made to the sensor data. Occupancy is set in IDA ICE is by specifying a profile for each day. The profiles consist of information on if, and between which time steps, the specified room is occupied. The profiles can also be saved to be used on other days. In order to convert the sensor data to profiles for the offices, three Matlab functions were written. A flowchart of the conversion process can be seen in figure 5 below. The rounded corner boxes represent input data and the sharp corner boxes represent functions. The rounded corner boxes within the sharp corner boxes show examples of what happens within the functions.

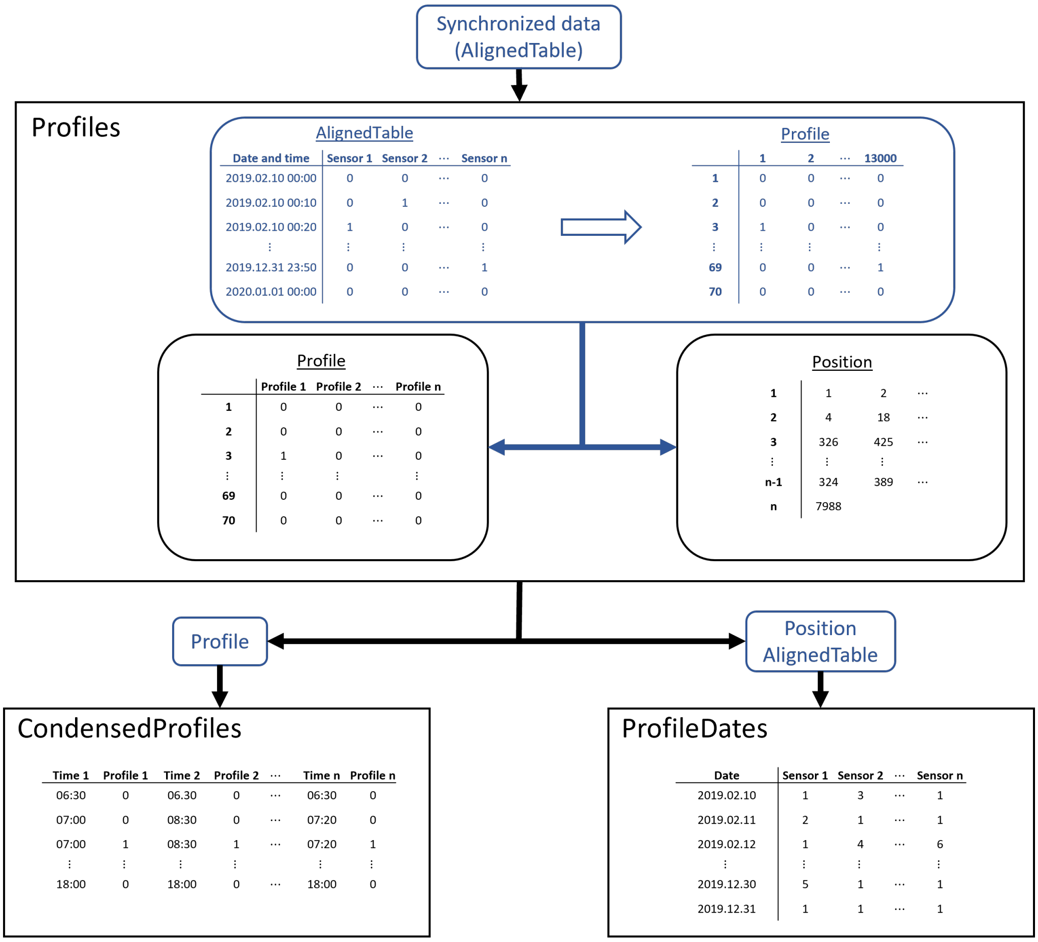


Figure 5 – A flowchart of the conversion of the sensor data from synchronized data to profiles, where the final outputs are used to set the occupancy in IDA ICE.

First, a function called *'Profiles'* was written. The function determines how many different profiles there are between all the offices throughout the investigated time period. The function takes the synchronized sensor data timetable 'AlignedTable' as input. The function then goes through the investigated time period, which was 325 days in this case, for each sensor and stores 144 sensor data outputs, corresponding to a days worth of data points, in a column of an array before moving to the next 144 sensor data outputs. The function then removes the last 35 rows and the first 39 rows, thereby only considering the times between 6:30 and 18:00. This results in a 70 times 13 000 sized array, which was named 'Profile'. Here each column represents a profile for a day throughout the investigated time period with columns 1 through 325 representing the data collected from sensor 1, columns 326 through 650 representing sensor 2 and so on for all sensors.

The function then goes through each column of the array and compares one column at a time to the others to find out if there are any duplicates. The column number for the compared column as well as the duplicates are then stored in an array, named 'Position', with each row number corresponding to a column number in 'Profile'. All the duplicate columns in 'Profile' were then removed resulting in an array where each column represents a unique profile. The arrays 'Position' and 'Profile' were then set as outputs for the function.

The second function, *'CondensedProfiles'*, takes the output 'Profile' from the function *'Profiles'* and makes a condensed version of it, i.e., a version where consecutive rows with the same signal outputs are removed making it more condensed. This is done by first creating a table with all the different profiles and a timetable from 6:30 to 18:00 for each profile as columns. The function then goes through one profile and the corresponding timetable at the time removing all consecutive rows with the same sensor output value, only keeping the rows where a change from 1 to 0, or vice versa, takes place. The function then adds a row directly before the change with a copy of the timestamp and the opposite sensor output value. For example if a change from 0 to 1 takes place at the timestamp 7:30 the function includes two rows, the first one being 7:30 with the value 0 and the second one being 7:30 with the value 1. The output from the function is a table consisting of condensed versions of each profile.

The third and final function, *'ProfileDates'*, takes the output 'Position' as well as the sensor data table 'AlignedTable' as input. The function then creates a timetable with rows for each date within the investigated time period and a column for each sensor, which corresponds to 325 rows and 40 columns in this case. The function then goes through the array 'Position' matching the profile, which is represented by the row number in 'Position', for each day with the right sensors. The output from the function is a timetable 'SensorProfiles' where each column represents a sensor and each row represents a day within the investigated time period and the profile that corresponds to that day for each sensor, resulting in a complete description of the investigated time period.

From *'CondensedProfiles'* one can now transfer all the profiles into IDA ICE, and with the help of 'SensorProfiles' one can match the profiles to each office throughout the investigated time period.

