ACHIEVING ENERGY EFFICIENCY AND INDOOR CLIMATE
A comparison of varying control system and building envelope modification

Oskar Andersson
Abstract

This thesis investigates the performance of varied control systems in an office building in the southern parts of Sweden. The control system is designed according to standard EN15232 with three levels of building automation and control systems with a multi-zone approach. Highest standard, class A, is a demand control system with VAV controlled by temperature and CO$_2$-levels in each zone. The lighting in class A is controlled by user demand and dimmers with regard to daylight to meet lighting regulations. The ventilation in the middle system, class B, is VAV controlled by temperature and demand in a zone. lighting is only on when a zone is used but no opportunity to dimmer. The reference object, class C, uses constant air volume CAV based on Swedish regulation and has lighting as in class B. The building envelope is varied between an existing model with 70’s building standard, according to today’s standard, and passive house standard in Sweden. All simulations are evaluated through energy performance and indoor climate in terms of temperature, PMV, PPD and CO$_2$-levels.

Simulations showed that the class A system has the highest possibility to decrease the energy use compared to the other systems. The reduction in total energy use differs from about 9-27% compared to class C and about 29-34% in electric energy use. Simulations also showed that class A and B are more advantageous to apply in a passive house rather than in the existing building if the total energy is evaluated. With regards to electric energy use, the difference between the building envelopes is too small to state that any difference exists. Neither one of the systems corresponds to ”good” indoor climate in the critical zones, all three is between the range ”good” and ”acceptable” according to standard SE-EN15251. Class A and B show an overall improvement of PMV and PPD compared to class C system. The class B system is closest to fulfill a ”good” indoor climate, especially in the passive house model. Evaluation with respect to CO$_2$-levels class A and C showed acceptable levels.
**Acknowledge**

I would like to thank my advisor at the university, Mark Murphy, for his help and guidelines throughout this project. I will also thank my advisor at Siemens Building Technologies, Louise Johansson, for all the help and good Friday meetings.

_Oskar Andersson_
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1 Introduction

In 2018, the building sector contributes to about 40% of the total energy consumption in Sweden, where the main contributors to energy consumption consist of electricity 50% and district heating 32% [1]. Except for electric heating, the main use for electric energy in commercial buildings is through electric cooling, ventilation, lighting and equipment. A considerable part of the building stock stand in front of renovation which increases the importance of energy efficient systems to provide low energy consumption and good indoor climate. In order to succeed in creating sustainable buildings, both energy efficiency and indoor climate must be taken into account since they can stand in conflict with each other [2].

The most common ventilation strategy in commercial buildings in Sweden is mechanical ventilation. In many of these building the ventilation system is through constant air volume CAV that not vary with user level, which often entails high energy use. The high use of electrical energy to fans entails a possibility of reducing consumption through active control of the system. This can be managed with demand controlled ventilation DCV that controls the ventilation flow by the user demand in a room without compromising with indoor air quality. The energy savings from DCV have been studied over time and shows potential to savings up to 50% [3], [4], [5]. It is also of interest to control the use of artificial lighting to lowering the energy use in a building since it stands for about 20% of the electrical energy.

In order to create energy efficiency buildings it is of great importance that all system can respond to each other since there is a strong interaction between them. A automation and control system corresponds to one specific system and is often connected to a management system to provide a superior control of the whole building. This superior control has the opportunity to predict and minimize unnecessary energy use. According to the standard EN 15232 [6], high performance control system has the ability to decrease energy use in offices up to 30% [6]. In an early design stage, the use of building simulation tools is powerful in order to predict and evaluate the outcome from different design approaches. It gives the opportunity to vary ventilation methods, user level and building envelope and verify it through energy use and indoor climate.

1.1 Related works

Reducing a building’s total energy use can be met in several ways. In a study by Flodberg et.al (2012) [7], the most successful methods for reducing energy use are highlighted by simulations of an office building in the IDA ICE software. The result showed that utilization of DCV and reduced window surface has the greatest impact on energy use. They also sees great potential when selecting product control which results in low internal heat loads from lamps and technical equipment. Important to point out is that the study not take indoor climate in account, which is a parameter that is of great importance according to Seppenen (2008) [8].

In order to improve indoor air and reduce energy consumption in buildings, Nassif (2012) [5] evaluates if CO2-controlled ventilation can contribute to achieving this. With a multi-zone approach the study compare variable ventilation systems with varying user level and ventilation solutions. It
showed that usage of CO$_2$-controlled ventilation resulted in a 23% reduction of energy use compared to a CAV system.

A negative factor for DVC can be the complexity of the system compared to CAV, which makes the system more difficult to apply on a larger scale. It requires both extensive adjustment of the system and which, in case of changes in the building, requires that systems be re-adjusted. A complex system can also increase the cost of installing the system since it comprises more products. Gruber et al. (2014) [9] evaluates, if a reduced complexity of a DCV entails higher energy use by simulating the performance of different systems. The common denominator is the input of CO2-content and temperature of the systems. It showed that increased complexity of a DCV not always have to significantly improve the performance of the building.

1.2 Aim of the study

Over the years, a large number of studies have been presented in this field, but there is a certain lack of how different control systems are advantageous in the case of varied building envelope. This thesis aims to design and evaluate how different control systems adapt to different building envelopes through building simulations. The control systems is designed according to the European standard EN15232 to investigate whether it corresponds to Swedish buildings. Result from simulations is validated based on energy performance and indoor climate with the objectives:

How adapted are the European standard rates in a Swedish market and in Swedish properties?

Will a control system result in a significant difference between the different building envelope or will the difference prove to be marginal?

1.3 Object description

The object in this study is a part of the Landskrona city hall, called building C. The city hall is under a major renovation where building C is the first stage of the project. The building is available to the study since Siemens building technology is responsible for the design and execution of installation products in the renovation project. Building C is a typical Swedish office building of time with separate office rooms, meeting rooms and lunch rooms distributed on each floor. It is built around 1970 and have 4 floors and a basements. Each floor plan is about 600 m$^2$ with a ratio between window and envelope area on 8.8%.

Before renovation, the building uses district heating as primary heat source. The secondary heat source is supplied with fan convectors that combining heating and ventilation in each room. The ventilation system is CAV combined with a rotating heat exchanger. The building has fixed windows that not allows the users to open them for ventilation. After renovation, the primary system will be retained but the secondary will be replaced by radiators for heating and supply air diffusers in the ceiling. The ventilation system is replaced by a DCV with zone control for each room. The system will control heat, ventilation and lighting through a superior control system. No renovation will take place on the building envelope except for the replacement of the most critical windows.
1.4 Demarcation

In this thesis, the main focus is on energy saving and indoor climate, the economic perspective of these systems is not evaluated. This because an economic analysis of all cases would be too time consuming and it is hard to predict costs of certain systems in a theoretical way. Evaluation of energy consumption is based on the whole building, indoor climate is only evaluated through certain rooms called critical rooms. The evaluation of indoor climate is only comparing temperatures, comfort indicators and carbon dioxide levels, other indicators for indoor climate are delimited. The systems that is evaluated is mainly based on the standard EN 15232 [6] which can demarcate other types control systems.
2 Theory

In this section, necessary theory about building simulations and indoor climate is presented.