4.4 Settings for the building model

For the energy simulations an IDA ICE building model, previously used in [51], was used as a reference building. The model was of the fifth floor of the LU1 section of the natural science building at Umeå University and contained information about the structure of the building, including the thermal transmittance for walls, windows etc. Information about the model can be found in table A.1 in appendix A. The model can be seen in figure 6 below.

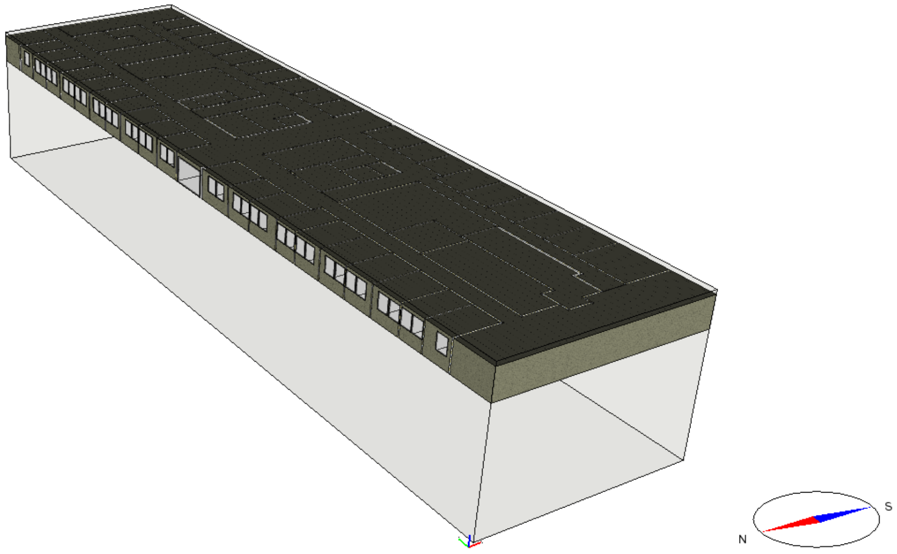
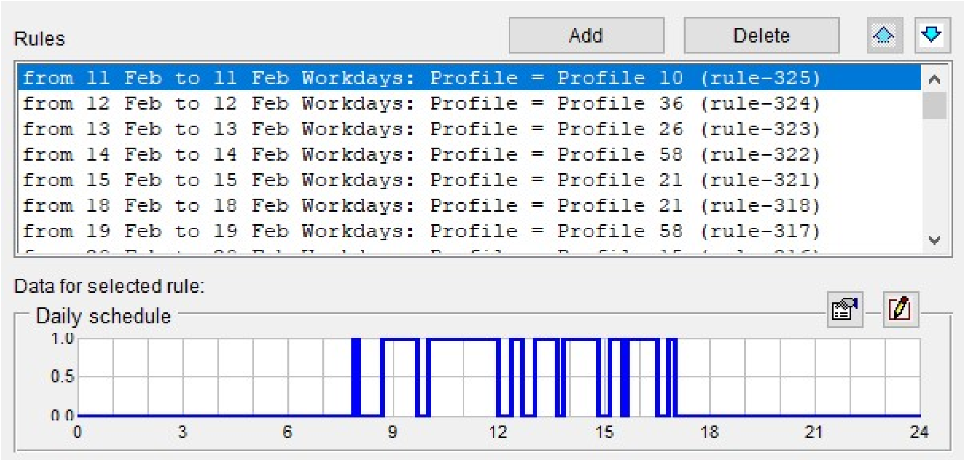


Figure 6 – The IDA ICE model of the fifth floor of the LU1 section of the natural science building at Umeå University.

The offices that are investigated are located alongside the north and the south facing walls. For the offices on the building floor the schedules created in section 4.3 were implemented for each office and named *S01* through *S40* corresponding to the sensor the data was from. This was done by transferring the profiles into IDA ICE and assigning the profiles to the corresponding day. Weekends and holidays were excluded from the simulations, resulting in a comparison of only workdays. An example of a schedule and how the profiles are used within the schedules can be seen in figure 7.



```
from 11 Feb to 11 Feb Workdays: Profile = Profile 10 (rule-325)
from 12 Feb to 12 Feb Workdays: Profile = Profile 36 (rule-324)
from 13 Feb to 13 Feb Workdays: Profile = Profile 26 (rule-323)
from 14 Feb to 14 Feb Workdays: Profile = Profile 58 (rule-322)
from 15 Feb to 15 Feb Workdays: Profile = Profile 21 (rule-321)
from 18 Feb to 18 Feb Workdays: Profile = Profile 21 (rule-318)
from 19 Feb to 19 Feb Workdays: Profile = Profile 58 (rule-317)
```

Figure 7 – An example of how schedules were made in IDA ICE. The lower part shows a profile and the upper part shows how the profiles were set to their corresponding days.

The schedules were used to control the occupancy, equipment (i.e. computers and other electronics plugged into a wall outlet) and lighting in each office. The lighting was also controlled by the amount of natural sunlight in the room, meaning that if the light intensity would exceed a setpoint value the lights would turn off. This was done by with the setting "*Setpoints+Schedule*" in IDA ICE. It is also assumed that the occupant turns off their computer and lights when leaving the office. The ventilation air flow rate for the offices was determined with equation (2), with a base flow rate of 0.35 $l/(s \cdot m^2)$.

For the other spaces on the building floor the ventilation air flow rates were determined with equation (2). For toilets, there is a requirement to have an exhaust ventilation air flow rate of at least 10 l/s [37]. This means that if the ventilation air flow rate determined with equation (2) did not exceed 10 l/s in the toilets, a value that corresponds to 10 l/s was used. The base flow rates and the occupancy densities for these spaces can be seen in table 1 below.

Table 1 – The ventilation flow rates and occupancy densities for the different spaces.

Space	Base flow rate $[\mathrm{l/(s \cdot m^2)}]$	Occupancy density $[\mathrm{m^{-2}}]$	Volume flow rate $[\mathrm{l/(s \cdot m^2)}]$	Reference
Conference rooms	0.35	0.5	3.85	[52]
Copying rooms	0.35	-	0.59	-
Hallway	0.5	-	0.76	[53]
Break room	0.35	0.25	2.10	[52]
Staircases	0.5	0.1	1.2	[53]
Storage rooms	0.35	0.02	0.49	[52]
Technical rooms	0.6	0.02	0.74	[53]
Toilet 1	0.35	0.12	3.66*	[37]
Toilet 2	0.35	0.12	1.99*	[37]
Toilet 3	0.35	0.12	3.86*	[37]
Toilet 4	0.35	0.12	1.89*	[37]
Toilet 5	0.35	0.12	3.33*	[37]

* The ventilation air flow rate determined with equation (2) did not exceed the requirement for toilets of 10 l/s, so a value corresponding to 10 l/s was used.