2.1 Energy flow in buildings

To maintain the thermal comfort in a building, certain amount energy is needed. What affects the building’s energy needs is a combination of several factors such as geographical conditions as weather and wind, how components of the building envelope handle the energy flows through them, the user behavior and demands, lighting etc. These factors affect the thermal comfort in different ways, which indicate that an interaction between the systems is required. A typical office room with heat transfer through adjacent surfaces, ventilation, heating system and internal gains is represented in figure 1.

![Figure 1 - Schematic energy flow in a typical office room](image)

The gradient between indoor and outdoor temperature together with the degree of insulation and air tightness of the building envelope determine the heat flow through the building. The internal heat loads in office buildings consist largely of personal load, lighting and electrical products which can be difficult to predict since they vary with area of use [11]. The energy flow in building is expressed in equation 1

\[ P_S + P_H + P_I = P_T + P_A + P_V, \]

where \( P_H \) represents heating load from heat source, \( P_S \) the solar radiation through building envelope and windows and \( P_I \) the internal gains from occupants, lighting and equipment. \( P_T \) represents transmission losses through building envelope and windows, \( P_A \) air leakage and \( P_V \) ventilation losses [11]. The energy flow are expressed in terms of heating as gain and cooling as loss factor.
Transmission losses is expressed by

\[ P_T = \left( \sum_{i=1}^{n} U_i A_i + \sum_{j=1}^{m} \Psi_j I_j + \sum_{k=1}^{p} \chi_k \right) (T_{IN} - T_{OUT}) \] (2)

where \( U_i \) is the heat transfer coefficient for a specific building component, \( A_i \) area of the building, \( \Psi_j \) heat transfer coefficient for a specific linear thermal bridge, \( I_j \) length of the thermal bridge and \( \chi_k \) a punctual thermal bridge. The energy required for ventilation is expressed by

\[ P_V = \rho c_p q_v \eta (T_{IN} - T_{SUPPLY}) \] (3)

where \( \rho \) is density of air, \( c_p \) specific heat capacity of air and \( q_v \) the ventilation flow. Air leakage from building components is expressed by

\[ P_A = \rho c_p q_L (T_{IN} - T_{OUT}) \] (4)

where \( q_L \) is the air flow of the leakage. Internal gain from occupants is depending on activity level and clothing. The heat generated from the occupant is measured in MET \([W/m^2]\), 1 MET is defined as the heat generated from one person at sedentary work.

### 2.2 Indoor climate

A building’s indoor climate depends on several physical factors such as indoor temperature, air quality, light and sound environment. The physical faults can, with relatively simple methods, achieve a good indoor climate, but what makes it a complex issue is how the users perceive of the indoor climate. The users’ perception is often related to the satisfaction level of the indoor climate, as measured for example in thermal climate, light, sound, aesthetics and sometimes the ability to control the indoor climate. According to Nilsson (2003) [12] there are three questions that need to be considered when designing a system since a good indoor climate differs depending on the area of use.

*What is the desired environment?*

*Which parameters should be considered?*

*What levels of disturbance can be accepted?*

Answering these questions in an early state of the design process is favorable to achieving the desired indoor climate for the building of choice. One way to measure a building’s indoor climate is through the model predicted mean vote PMV. The model is based on parameters as activity level, air temperatures, humidity, clothing, mean radiation temperature and relative speed of the ventilation air. By combining these parameters the PMV describing a mean value on the user experience of the thermal sensation. PMV is a 7-point scale where every point represents the users thermal sensation as seen in tab 1.
Table 1 – PMV scale where every point represents the thermal sensation of the user.

<table>
<thead>
<tr>
<th>PMV</th>
<th>Sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+3</td>
<td>Hot</td>
</tr>
<tr>
<td>+2</td>
<td>Warm</td>
</tr>
<tr>
<td>+1</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>0</td>
<td>Normal</td>
</tr>
<tr>
<td>-1</td>
<td>Slightly cool</td>
</tr>
<tr>
<td>-2</td>
<td>Cool</td>
</tr>
<tr>
<td>-3</td>
<td>Cold</td>
</tr>
</tbody>
</table>

Since the PMV only describes a mean value of the user experience it can be supplemented with predicted personal dissatisfaction PPD to illustrate the proportion of dissatisfied occupants that feel to warm or to cool. The users that do not feel dissatisfied are predicted to feel normal, slightly warm or slightly cool [13]. The relationship between the two methods is demonstrated in figure 2.

![Figure 2](image)

**Figure 2** – Relationship between PMV and PPD where the x-axis represent PMV and y-axis PPD [13].

The curve in fig 2 is symmetrical and has it min-value at PPD 5% for a PMV equal to zero. PPD never reaches 0 since it is almost impossible to satisfy everyone in a large group in the same indoor climate. According to the Swedish standard ISO 7730, an acceptable indoor climate is when PMV is in the range of ± 0.5 and PPD is below 10% [13]. The Swedish standard SS-EN 15251 defines indoor climate in levels as "good", "acceptable" or "unacceptable". The indoor climate is defined as "good" when PMV is in the range of ± 0.5 and PPD is under 10%. It is "acceptable" when PMV is in the range of ± 0.7 with a corresponding PPD under 15% and "unacceptable" if PMV outside ± 1.0 and PPD over 15% [14].
2.2.1 Indoor air quality

Indoor air quality IAQ is a concept that clarifies how clean the air in the building is. Generally, this is due to two factors, how good the system is to replace the air in the room and how clean the supply air is. The pollutants in the air may occur from human activity in the building as odorous compound, by emission from building products as volatile compounds VOC or polluted outdoor air which affects the supply air. The nature of the pollutant and the concentration at which the user is exposed to determines the influence it has on the IAQ. It is possible to achieve a non unhealthy indoor air with odorous compound which will make the user dissatisfied, therefore, it is necessary to take in consideration of how the air is perceived by humans [12]. Polluted outdoor air has a big impact of IAQ in specially bigger cities, according to Guang et.c (2013) [15] one way to deal with this is to use filter cleaning and well-thought out air devices to reduce the supply of pollutants.

It is not just for comfort reasons that good indoor air is important, a deficient IAQ can lead to illness as asthma and irritating skin but also lead to lower work capacity in commercial buildings. Illness syndromes in buildings depends mainly of deficient building materials and polluted outdoor air which indicates the importance of good ventilation system [16], [17]. Kosonen et.al (2014) [18] showed that work capacity can decrease 2-9 % in commercial buildings depending on ventilation system and evaluation method.

2.2.2 $CO_2$

The occupants in the building are often the most pronounced source of carbon dioxide $CO_2$ and other air pollutants. Since $CO_2$ is a small part of the air composition, it usually does not have much influence on the perceived air quality but it is relatively easy and inexpensive to measure. It has been showed that $CO_2$ correlates well with variations of other pollutants. The combination that carbon dioxide varies with other air pollutants and it is relatively easy to measure it is often used as an indicator of the air quality generated by occupants in the building [12] [19]. The $CO_2$-levels is often measured in parts per million PPM where different requirements are set depending on the area of use of the building. In Sweden, the general advice is that the $CO_2$-levels never exceeds 1000 ppm in buildings [20].

2.2.3 Operative temperature

There may be differences in the temperature of a room and how the occupants in the room experience the temperature. The radiant temperature from hot or cold surfaces can get an occupant to feel dissatisfied despite the air temperature is within approved values. Therefore, it is not enough to measure only the air temperatures since it can be misleading. For example, on a cold day the operative temperature is lower than the air temperature near a window which indicates that the air temperatures may be misleading. The operative temperature describes a mean value of the air temperature and the mean radiant temperature, the air humidity and it is also affected by the air velocity in the room. The mean radiant temperature measures the temperature of adjacent surfaces, which contributes to the radiation from the surfaces to occupants in the room [21]. It is
described by eq. 5.

\[ T_{mrt} = T_1 \cdot F_1 + T_2 \cdot F_2 + \ldots + T_N \cdot F_N, \]

(5)

where \( T_i \) is the temperature on the surface and \( F \) is the view factor between surface and person. The operative temperature \( T_{opt} \) is then described by eq. 6

\[ T_{opt} = \frac{T_{mrt} + T_{air}}{2}. \]

(6)

### 2.2.4 Lights

Lighting in a room is a very important element for the perception of the user’s indoor climate. It is a very individual perception what is perceived as good lighting, which is evident in the regulation that exists around lighting is relatively general compared to other regulation. The combination of daylight and artificial light from luminaries etc. is more or less a requirement for achieving an approved standard [12]. The Swedish standard institutes [22] recommends appropriate guidelines for lighting in offices, target values illustrates the minimum illuminance needed for various operations in table 2.

**Table 2** – Swedish standard institutes guidelines for lighting [22].

<table>
<thead>
<tr>
<th>Workplace</th>
<th>General lighting [lux]</th>
<th>Locational Lighting [lux]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary office work</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>Meeting room</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>Higher requirements</td>
<td>300</td>
<td>750</td>
</tr>
<tr>
<td>Fine drawing work</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>CAD workstations</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>Archiving, copying</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Cleaning</td>
<td>200</td>
<td>-</td>
</tr>
</tbody>
</table>

Since lighting is a significant part of the electrical energy use, it requires smart solutions both in the design phase of the building but also in the choice of products of lighting and how the system is to be controlled. In order to achieve a good indoor climate while keeping electric energy use low, it is advantageous if the system detects whether the room is used but also how much daylight contributes to lighting in the room in order to optimize the artificial lighting [23].

### 2.3 Ventilation strategies

Ventilation in a building is a major factor in how its IAQ is experienced by removing pollutants in the air and supplying fresh clean air. Generally, there are two ventilation strategies, mechanical ventilation where air is provided by electrical fans and natural ventilation where the system uses temperature and pressure gradient between indoor and outdoor for air motion. A mechanical ventilation has ability to generate a good indoor climate and is easy to control, the negative factor
with the method is that the fans contribute to a high energy use of electricity. Natural ventilation, in theory, requires no use of electric energy. But under some circumstances it may be difficult to achieve a good indoor climate without participation of fans. It is also a system that is difficult to control and has its limitations [24]. Application of natural ventilation requires that the building itself have a shape that supports natural ventilation which makes it difficult to apply in existing building.

In this project mechanical ventilation is in focus since it is the most common ventilation method in Swedish office buildings. A large part of the current system requires rebuilding, which indicates that this field needs to be analyzed further. Generally, there are two methods for controlling a mechanical ventilation system, constant air volume CAV where the system not varies depending on the person load in a zone and variable air volume VAV where the system is adapted to the person load in the zone. Both methods have ability to provide good IAQ, the main difference between them is how they can be controlled and the use of electric energy. An issue for system using mechanic ventilation is the conflict between low use of energy and good IAQ since low ventilation rates to reduce energy demand can lead to unhealthy environments for the occupants [2].

2.3.1 CAV

Constant air volume is configured according to the maximum demand that the zone will have for capacity, this often leads to a high energy consumption to fans since many zones do not require full capacity over time. In commercial buildings, offices, schools, etc., the system runs at full capacity during the time that the building is used regardless of personal load but is reduced to minimum levels at nights, weekends and holidays. A CAV system is associated with a good indoor climate because the zone usually is provided with adequate ventilation. The bluntness with the system is that it is not adaptive if, for example, the temperature in the zone increases, the system does not respond to it. CAV is widely used as a simpler system results in lower installation costs than a variable system.

2.3.2 VAV

In order to achieve low use of electric energy to fans it is to advantage to minimize supply air when a zone is not in use. A variable air flow can be controlled so that minimum in a zone are in use when the zone does not have a personal load. As personal load increases, the air flow is regulated to maintain a good IAQ. This regulation can either be done by physical forcing of the users in the zone or automatic regulation through sensor control, which is also referred to as the demand control ventilation DCV. Control with physical forcing does not require advanced systems, which is well suited to smaller systems where there is the possibility of reducing energy consumption to achieve an approved indoor climate [25]. The use of sensors in a zone to measure pre-selected indicator increase the ability of a system to regulate the supply air without compromise with good IAQ. A common used indicator to control a zone is by temperature, the problem can be that is not connected to the personal load in a zone so it is recommended to be complemented with measure either \( CO_2 \) and other air pollutants. To control the ventilation based on demand control it feed
back to a superior system that collects, analyze and sends control signal to fans to maintain required supply air.

2.4 Control systems

A building’s components are largely controlled by sensors that feed back to a control system. As the amount of components increases, a superior system is required that collects and categorizes data to facilitate control of the systems. Traditionally, building automation systems were built to control heating, cooling and ventilation. Today’s modern building automation and control system BACS controls all the building’s systems such as lighting, sun shading, fire, etc. in one system. This enables an overall control of the systems and whether it deviates from normal values. A simplified control system is seen in figure 3 where sensors for each specific area commutes feedback to their superior controller. The control model then adjust the signal to achieve the desired behavior [9].

![Simplified control system of BACS and TBM.](image)

As BACS provides effective automation and control of a system a technical building management TBM complement to provide information for operation, management and maintenance throughout the whole building. TBM’s have the possibility to collect data from all systems and manage trends and detect unnecessary energy use. Combining these systems is to advantage to create a superior system that controls interrelationships between the components of a building. The European Committee for Standardization [6] has provided a standard EN 15232 that categorize different levels of control systems. They categorize them in classes from A to D where class A corresponds as high performance BACS and TBM, class B to advanced BACS and some TBM functions. Class C corresponds as standard BACS and it is used as reference object. Class D corresponds to non efficient BACS and are stated as systems that should be retrofitted. The energy savings from system A and B compared to C is measured in energy efficiency factors. This efficiency factor differs depending on type of building. In offices the efficiency factor for class B system is
0.80 and class A 0.70.

2.5 Occupancy

Occupancy levels in a building have a great impact on the energy use and indoor climate. It varies over time in the day and with area of use of the building which indicates that it is an area that needs to be defined well to avoid wrong assumptions. In order to create occupancy levels it is necessary to clarify what the occupancy levels represent in terms of how many room that are occupied, for how long time and at which personal load the room is occupied [26]. According to Harrison et.al (2003) [27] around 45% of the office desks are occupied during a work day which is due to users are in meetings, at holidays, sick etc. It differs between what area of use in the building, the occupation-level at engineer offices around 60%, ordinary office work around 50% and in sale offices as low as around 35%.