The occupancy diversity for non-office rooms were set to a pre-defined schedule "*Flexible hours*" in IDA ICE, with the exception of technical rooms and conference rooms where the occupancy diversity factor was approximated according to the findings of Duarte et al. [54]. Another exception was the break room, where the occupancy diversity factor was assumed to rise during coffee and lunch breaks, determined from the average value of the diversity factors of the office. All of the aforementioned occupancy diversities were assumed to be reduced by half during the month of July, when most of the vacations are being held. The occupancy diversity factors used can be seen in figure 8 below.

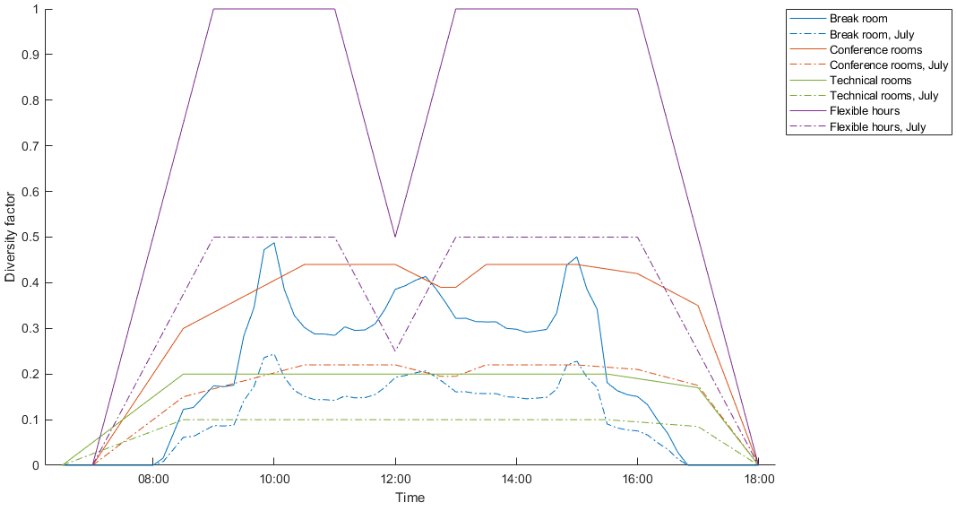


Figure 8 – The occupancy diversity factors used for the non-office rooms.

The lighting and equipment control for these spaces varied from room to room. In many cases the pre-defined schedule "*Flexible hours*" was used to control both the lights and equipment. The exceptions to this were conference rooms, the hallway and staircases, the break room and technical rooms. In conference rooms and the break room the lighting control and equipment was set to follow the occupancy schedules of the particular space. In technical rooms the lighting control was set to follow the occupancy schedule, but the equipment was set to always be on. Finally in the hallway and the staircases the lighting was set to be on from 6:30 to 18:00 and the equipment was set to always be on. In all the aforementioned cases the lighting was also controlled by the amount of natural light.

All simulations were made with the option "*Custom*" and the method set as "*Dynamic*" in IDA ICE. The option "*Custom*" meant that a specific time period could be simulated, instead of a whole year, and the method "*Dynamic*" meant that the time period was simulated once with a startup phase at the beginning. This led to the time period of the simulations being from 10th of February 2019 until the 31st of December 2019. The startup phase was set to 14 days as recommended in [55].

4.5 Ventilation system energy savings potential

Four different scenarios of ventilation control were investigated in this thesis, in order to investigate their effect on the energy usage of the building ventilation system. First, we have a baseline where there is no HRU and the ventilation is on from 6:30 in the morning until 18:00 in the evening in all rooms on the office floor. This scenario is used to compare the energy savings potential of the other scenarios against.

The equipment and lighting were included in the simulations in order to account for the heat radiation that they contribute with. However, the electrical energy needed for lighting and equipment as well as the thermal energy needed for heating the domestic hot water were excluded from the results in all the scenarios. This was done because the aforementioned energy meters were set to be dependent on the occupancy and can therefore be considered constant, since the occupancy is the same in all scenarios.

4.5.1 Variations in heat recovery unit efficiency

The second scenario investigates the impact of varying the efficiency of the HRU. Two different efficiencies of the heat exchanger were investigated; 80 %, which is in line with [8, 37, 50], and a high efficiency of 95 % which is in line with the approximation of the actual heat exchanger of the building, as stated in [51].

The ventilation control schedules used in this scenario were the same as in the baseline scenario, i.e. on from 06:30 to 18:00. The potential energy savings in thermal energy and the electrical energy were determined and plotted in a graph and compared for the different heat exchanger efficiencies.

4.5.2 Demand controlled ventilation

In the third scenario DCV was introduced. The ventilation in the offices was controlled according to the occupancy schedules created in section 4.3. Conference rooms and the break room had their ventilation controlled by their respective occupancy schedules and the toilets and copying rooms had their ventilation controlled by the schedule "*Flexible hours*". The ventilation control for the hallway, staircases, storage rooms and technical rooms were left at 06:30 to 18:00.

Simulations were performed for the different efficiencies on the heat exchanger defined in section 4.5.1 as well as without a heat exchanger. The potential energy savings in thermal energy and electrical energy were determined, by comparing the results with the results from section 4.5.1, and plotted in a graph.

4.5.3 The impact of longer intervals between sensor signals

In the fourth and final scenario the impact of longer time intervals between ventilation control signals from the sensors was investigated. The time intervals investigated were fifteen and twenty minutes, compared to the base setting of ten minutes. This was done by writing a ventilation control macro in IDA ICE. The layout of the macro can be seen in figure 9.