In energy simulation of demand control in buildings, estimation of user behavior is a major contributing factor to the result. In recent years, studies in the area have intensified, which will most likely contribute to more precise simulations according to Hong et al. (2016) [28]. As demand control increases in use, the collection of statistics has increased significantly, which contributes to an increased understanding when mathematical models can be applied. In most of today’s energy simulation programs, the user has the opportunity to manually indicate the user’s behavior, but in order to enable simulation based on this data, models of user behavior can be imported into energy simulation programs or simulate in parallel, which is an area that will greatly increase with time [28].

There are in general two approaches to predict the user behavior in a model, deterministic or probabilistic. In deterministic approach the user pattern is mainly based on statistics and do not vary during simulation. A probabilistic approach takes stand in that user behavior is irrational, it is built on stochastic user behavior based on statistics and mathematical modelling. Depending on the type of building used, the methods have different advantages and disadvantages. If users have the possibility to interact with the control system, e.g. window opening, a deterministic approach is not irrational enough to predict the user behavior as a probabilistic approach. The outcome of these simulations have a wide spread where the deterministic tend to underestimate user impact [29]. On the other hand, with a superior control system where the users interaction with building is low, the irrational behavior from users tend to have less impact and a deterministic approach can be to advantage.
3  Method

For simulations of energy and indoor climate in the project, the simulation tool IDA Indoor climate and energy IDA ICE [30] is used. IDA ICE is developed by Equa simulation and enables to perform full year simulations of entire buildings with a multi-zone application. The possibility of simulating multi-zones is advantageous for large buildings where different zones have different requirements. The program has the possibility to vary parameters such as the building envelope, primary and secondary heating system, ventilation system, user pattern etc.

The simulations have a multi-zone approach to make sure that every zone requirement is fulfilled. According Raftery et.al 2011 [31] it is advantageous not to agglomerate multiple zones into large zones as it has been shown to give less accurate simulations. This is because it can ignore the fact that a zone may have a heating requirement while an adjacent one has a cooling requirement. It also not allows to create accurate user profiles and internal loads which can have big impact on the energy requirements and indoor climate in a zone.

Two parametric runs were performed on a theoretical model to predict how a certain system react to different variations. The runs were performed with IDA ICE built in Monte Carlo parametric simulation where the simulation randomly selects input argument between user stated boundary level. A full scale building simulation was performed with a case study approach where a certain system is tested with different user level and building envelope. Validation of energy use from heating, cooling, ventilation and electrical components is compared through kWh/m². The indoor climate is validated through air and operative temperature, PMV and PPD and CO2-levels in the zones.

3.1  Case study

This section describes the setup for design and simulations in the case study.

3.1.1  Building model

The building model is based on drawings provided by Siemens Building Technologies to meet the existing house standard. The model is in full scale with offices, meeting rooms and common areas represented by own zones as seen in figure 4. In order to facilitate comparison of indoor climate, critical zones have been chosen which are regarded as the marked zones in figure 4. The critical rooms are chosen where the indoor climate is most difficult to achieve [32]. Critical rooms consist of one office and meeting room located in corners facing south. The meeting room is located on the first floor, 20 m² with one window facing south and one facing west. The window/floor area ratio is 0.1 and have a user level at 8 users. The office room is located at the third floor, 13 m² with 2 parallel windows facing south with a window/floor area ratio is 0.23.
The simulations have been carried out on three different building envelopes, as the existing house, to meet BBR’s requirements for renovation and a high performance building referred as passive model. U-values for each building component in respective building envelope is presented in table 3. Only the building envelope is changed, the building construction, window size and the floor plan’s design remain constant during the project. The provided drawings were not completely detailed which entailed that the building envelope for the existing model is partly estimated but controlled against energy consumption for a typical building of the time. To meet building requirements from BBR their regulations and general advice where building performance and components is explained in detail [33]. The high performance building is based on Sweden green building council environmental building certificate [34] where the building envelope was calibrated to meet the building performance.

<table>
<thead>
<tr>
<th>U-value [W/m²K]</th>
<th>Existing</th>
<th>BBR</th>
<th>Passive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows</td>
<td>2.900</td>
<td>1.20</td>
<td>0.900</td>
</tr>
<tr>
<td>External walls</td>
<td>0.654</td>
<td>0.342</td>
<td>0.195</td>
</tr>
<tr>
<td>External door</td>
<td>1.20</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>Roof</td>
<td>0.607</td>
<td>0.329</td>
<td>0.225</td>
</tr>
<tr>
<td>Slab towards ground</td>
<td>0.920</td>
<td>0.920</td>
<td>0.920</td>
</tr>
<tr>
<td>Average</td>
<td>0.964</td>
<td>0.515</td>
<td>0.350</td>
</tr>
</tbody>
</table>

3.1.2 Control system

Three types of control system are simulated and compared in this project. The systems varies off the sensor control from a range where the system is partly controlled by user demand to full user demand control. All the systems is turned off at nights and started 1 hour before scheduled work time to provide fresh indoor air. In offices and meeting rooms, the system varies depending on the type of system class. In public areas such as corridors, stairs and toilets, CAV systems are always used, regardless the system class of the total building. This because IDA ICE controls each zone separately, which means that each zone has supply and exhaust air. In Swedish office buildings,
the ventilation system is often based on supply air in offices and meeting rooms, while extract air devices are usually located in toilets and corridors.

The most basic system class C is using IDA ICE built in CAV system for ventilation. The system is always on daily scheduled but turned off at nights. Supply air is maintained constant at 0.35 l/sm$^2$ + 7 l/s for each user if the zone is occupied, lighting system is always completely on when a zone is occupied and does not take into account the impact of daylight. The middle system class B uses VAV system with temperature sensors that has the range from 21 - 25°C. The supply air varies from 0.35 l/sm$^2$ when a zone is not occupied to a maximum of 7 l/sm$^2$. lighting system is always completely on when a zone is occupied and does not take into account the impact of daylight. The most intelligent system class A uses VAV system with sensors measuring temperature and CO$_2$. The CO$_2$-level is possible to vary from 400 up to 1000 ppm before the ventilation system needs to correct it. The temperature sensor uses the range from 21 to 25°C. The supply air varies from 0.35 l/sm$^2$ when a zone is not occupied to a maximum of 7 l/sm$^2$. The lighting is controlled by dimmers where the artificial lighting is completely switched on until 300 lux and then dimmers linearly until 700 lux when they are completely switched off.

### 3.1.3 User profiles

In IDA ICE it is possible to control the internal gains from occupancy, lights and electrical products with user profiles. The simulation model differs between the user profiles in office, meeting rooms and public areas to achieve an accurate simulation as seen i table 4. Offices and meeting rooms always have internal gains from all three parameters, other room types varies in what type of internal gains.

<table>
<thead>
<tr>
<th></th>
<th>Offices</th>
<th>Meeting rooms</th>
<th>Corridors</th>
<th>Lunch room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>Lights</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Electrical products</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The activity level of the users is at level 1 which is approximated as standard office work activity, the level remains constant through all simulations. It is also possible to control the insulation from clothing clo. In all models a clo value of 0.85 ± 0.25 is used, the variation of ± 0.25 is depending in the insulation degree for clothing at summer or winter time. lighting in all occupied areas is at 10 W/m$^2$ and the energy required for equipment at 100 W [35]. Worth notice is that lighting and equipment is only on when a zone is occupied.

The model is occupied 8-17 which is typical Swedish standard office hours. Three different user profiles were created with a occupancy rate of 45, 60, 75% of the work day. These different levels were chosen to meet different types of workplaces according to Harrison et.al (2003) [27]. For every user profile several different patterns were created to get heterogeneous patterns from different zones, user profiles is found in appendix A. These patterns are occurring in office and meeting
rooms and have a variation during the day so the model is occupied through the office hours. It differs between schedule for offices and meeting rooms, in offices only the time scheduled varies, in meeting rooms both the time scheduled and personal load varies. There are no changes for public areas which are in use for the whole work day 8-17 except for the lunchroom which intensifies at lunch hour.

3.2 Parametric run

The parametric runs were performed on a theoretic model with a total floor area of 400 $m^2$ with 8 separate zones. The theoretic model is based on the building models in section 3.1, except a user level of 5 user per zone and a operation time in the model from 7-17 weekdays. Three types of systems were tested, class A, B and C as mentioned in section 3.1.2. Simulations were performed with IDA ICE built in Monte Carlo simulation with series of 20 simulations. In the first run, insulation thickness of outdoor walls and roof was selected as input with boundary condition from 0.05 to 0.2m. In the second run, user level in every zone was selected as input and with boundary condition from 2 to 10 users. Output was selected as lighting, HVAC, cooling, heating and equipment in kWh for both runs.

4 Results

The results from simulations is separated into three sections, parametric run, energy savings and indoor climate. The calibration run for each model is found in appendix B.

4.1 Parametric run

The electric energy use in fans is presented in figure 5 and 6. The insulation thickness varies from 0.05 to 0.2 meters and the user level varies from 2 to 10.

With varying insulation thickness, figure 5a, the electric energy use varies from about 1425.5 to 1424 kWh and $R^2 = 0.8285$ with the class C system. This makes the variation to about 0.001%. The class B system the electric energy use varies from 320 to 490 kWh with $R^2 = 0.9831$, figure 5b. In the class A system, the electric energy use varies from 250 to 330 kWh with $R^2 = 0.9821$, figure 5c.
(a) Parametric run for class C where insulation thickness varying from 0.05 to 0.2 m and electric energy use kWh from fans as output.

(b) Parametric run for class B where insulation thickness varying from 0.05 to 0.2 m and electric energy use kWh from fans as output.

(c) Parametric run for class A where insulation thickness varying from 0.05 to 0.2 m and electric energy use kWh from fans as output.

**Figure 5** – Twenty parametric runs with varying insulation thickness from 0.05 to 0.2 m as input and electric energy use from fans as output. Figure (a) represent CAV system, (b) VAV and (c) DCV.

With varying user level and a class C system, figure 6a, the electric energy use varies from about 1426 to 1424 kWh which makes the variation to about 0.001% with $R^2 = 0.8285$. In class B system the electric energy use varies from 350 to 520 kWh with $R^2 = 0.997$, figure 6b. In figure 6c, the electric energy use varies from 200 to 500 kWh with $R^2 = 0.995$. 
4.2 Energy savings

The energy use for a user level of 45, 60 and 75% is presented in figure 7, 8 and 9. The energy use is normalized to easily demonstrate difference between the systems. It is normalized for every specific building envelope with class C as the reference object. The normalized total energy use is compared in (a) the normalized electric energy use and in (b) for every user level.

In the existing model in figure 7a the ratio between class B and C is 0.95 and A to C is 0.90. In BBR model the ratio B to C is 0.90 and A to C 0.83 compared to the passive model where ratio B to C is 0.85 and A to C is 0.80. The normalized electric energy use in figure 7b shows that the difference with varied control system in every specific building envelope is marginal. In the existing
model the ratio A to C is 0.70 and A to C in the passive model is 0.68. Energy use from fans in the existing model, the ratio B to C is 0.71 and A to C 0.61. In the BBR model, ratio B to C is 0.69 and A to C is 0.57. In passive model B to C is 0.65 and A to C 0.53.

(a) Normalized total energy use for a user level at 45%. (b) Normalized electric energy use for a user level at 45%.

Figure 7 – Normalized energy use for a user level at 45%. Each model type is normalized separately with system class C as the reference object.

For the existing model in figure 8a the ratio B to C is 0.92 and the ratio A to C 0.89. The ratio B to C in the BBR model is 0.89 and A to C 0.83. For the passive model the ratio B to C is 0.86 and A to C 0.78. Compared to the energy use with a user level of 45% the difference between A and C shows a small decrease with higher user level. The electric energy use in figure 8b, the ratio B to C is 0.89 and A to C 0.71 for the existing model. In the BBR model ratio B to C is 0.85 and A to C 0.70. The ratio in the passive model for class B to C is 0.83 and A to C 0.67. Energy use from fans in the existing model, the ratio B to C is 0.73 and A to C 0.60. In the BBR model, ratio B to C is 0.70 and A to C is 0.59. In passive model B to C is 0.67 and A to C 0.55.
The energy use for a user level of 75% in figure 9a, the ratio between class B and C for the existing model is 0.95 and the ratio A to C is 0.92. In the BBR model the ratio B to C is 0.89 and A to C 0.83. The ratio B to C is 0.85 in the passive model and A to C is 0.76. In figure 9b the ratio between the electric components in the existing model the ratio B to C is 0.89 and A to C is 0.71. In the BBR model the ratio B to C 0.84 is and the ratio A to C is 0.68. The ratio B to C is 0.82 in the passive model and the ratio A to C is 0.66. The energy use from fans in the existing model, the ratio B to C is 0.74 and A to C 0.62. In the BBR model, ratio B to C is 0.70 and A to C is 0.60. In passive model B to C is 0.68 and A to C 0.57.
Common to all user levels is the big impact of district heating in the total energy use. In all user level, district heating is decreasing with level of insulation grade in the model. As the impact of district heating decreasing with insulation grade the cooling increasing. The energy use in fans is relatively small, from 2-4% of the total energy use with a class A system to 4-10% in a class C system.

4.3 Indoor climate

The result from indoor climate is separated into three sections, temperature, comfort indicators and carbon dioxide level. Every section is focused on changes for each building envelope with respectively system class.

4.3.1 Temperatures meeting room

The total hours per year the operative and air temperature is outside limit of 21 to 25°C for a user level at 45% is presented in figure 10. In the existing and BBR model, the dominant factor for the number of hours when operative temperature is outside limit is the lower limit of 21°C. The number of hours above the upper limit increases with degrees of insulation in figure 10a. Most hours is reached in the existing model with a class B system where 1180 hours per year is outside limit values. The lowest value of 360 hours per year is reached in the passive model with the class C system. The highest operative temperature is 26.6°C and the lowest 20.7°C. Air temperature, figure 10b, is never below the lower limit of 21°C. Most hours outside limit is reached in the BBR model with a class B system where 148 hours per year is outside limit. Lowest hours is found in existing model with class B system where 75 hours i outside. The highest air temperature is 26.2°C

(a) Total hours per year the operative temperature is (b) Total hours per year air temperature is outside outside limit values 21 to 25°C for meeting rooms. limit values 21 to 25°C for offices.