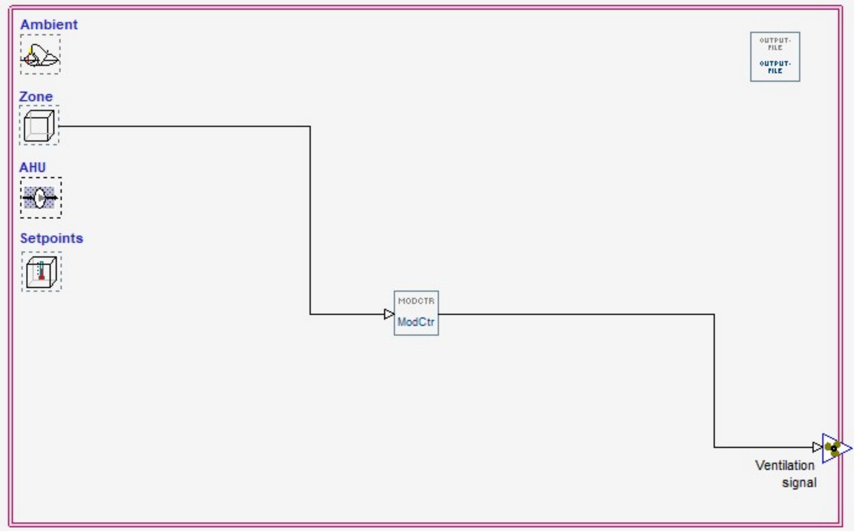


Figure 9 – The layout of the ventilation control macro. The block in the middle checks for occupancy at specified time intervals and sends a signal to the ventilation system.

As seen in figure 9 a block, "*Time modulated controller*", was inserted between the input signal from the "*Zone*" block and the output signal. In the "*Time modulated controller*" block the parameter "*TIME_ CYCLE*" was set to fifteen or twenty minutes, "*HI*" was set to 1.0 and "*LO*" was set to 0.0. The input to the block was set to "*Occupancy*". This caused the block to check the occupancy at the specified intervals and send out a ventilation control signal accordingly.

The ventilation control macro was set to control the ventilation for each office. Simulations were performed for DCV with a heat exchanger efficiency of 80 % with sensor intervals of fifteen minutes and twenty minutes. From these simulations the CO_2 levels for all the offices during the investigated time period as well as the energy savings potential were compared. Since the base CO_2 level is 400 ppm, the values below or equal to 400 ppm were excluded from the comparison. This was done so that the comparison would only consider the time periods when the offices are occupied. The results from the CO_2 level comparison were gathered in a plot showing the percentage of data points within CO_2 levels ranging from 700 ppm, with steps of 5 ppm, up to 1200 ppm, which is considered the CO_2 level for when the offices are in use.

4.6 Limitations

The findings of this thesis have to be seen in light of a few limitations. First and foremost; there was no sensor data from January and the beginning of February, meaning that an energy simulation of a full year was not possible. Second, there was no ground truth data for the occupancy, which meant that there was no way to know if the data from the sensors was accurate or not. It was also assumed that the offices were occupied/unoccupied for ten minute intervals at a time, corresponding with the sensor data intervals, which most likely is not the case in practice.

5 Results

In this section the results from sections 4.2 and 4.5 are presented.

5.1 Missing data and average occupancies

The percentage of missing data from the sensor data is presented per sensor in figure 10 below. Each of the bars,*S01* through *S40*, represent a sensor and the y-axis shows the percentage of missing data.

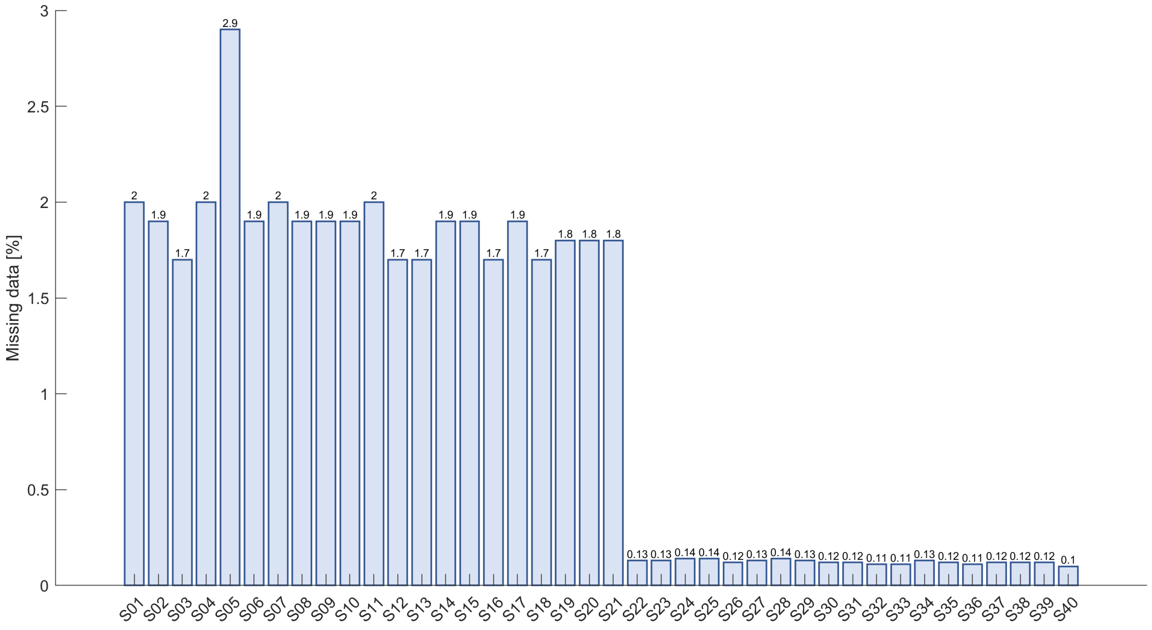


Figure 10 – The percentage of missing data per sensor.

As one can see in figure 10 the sensor with by far the most missing data is sensor *S05* with 2.9 %. Excluding sensor *S05* the missing data percentage is divided into two groups. One group is sensor *S01* to sensor *S21*, having between 1.7 % and 2 % of missing data, and the other group being sensor *S22* to sensor *S40* having only between 0.1 % and 0.14 % of missing data.

In figure 11 the average occupancies in all the offices throughout the investigated time period are presented. The grey lines represent occupancies for the offices. The office with the highest average occupancy is highlighted in blue and the office with the lowest average occupancy is highlighted in green. The average occupancy for the whole fifth floor of the building is represented by a red line.