**Figure 10** – Total hours per year operative and air temperature is outside limit values 21 to 25°C for a user level of 45%. Figure (a) represent operative temperature and (b) air temperature.
In figure 11, the total hours when operative temperature is outside limit values for a user level at 60% is presented. As in figure 10a, the lower limit value, 21°C, have the highest impact on the total hours outside limit for the existing and BBR model in figure 11a. The hours over the upper limit increasing with insulation grade. Class B has most hours outside limit for each model type, the existing model with class b has the maximum of 1310 hours outside limit. The minimum value of 390 hours per year is reached in the passive model with class C system. The highest operative temperature is 26.8°C and the lowest 20.7°C. As for the user level of 45%, the air temperature with a user level of 60% is never below the lower limit of 21°C, figure 11b. Most hours above limits is found in BBR model with class B system at 152 hours. The highest air temperature is 26.4°C.

(a) Total hours per year the operative temperature is outside limit values 21 to 25°C for meeting rooms. (b) Total hours per year the operative temperature is outside limit values 21 to 25°C for offices.

Figure 11 – Total hours per year operative and air temperature is outside limit values 21 to 25°C for a user level of 60%. Figure (a) represent operative temperature and (b) air temperature.

The total hours per year operative and air temperature is outside limit for a user level at 75% is presented in figure 12a. Compared to figure 10a and 11a the higher limit, 25°C, tend to have bigger impact on the total hours per year in figure 12a. The highest value in figure 12a is reached in existing model with class B system at 1190 hours. The maximum operative temperature is 26.8°C and the lowest 20.7°C. As for both 45 and 60% user level, the air temperature is never below the lower limit of 21°C, figure 12b. Most hours above limits is found in BBR model with class B system at 265 hours. The highest air temperature is 26.4°C.
(a) Total hours per year the operative temperature is outside limit values 21 to 25°C for meeting rooms.

(b) Total hours per year air temperature is outside limit values 21 to 25°C for offices.

Figure 12 – Total hours per year the operative temperature is outside limit values 21 to 25°C for user level 75%. Figure (a) represent operative temperature and (b) air temperature.

4.3.2 Temperatures office

The office room in figure 13a, the dominant factor for hours outside limit is upper limit of 25°C. The class C system has least hours outside limit values in all models. Lowest hours outside limit is found in passive model with 710 hours outside limit. The highest value is found in passive model with class B system at 1405 hours outside limit. The highest operative temperature is 28.2°C and the lowest 20.7°C. Air temperature with 45% user level is never below the lower limit, figure 13b. The longest hours outside limit is in passive model with class B system at 1190 hours. The highest air temperature is 27.4°C

(a) Total hours per year the operative temperature is outside limit values 21 to 25°C for meeting rooms.

(b) Total hours per year air temperature is outside limit values 21 to 25°C for offices.

Figure 13 – Total hours per year the operative temperature is outside limit values 21 to 25°C for user level 45%. Figure (a) represent operative temperature and (b) air temperature.
In figure 14a, the dominant factor for hours outside limit is the upper limit. The highest value is reached in the BBR model with class B system at 2050 hours per year. As in figure 13a the lowest value is reached in the passive model with class C system at 520 hours per year. The maximum operative temperature is 28.2°C and the lowest 20.7°C. Air temperature in figure 14b is never below the lower limit. The longest hours outside limit is in passive model with class B system at 1180 hours. The highest air temperature is 27.4°C.

(a) Total hours per year the operative temperature is outside limit values 21 to 25°C for meeting rooms. 

(b) Total hours per year air temperature is outside limit values 21 to 25°C for offices.

Figure 14 – Total hours per year the operative temperature is outside limit values 21 to 25°C for user level 75%. Figure (a) represent operative temperature and (b) air temperature.

As in figure 13a and 14a for office, the highest value is reached in the BBR model with class B system and the lowest value in passive model with class C system, figure 15a. The maximum operative temperature is 28.3°C and the lowest 20.7°C. Air temperature in figure 13b is never below the lower limit. The longest hours outside limit is in passive model with class B system at 1090 hours. The highest air temperature is 27.6°C.
Total hours per year the operative temperature is outside limit values 21 to 25°C for meeting rooms. Total hours per year air temperature is outside limit values 21 to 25°C for offices.

Figure 15 – Total hours per year the operative temperature is outside limit values 21 to 25°C for user level 75%. Figure (a) represent operative temperature and (b) air temperature.

### 4.3.3 Comfort

The comfort indicators PMV and PPD for every user level and scenario is presented in figure 16, 17 and 18. The results is presented in total hours per year the indicators is outside limits. PMV limit is total time under -0.5 and above 0.5 and PPD is tested for total hours it is above 10 percent.

At user level of 45 percent the most hours for both PMV and PPD are in existing model with class A system, figure 16a. Minimum hours outside limit is reached in passive model with 750 hours outside limit for PMV and 800 for PPD. Both class A and B tend to get lower hours outside limit with a tighter model envelope. In both figure 16a and 16b, the minimum hours outside limit for PMV and PPD is reached in class B for all model type. The maximum hours for both PMV and PPD in figure 16b is reached with BBR model class C system.
(a) Total hours per year the PMV and PPD is outside (b) Total hours per year the PMV and PPD is outside limit for meeting rooms. PMV levels is below -0.5 and limit for offices. PMV levels is below -0.5 and above above 0.5, PPD is over 10 percent.

Figure 16 – Total hours per year the PMV and PPD is outside limit for a user level of 45%. PMV levels is below -0.5 and above 0.5, PPD is over 10%. Figure (a) represent meeting room and (b) offices.

With a user level of 60%, in figure 17a, the minimum hours outside limit values for both PMV and PPD is reached in the passive model with class B system. As in figure 16a, class A and B tend to get lower hours outside limit with tighter model envelope. Maximum hours outside limit is reached in existing model with class A, PMV at 1820 and PPD at 1900 hours. In the office, figure 17b, the maximum hours outside limit for PMV and PPD is reached in existing model with class A system. The minimum hours is reached passive model with class B system as in figure 17a.

(a) Total hours per year the PMV and PPD is outside (b) Total hours per year the PMV and PPD is outside limit for meeting rooms. PMV levels is below -0.5 and limit for offices. PMV levels is below -0.5 and above above 0.5, PPD is over 10%.

Figure 17 – Total hours per year the PMV and PPD is outside limit for a user level of 60%. PMV levels is below -0.5 and above 0.5, PPD is over 10%. Figure (a) represent meeting room and (b) offices.
In figure 18a, the minimum hours outside limit is reached in passive model with class A system for both PMV and PPD. The maximal hours outside limit is reached in existing model with class C system. All system in figure 18a and 18b tend to lowering the hours outside limit with tighter model envelope. In the office, figure 18b, the minimum hours outside limit is reached in passive model class B system and the maximal hours outside in existing model with class C system.

(a) Total hours per year the PMV and PPD is outside limit for meeting rooms. PMV levels is below -0.5 and above 0.5, PPD is over 10%.

(b) Total hours per year the PMV and PPD is outside limit for offices. PMV levels is below -0.5 and above 0.5, PPD is over 10%.

Figure 18 – Total hours per year the PMV and PPD is outside limit for a user level of 75%. PMV levels is below -0.5 and above 0.5, PPD is over 10%. Figure (a) represent meeting room and (b) offices.

4.3.4 CO₂-levels

The total hours when the CO₂-level is more then 1000 ppm is presented in figure 19. Common to all user levels is that the existing model with class B system has the maximal hours with CO₂-levels over 1000 ppm in both meeting room and office. CO₂-levels is always under 1000 ppm with the class C system for all user level and model types. In all class A system maximum CO₂ = 1015 ppm, the class B system maximum is CO₂ = 2515 ppm. The hours outside limit tend to increase with the user level in the zone.
(a) Total hours per year $CO_2$-level $> 1000$ ppm in meeting rooms and offices.  

(b) Total hours per year $CO_2$-level $> 1000$ ppm in meeting rooms and offices. 

(c) Total hours per year $CO_2$-level $> 1000$ ppm in meeting rooms and offices.

**Figure 19** – Total hours per year $CO_2$-levels $> 1000$ ppm in meeting rooms and offices. Figure (a) represent a user level of 45%, (b) 60% and (c) 75%.
5 Discussion

In cases where reality is simulated through models, there will always be limitations since some parts are too complex to model. The user level was set to fixed level of 45, 60 and 75% throughout each workday. Variation is by fact more complex than these fixed values but it was meant to show the variations for different user levels. One way had been to do user studies to make the simulation more realistic. It would also be of interest to run simulations on the model with a probabilistic approach of the user level and compare the results. This is not done since the size and the number of zones of the building model is too big. The fixed activity level and the variation of the users clothing to $0.85 \pm 0.25$ may not reflect reality since it is personal and may vary. However, since the same values were used in all simulations, the significance of the limitation decreases.

The results in this project only relies on simulations in IDA ICE. There was no possibility to verify the energy performance against the existing building since the information was too deficient. This means that the model can rather be seen as a theoretical model that takes in certain parameters from an actual building. Whether it is good or not can be discussed but from the point of view of being able to reflect this on the similar buildings at similar geographical location it may be positive. In IDA ICE, the evaluation of PPD, PMV and $CO_2$-levels is performed through measurement on a single point in a zone. It can be misleading with a single point measurement since these parameters differs through out the zone but it can still be a good indicator for indoor climate. The difference when evaluating energy performance of the whole building and the indoor climate for a specific zone is made since IDA ICE only specifies indoor climate parameters for each zone. This made the choice of critical zones extra important since it would represent the entire building. The critical zones are chosen after simulations and represent the zones who have the most difficulty in meeting the requirements for a good indoor climate.

It can be seen as the parametric simulations show the obvious, but it is important to be able to understand variations in a larger system. For example, with varied user level, systems A and B have a significant increase in energy use in fans while system C has a barely noticeable change. The fact that the increase with user level is greatest in A is probably due to the fact that $CO_2$ levels increase with personal load, which contributes to an increased air volume. With variation of the insulation thickness the result is similar, system C has a slight change while systems A and B show a significant increase. In this case, system B has the largest increase, which may be because internal gains from users and lighting have a major contributing factor to the temperature in the zone. Comparison of energy use from class A systems shows that the electric energy use from fans system tends to have a larger ratio with varying user level than insulation thickness. For class B system the variation between the two parameters only shows a small difference in electric energy use from fans. The variation of electrical use from class C system shows close to zero difference in energy use, both for user level and insulation thickness variation. Worth noting is the large variation between systems where class C results in considerably higher electrical energy use than both class A and B.
5.1 Energy savings

For all user level the ratio between system A and C of total energy use increases with higher insulation grade of the model. This can be explained by the decreasing impact of zone heating with higher insulation grade. The lower impact of the zone heating will contribute to the fact that variations in HVAC and lighting will have a greater impact on the total energy use. Therefore, increased impact of HVAC and lighting will be advantageous for system A and B which has more variety. This also correlate with the parametric runs when the insulation grade of the model varied. When evaluating the electric energy use, the ratio between system A and C only shows a small variation with insulation grade of the model, about 2-5% between existing and passive model depending on the user level. As the insulation grade of the model increases, ventilation rates and cooling requirements increase to maintain a good indoor climate. An active control of these systems is then advantageous to lower the energy requirements. However, the differences are in the range that it is difficult to detect a significant difference between the models when comparing electric energy use.

The total energy use for different user levels shows that the ratio in total energy use between class A and C increases with higher user level. The energy use to fans and cooling requirements is increasing with higher user level. A higher user level in a zone also contributes to increasing internal gain from user, lights and equipment. Since internal gains is increasing the heating requirements is decreasing with user level. The major factor in the energy use in these simulations are zone heating. Energy use in HVAC i relatively small, 2-10% depending on user level and system compared to district heating that contributes with 45-80% to the total energy use. A decrease in heating requirement will have the highest impact on the total energy use. This will explain why the ratio between total energy use increase with higher user level.

The electric energy use shows a small decrease with higher user level. The cooling requirements stands for about 30-40% of the total electric use compared to fans that contributes with about 8-28%. As the user level gets higher the internal gains increase and HVAC will compensate to maintain a good IAQ. This is why an active control of a system as in class A has an decrease of electric energy use with higher user level. In fact, the decrease is only about 2-4% which makes it hard to draw too big conclusions of the result.

When comparing class A and C, the decrease of the total energy use is 9-24%, electric energy use between 29-34% and energy use in fans from 39-47% depending on model type and user level. Nassif 2012 [5] showed an decrease in energy use in ventilation and cooling of 23% with CO₂ and temperature controlled ventilation compared to and CAV system in a office building. Merema et.al 2018 [4] showed an decrease in energy to fans with about 25-55% when comparing a CAV system with DCV in a office building. The wide spread of the results in these studies shows how important it is to indicate how a system will contribute. It is necessary to state if the reduction will be in terms of total energy use, electrical energy use or for a specific component. When comparing energy use in fans with [4] the results from this study is on the upper limit which can indicate that the result is overestimated.

The standard EN15232 [6] states that a efficiency factor for a class A system compared to C is 0.7 and B to C 0.8. This efficiency factor corresponds very well with results for electric energy use
with class A system that differs between 0.66 to 0.71. This shows that the European standard rates corresponds well for class A systems for this type of buildings in this certain climate zone in Sweden. It is hard to say how well this will correlate for buildings in other parts of Sweden since geographical conditions play a major role. The class B system does not corresponds as well as system A where the efficiency factor differs between 0.83 to 0.90 compared to 0.8. The fact that class B systems do not correlate as well as class A can have several different explanations, but it may depend on how the system is defined. A vague part of the standard EN15232 is how the systems are defined since it is only defined as high, advanced or standard performance control system.

5.2 Indoor climate

There are differences in the operative temperature between meeting room, section 4.3.1 where the hours under 21°C is clearly more than in offices, section 4.3.2. This can be explained by the window/floor area ratio in the office is larger which will contribute to higher indoor temperatures, especially with windows facing south. The hours when temperature < 21°C in the meeting room is tending to decrease with higher user level. This shows that there is a small user impact on the operative temperature. The hours under 21°C is also decreasing with insulation grade of the model which can be seen as obvious since the heat transfer through building envelope decreases. For all building models and user level the class B system has the most hours outside temperature limits.