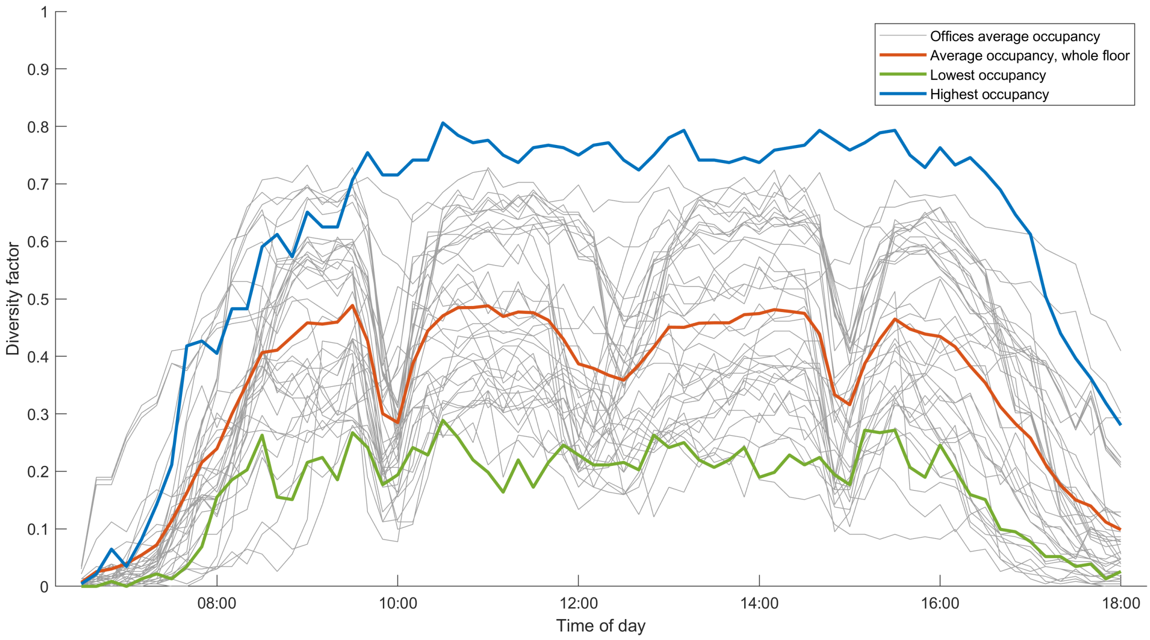


Figure 11 – The average occupancy of each of the offices on workdays during the investigated time period. The grey lines represents the occupancies for the offices.

As seen in figure 11 the average occupancy on the office floor has three distinctive dips; one at approximately 10:00, one at approximately 12:30 and one at approximately 15:00. On average the offices are occupied 34.8 % of the time. The office with the highest average occupancy, highlighted in blue, is occupied 61.7 % of the time. The office with the lowest average occupancy, highlighted in green, is occupied 16.9 % of the time. It is also worth noting that neither the office with the highest occupancy on average nor the office with the lowest occupancy on average show as distinct dips in occupancy at the previously specified timestamps as the other offices.

5.2 Heat recovery unit

In figure 12 the building energy usage is compared for a ventilation system without an HRU as well as for ventilation systems with HRU:s with efficiencies of 80 % and 95 %. The compared energy usages consist of heating, represented in red, cooling, represented in blue and electrical energy usage which is represented in yellow. Heating comprises energy delivered by district heating that is used for heating the rooms as well as for heating the incoming air to the air handling unit. Cooling is the energy delivered by district cooling, used for cooling the rooms. Electrical energy consists of the energy needed to run the fans in the air handling unit.

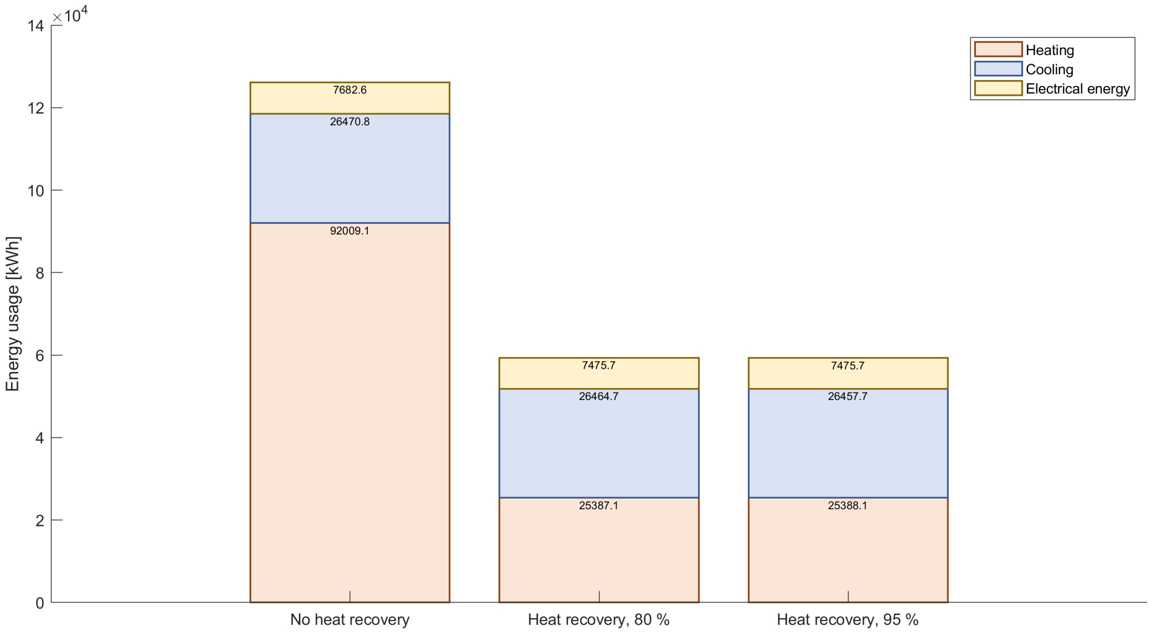


Figure 12 – The energy usage without an HRU compared to HRU:s with 80 % and 95 % efficiencies.

From figure 12 one can determine that while there is a considerable decrease in energy used for heating between no HRU and an HRU with an efficiency of 80 %, the difference between having an HRU with an efficiency of 80 % and 95 % is marginal. Between no HRU and an HRU with an efficiency of 80 % the energy saving potential for heating is 72.41 %, for cooling 0.02 % and for electrical energy 2.69 %, resulting in a total energy savings potential of 52.98 %. When comparing an HRU with an efficiency of 80 % to an HRU with an efficiency of 95 % the only difference is a slight increase in the energy savings potential for cooling, which increases from 0.02 % to 0.05 %. This does not, however, notably affect the total energy savings potential.

5.3 Demand controlled ventilation

In figure 13 the results from the comparison of the energy savings potential if the ventilation system control strategy is changed from a constant air flow rate throughout the workday to DCV. The comparison is made for an air handling unit without an HRU and for HRU:s with efficiencies of 80 % and 95 %, respectively. The energy usages compared in this section are the same as specified in section 5.2.

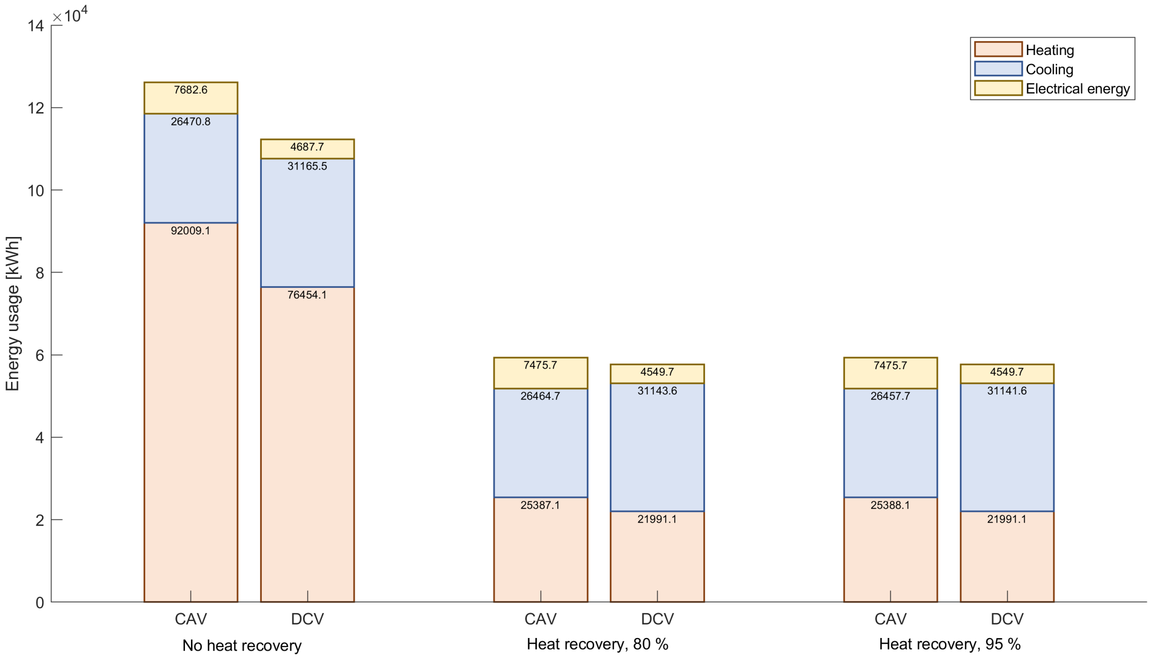


Figure 13 – The energy usage for a CAV system compared to DCV for a ventilation system without an HRU and with HRU:s with 80 % and 95 % efficiencies.

When comparing the energy usages seen in figure 13 one can notice that while there is a energy savings potential in the energy used for heating and the electrical energy usage, the energy usage for cooling increases. In the case with no HRU the energy savings potential for heating is 16.91 % and for electrical energy it is 38.98 %. However, the energy needed for cooling increases by 17.74 %. This results in a total energy savings potential of 10.98 %. When the efficiency of the HRU is increased to 80 %, the energy savings potential for heating is 13.38 % and for electrical energy it is 39.14 %. As in the previous case the energy usage for cooling increases, by 17.68 % in this case, resulting in a total energy savings potential of 2.77 %. If the efficiency of the HRU is increased to 95 % the heating and electrical energy savings potential remains the same, but the cooling energy usage increases to 17.70 %. This results in a total energy savings potential of 2.76 %.

5.4 The impact of longer intervals between sensor signals

In figure 14 the impact that longer intervals between sensor control signals to the ventilation system has on the energy usage of the building is presented. The bars represent different intervals between sensor control signals, from the original ten minutes to fifteen and twenty minutes, respectively. The energy usages compared in this section are the same as specified in section 5.2.

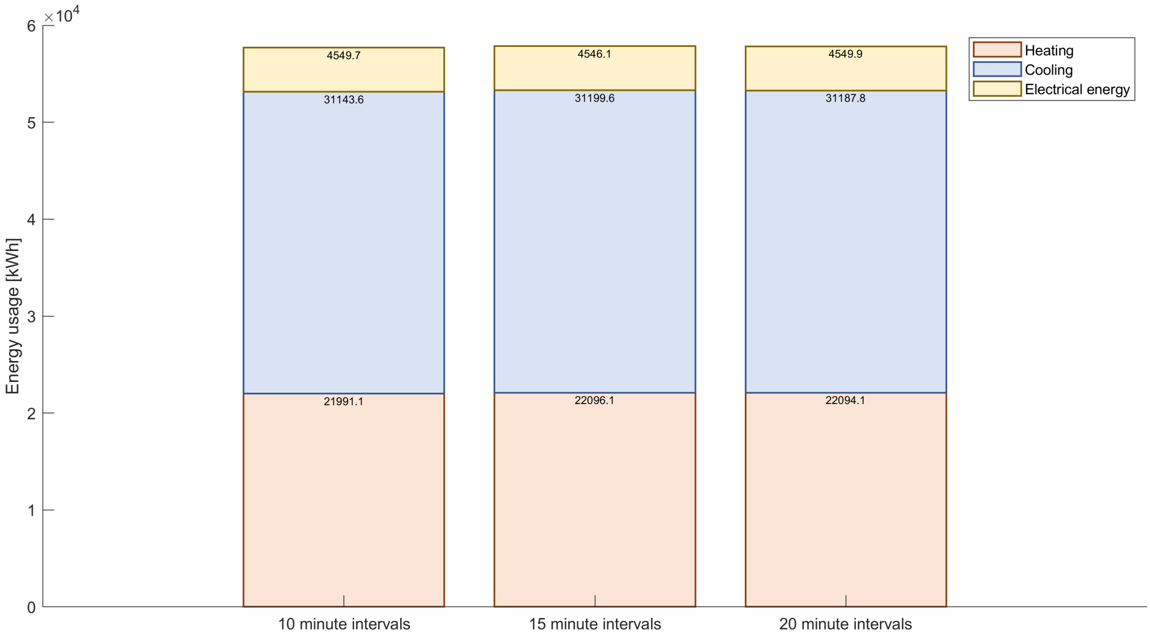


Figure 14 – A comparison of energy usage if the interval between sensor control signals are increased from ten minutes to fifteen and twenty minutes, respectively.