In the meeting room, where temperature is mostly under the lower limit of 21°C, the temperature is usually within 0.3°C below. This can be explained by the sensors measure and control the air temperature, which often differs from operative temperature. A temperature difference of 0.3°C can be seen as low and should not disturb the users to any great extents. In offices, the hours below 21°C only occurs in the existing model, this because the heat transfer through building envelope is higher compared to the BBR and passive model. The hours above 25°C shows an increase with higher insulation grade for class A and B which indicate that these systems have problem to maintain temperature. The class C system shows barely noticeable difference with higher insulation grade which can indicate that the supply air can be slight over-dimensioned.

The air temperature in both meeting room and office is never outside the lower limit, except in passive model with class C system where it is under for 2 hours. The hours air temperature is above the upper limit is less than operative temperature in all cases. As mentioned above, the explanation is because the sensors control air temperature, not operative temperature. There is though a big difference, about 1100 hours in the worst case to about 400 hours in minimum case. This would indicate that measurement of air temperature can be misleading when supply air and solar radiation from windows has high impact. An important point to emphasize in this is the lack of solar shading in the models and the actual building. This should contribute to lowering the hours outside upper limit and can very likely contribute to a better indoor climate. As a theoretical model it would be of big interest to investigate the impact of solar shading.

The comfort indicators PMV and PPD have very similar hours outside limit values with a maximal difference in 40 hours. This coherence is expected since the indicators are based on each other. Common for all building models and user level is that the class B system has the lowest hours outside limit for both PMV and PPD. Comparing the results to the operative temperature in
section 4.3.1 and 4.3.2 where hours outside limit is in most cases highest with class B system the dependence in operative temperature is low. This low dependency can be explained by the fact that the lower temperature is usually within 0.3°C below the lower limit, which means that it does not significantly affect PMV and PPD.

There is a spread of the difference in indoor climate in the meeting room between A and C with user level and building type. With a user level of 75%, the improvement with class A is obvious. With user level 45 and 60%, the hours outside limits is higher with class A. This makes it difficult to state that a class A system contributes to a better indoor climate in this certain room. In the office room, the difference is more apparent between class A and C. In this type of room is it possible to state that a class A system contributes to an better indoor climate compared to class C.

In almost all cases the comfort indicators is long period outside limits compared to a full year of 8760 hours. On the other hand, a boundary of -0.5 > PMV < 0.5 can be seen as relatively low limits. If the limit extends to ”acceptable” limits of -0.7 > PMV < 0.7, the hours outside limit is zero for all cases. If the limit of PPD extends to PPD < 15%, hours outside limit is decreasing to a maximal of 315 hours outside limit in existing model with class C. The indoor climate is according to SS-EN 15251 [14], somewhere between ”good” and ”acceptable” since the PMV value never extends the range of ± 0.7. Class B is the system that is closest to be classified as ”good” indoor climate but both class A and B shows an improvement compared to class C in most cases. This difference in the performance of each system shows the importance to define what the desired environment is and at which levels can a disturbance be excepted according to Nilsson (2003) [12].

The CO₂-levels are considerably higher with the class B system compared to A and C for all user levels and building models. This result is expected since the sensor in a class B only measures temperature, not CO₂-levels. There is a big difference between meeting room and offices which indicates that the user level has high dependency of the CO₂-level which also correlate to parametric runs in section 4.1. The CO₂-level seems to decrease with higher insulation grade which can be explained by the fact that higher insulation grade entails higher ventilation flow to maintain good indoor air quality. The class A CO₂-levels in figure can be seen as close to zero since the maximum CO₂-level = 1015 ppm.
6 Conclusion

It has been showed that the class A system has the highest possibility to decrease the energy use compared to the other systems. The reduction in total energy use between class A and C is 9-27% compared to reduction in electric energy use of 29-34%. With regard to the total energy use there are differences between how the system contributes to variations of building envelope. Systems of class A and B are more advantageous to apply in a passive house rather than in the existing building if the total energy is evaluated. With regard to electric energy use the difference between the building envelope is in the range of 2-4%, this makes it hard to state any difference between the performance of a system in varied building envelopes.

Simulations with class A system corresponds well to the standard EN15232, with variations of ± 0.04 of the efficiency factor. Since the simulations are performed in a specific geographical zone it can be hard to generalize it through out Sweden but it can be a benchmark for similar buildings in the southern parts of the country. The class B system does not correlate as well as class A. This can have many explanations, but it may depend on the difference between how the system is defined in EN15232 and the actual system that is simulated. A vague part of the standard EN15232 is how the systems are defined since it is only defined as high, advanced or standard performance control system.

Evaluation of operative temperatures shows that all systems have problems to stay inside limits of 21 to 25°C. System C and A has least hours outside limit through out the simulations. The results can be a little bit misleading since the operative temperature often is somewhere between ± 0.3°C beyond or above limits. The air temperature has always less hours outside limits than operative temperature through out the simulations. This would indicate that measurement of air temperature can be misleading to achieve good indoor climate when supply air and solar radiation has high impact on the temperature.

Neither one of the systems corresponds to "good" indoor climate according to standard SE-EN15251, all three is between the range "good" and "acceptable". Class A and B shows an overall improvement of PMV and PPD compared to class C system. Class B system is closest to fulfill a "good" indoor climate, especially in the passive house model. Evaluation of \( CO_2 \)-levels showed that Class C fulfills the requirement throughout the year. Class A has many hours outside limit but a highest value of 15 ppm over limit, which means that it can be disregarded.
References


[32] Swedish green building council. Miljöbyggnad 3.0, metodik. [https://www.sgbc.se/app/uploads/2018/07/Milj\unhbox\voidb@x\bgroup\accent127o\penalty1050\hskip\z@skip\egroupbyggnad-3.0-Metodik-vers-170915.pdf](https://www.sgbc.se/app/uploads/2018/07/Milj\unhbox\voidb@x\bgroup\accent127o\penalty1050\hskip\z@skip\egroupbyggnad-3.0-Metodik-vers-170915.pdf), 2017. (Accessed 2019-02-27).


[34] Sweden Green Building Council. Miljöbyggnad 3.0, bedömningskriterier för nyproduktion. [https://www.sgbc.se/app/uploads/2018/07/Milj\unhbox\voidb@x\bgroup\accent127o\penalty1050\hskip\z@skip\egroupbyggnad-3.0-Nyproduktion-vers-170915.pdf](https://www.sgbc.se/app/uploads/2018/07/Milj\unhbox\voidb@x\bgroup\accent127o\penalty1050\hskip\z@skip\egroupbyggnad-3.0-Nyproduktion-vers-170915.pdf), 2017. (Accessed 2019-02-25).

A Occupancy schedules

Occupancy schedules for a user level of 45, 60 and 75% in table 5, 6 and 7. The activity level in meeting rooms differs between the schedules, in offices the user level is always 1.

A.1 User level 45%

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<th>Office 2</th>
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Table 5 – Occupancy schedule for a user level of 45%.

A.2 User level 60%

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Table 6 – Occupancy schedule for a user level of 60%.
A.3 User level 75%

Table 7 – Occupancy schedule for a user level of 75%.

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B Calibration run

Table 8 – Calibration run for all building models evaluated in kWh/m² year.

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