As seen in figure 14 the change in energy usage when the interval between sensor control signals is increased is small. When the interval is increased from ten to fifteen minutes the energy used for heating increases by 0.48 % and the energy used for cooling increases by 0.18 %. The electrical energy usage decreases by 0.08 %. In total the energy usage increases by 0.27 %. When the same comparison is made between ten and twenty minute intervals the heating and cooling energy usage increases by 0.47 % and 0.14 %, respectively. In this case the electrical energy usage remains unchanged, resulting in an increase of the total energy usage of 0.26 %.

In figure 15 the impact of longer intervals between sensor control signals on the CO_2 levels in the offices is presented. Here each bar represents a five ppm interval ranging from 700 ppm up to 1200 ppm. The height of the bars represents the percentage of time during the investigated time period that the CO_2 level is within the specified intervals. The red bars represent ten minute intervals between sensor signals, the blue bars represent fifteen minute intervals and the green bars represent twenty minute intervals.

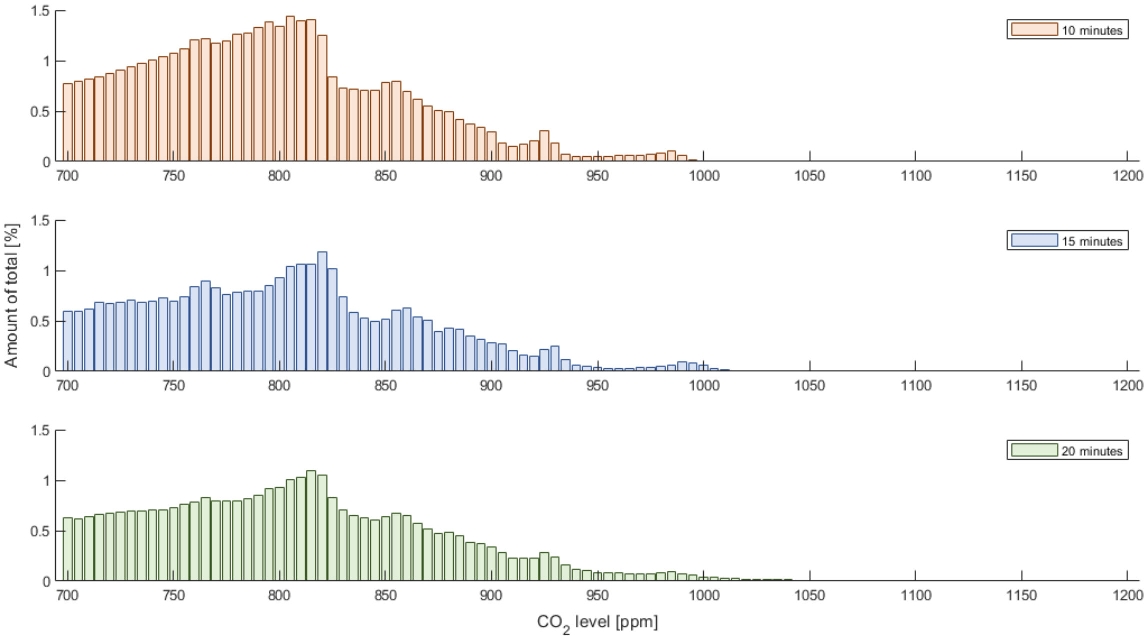


Figure 15 – The impact of increased time between sensor control signals, from ten minutes to fifteen and twenty minutes, respectively, on the CO_2 levels in the offices.

As seen in figure 15 the CO_2 levels stay under the limit for what is considered poor IAQ, 1000 ppm, for the majority of the time regardless of the interval between sensor control signals. If the interval is ten minutes the percentage of time over 1000 ppm is $9.4 \cdot 10^{-5}$ %. The total occupancy time for all the offices during the investigated time period is 38437 hours and 30 minutes, which means that the IAQ was poor 2.4 minutes divided over all the offices. When the interval between sensor control signals is increased to fifteen minutes the IAQ is poor 0.06 % of the time, which corresponds to 22 hours and 24 minutes. Finally if the interval is increased to twenty minutes the IAQ is poor 0.23 % of the time, which in turn corresponds to 86 hours and 57 minutes.

6 Discussion

In this section the results presented in section 5 will be discussed and reviewed.

6.1 Missing data and average occupancies

The method used for estimating the value of missing data points, explained in section 4.2, should not have a noticeable effect on the results. This is because the sensor with most missing data points, *S05*, is missing less than 3 % of the total data points. Furthermore, the offices with the highest and lowest average occupancies, seen in figure 11, are from sensor *S31* and *S33* respectively. These are sensors that are missing less than 0.15 % of the total, meaning that the occupancy estimations from sensors with more missing data falls between the minimum and maximum occupancies.

It was noted that all the sensors with fewer missing data points, *S22* to *S40*, were localized in the west half of the building. A reason for there being more missing data on sensors *S01* to *S21* might be that they are on the same subsystem hub, i.e., the part of the system that connects these sensors to the rest of the system. This would mean that if there were a problem with the subsystem it would affect all of the sensors that are connected to it [56]. Further, the variations in missing data from sensors *S01* to *S21* might be caused by disconnected plugs or malfunctions within the sensor [56].

When comparing the occupancy in the offices seen in figure 11 with ASHRAE standards seen in figure 1 one can see that there is a big difference. In ASHRAE standards there is only one dip, which occur at lunchtime, while the result from this thesis shows three dips. These dips occurs at times which could be considered coffee breaks and a lunch break, with the ones at 10:00 and 15:00 being coffee breaks and the one at 12:30 being a lunch break. The reason behind there being such a big difference between the results and ASHRAE standards could be because of cultural differences, since the ASHRAE standards originates from America. Also worth noting when comparing figure 11 with figure 1 is that the diversity factor is lower in figure 11. This can be explained by the fact that the investigated floor in the reference building is occupied by researchers, and therefore it might not always be necessary to work from the office and working times can vary. This is also evident when comparing the occupancies between offices in figure 11. However, when comparing the average occupancy found in this thesis, 34.8 %, with other similar studies some resemblance can be found, for example Merema et al. [8] found an average occupancy of 33.0 % and 42.0 % in an office building in Belgium.

6.2 Energy savings potential

When an HRU was introduced to the ventilation system a reduction of 72.41 % in energy needed for heating was observed. This corresponds well with results found in [57–59]. It was also observed that there is only a marginal difference between the energy savings potential of an HRU with an efficiency of 80 % and one with an efficiency of 95 %. One potential reason behind this is that the thermal energy that an HRU can recover levels out after a while with respect to the efficiency of the heat exchanger. The efficiency at which this happens is dependent on the room temperature. If the air that is entering the room via the ventilation system is of a lower temperature than the room temperature, the amount of thermal energy that the HRU can recover will level out at a lower efficiency. This is because if the air entering the room is of a lower temperature than the room temperature it leads to more heating energy needing to be applied to the room to reach the desired room temperature. In the studied building the room temperature was set to 22 °C and the ventilation supply air temperature to 15 °C, leading to the aforementioned phenomenon. One could potentially find an optimal efficiency of the heat exchanger in the HRU by determining at which efficiency the thermal energy recovery potential starts to level out.

When reviewing the results found by introducing DCV to the ventilation system one can note that the energy savings potential is on the smaller side, with the energy savings potential being between 2.76-10.98 % depending on the heat recovery unit efficiency. If one were to just compare the energy savings potential from heating energy the results, 16.91 % without heat recovery and 13.38 % with heat recovery, would correspond with the results found in [9, 27]. Similarly, if one were to compare just the energy savings potential for the electrical energy, 38.98 % without heat recovery and 39.14 % with heat recovery, the results align with results found in [14, 27]. However, when looking at the results for the whole system, there is a large reduction in the energy savings potential caused by an increase in the energy needed for cooling. The increase in energy needed for cooling could be explained by the fact that the air coming into the AHU, which is at a temperature of 15 °C, is also used for cooling the offices. If by using DCV one stops the cold air from entering the office when it is unoccupied the cooling needed would have to come from another source, hence the increase in district cooling. In figure 13 it is also worth noting that the energy savings potential is much smaller if an HRU is included in the ventilation system. This is because the energy needed for heating is much smaller compared to a system without an HRU, as seen in figure 12. However, cooling energy use remains approximately the same. This leads to a smaller total energy savings potential. One potential way of avoiding these problems would be to have a setback temperature on the radiators in the office that would set the temperature on a higher level when the office is unoccupied during the cooling season [3–5]. By increasing the temperature setpoint on the radiators during unoccupied times, the need for cooling would not be as great. This combined with the outside temperature providing the heat for increasing the temperature in the room could lead to a reduction in energy usage.

6.3 The impact of longer intervals between sensor signals

From figure 14 one can see that increasing the length of the intervals between sensor control signals to the ventilation system leads to an increase in the energy usage. Increasing the length could also mean that the room is occupied for a while before the ventilation system turns on. On the other hand, it could also lead to the room being ventilated when the occupant has already left. The effects from this scenario would not be all negative, since ventilating after occupancy would remove the air pollutants that has built up during occupancy. However, from an energy usage perspective there is no justification for the intervals being longer.

Apart from a higher energy usage, from figure 15 one can see that lengthening the intervals between sensor control signals leads to a higher amount of time when the IAQ is poor. In the worst case, twenty minute intervals between sensor control signals, the total amount of poor IAQ during the investigated time period adds up to approximately 87 hours distributed over forty offices. Under the assumption that an equal amount is distributed to each office, which very well might not be the case, this would mean that the IAQ is poor just over two hours in each office. If there had been some substantial energy savings the two hours of bad IAQ might have been remedied by opening a window or a door. However, since there was no improvements in energy usage nor IAQ, there is no reason to lengthen the intervals between sensor control signals.

7 Conclusion

The energy savings potential of an HRU and DCV as well as the impact of lengthening the interval between sensor control signals to the ventilation system in a office building were investigated. The investigated office building consisted of 40 offices for which the occupancies were known. The average occupancy for all the offices combined throughout the investigated time period added up to 34.8 %. Based on the results the following conclusions can be drawn: (1) An energy savings potential of 52.98 % can be achieved by an HRU with an efficiency of 80 % or 95 % compared to no HRU. (2) An energy savings potential of 2.76-10.98 % can be achieved with DCV, where the energy savings potential decreases with a higher efficiency of the HRU. (3) Longer intervals between sensor control signals to the ventilation system leads to an increase of energy usage and a poorer IAQ.

7.1 Future studies

Future studies within the subject matter could include: (1) Investigation of energy savings potential if a temperature setback schedule were implemented for the radiators. By implementing temperature setback schedules on the radiators, meaning that the temperatures in the offices are set to a higher level when the offices are unoccupied during cooling seasons, one could investigate whether the cooling energy usage could be reduced. (2) Using a combination of motion and CO_2 sensors to get a more accurate estimation of occupancy. By using a combination of both motion and CO_2 sensors on could reduce the amount of potential false negatives/positives from the motion sensors by comparing the same timestamps with data from CO_2 sensors.

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Appendix

A Building parameters

The parameters for the building, as well as the equipment and lighting effect, used in a previous study, [51], can be seen in table A.1.

Table A.1 – Building parameters and values used in [51].

Parameters and inputs to IDA ICE	**Value**	**Unit**
Activity level, office work	1.2	met
Activity level, office walking/cooking	1.7	met
Clothing	0.5-1	clo
U-value, windows	0.96	$W/(m^2 \cdot K)$
U-value, doors	0.96	$W/(m^2 \cdot K)$
U-value, attic	0.11	$W/(m^2 \cdot K)$
U-value, external wall	0.33	$W/(m^2 \cdot K)$
U-value, external floor	1.2	$W/(m^2 \cdot K)$
U-value, slab towards ground	2.5	$W/(m^2 \cdot K)$
Mean U-value	0.65	$W/(m^2 \cdot K)$
District heating, COP	1	
District cooling, COP	1	
Domestic hot water, COP	1	
Temperature setpoint, indoor air	22	°C
Temperature setpoint, ventilation supply air	15	°C
Average hot water use	5000	kWh/year
Total area, LU1	6700	m^2
Total area, fifth floor, LU1	1340	m^2
Thermal bridges, walls	"Poor"	
Thermal bridges, windows and doors	"Typical"	
Thermal bridges, roof	"Good"	
Distribution system losses	"Poor"	
Equipment		
PC	125	W
Copying machine	400	W
Fax	30	W
Printer	160	W
Charger	10	W
Workspace	20	W/workspace
Break room	1.7	kWh/m^2
Lighting effect		
Single room office	12	W/m^2
Corridor	6	W/m^2
Open office area	10	W/m^2