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Factors contributing to energy performance of school buildings

EPC analysis and building simulations

Chujun Wang
Shukri Yasin

Department of Architecture and Civil Engineering
Chalmers University of Technology
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CHUJUN WANG, SHUKRI YASIN

Supervisor:Despoina Teli, Department of Architecture and Civil Engineering
Blanka Cabovska, Department of Architecture and Civil Engineering
Examiner: Jan-Olof Dalenbäck, Department of Architecture and Civil Engineering

Department of Architecture and Civil Engineering
Division of Building Technology
Chalmers University of Technology
SE-412 96 Gothenburg

Cover: A photo of one school.

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Abstract

The buildings and construction sector account for 40% of the global energy consumption and CO2 emission. School buildings have potential of reducing energy consumption. The energy performance certificate is a document that aims to help to reduce consumption and tackle emissions. The aim of this thesis is to evaluate the main factors contributing to the energy performance of a sample of school buildings in Gothenburg, Sweden. This was conducted through EPC analysis and the factors that contributing to the energy performance were evaluated. Two schools were selected and modeled in the software IDA ICE for detailed evaluation of differentiating characteristics. Moreover, a sensitivity analysis was further constructed to evaluate main factors affecting energy use and finding the reason for the divergence in performance.

The significant correlation found in the statistical analysis of the EPCs was that newer schools had lower heating use intensity and total energy performance. This is due to stricter regulations and heat recovery system installations. Weak correlations found was electricity use intensity increasing with the construction year which is probably due to having electricity demanding mechanical ventilation systems in newer buildings.All meters decreased with area, and this is thought to be due to larger schools having different use thereby having lower intensity of energy use.

The difference in surface to volume ratio could possibly explain 73% of the gap between the schools envelope heat losses; and for the difference in window U-value it could explain 22% of heating use intensity gap.

The sensitivity analysis resulted in a ranking list for both schools where it could be seen that the most influential factors according to the model of the schools are heat recovery efficiency, temperature setpoint, window U-value, SFP and ventilation flow dimensions. The heat recovery efficiency is the most interesting factor since it is unknown for the energy use intense school and is low for the other school.

Based on the analysis of the school buildings, these recommendations can be stated, higher heat recovery efficiency, energy efficient windows, better fans with lower SFP, balancing of ventilation system and taking compactness into consideration at the design phase.

Keywords: Energy performance certificate (EPC) school buildings, School buildings energy use, Building energy simulation (BES)

Sammanfattning

Byggnadssektorn står för 40% av den globala energiförbrukningen. Skolbyggnader har signifikant potential att minska energiförbrukningen. Energideklaration är ett dokument som har till syfte att minska energianvändning och utsläpp för byggnader. Syftet med denna studie är att utvärdera de viktigaste faktorerna som påverkar energiprestandan hos 23 skolbyggnader i Göteborg, Sverige. Detta genomfrst genom en en statistisk analys på energideklarationer. Därefter väljs två skolor som anses intresanta att studera mot basis att de är lika med presetrar olika. De modelleras i programvaran IDA ICE för detaljerad utvärdering av avvikande egenskaper. Därutöver utförs känslighetsanalys för att testa modellernas känslighet till faktorerna som kan påverka enrgianvändningen. Målet är att finna de faktorer som är viktigast när det kommer till energiprestanda.

Den signifikanta korrelationen som kunde påvisas i den statistiska analysen är att nyare skolor tenderar att ha lägre uppvärmningsintensitet och energiprestanda. Det beror troligtvis på att striktare byggregler har införts med åren och installation av värme återvinningssystem i nyare byggnader. Två svaga korrelationer hittades; elanvändnings intensiteten ökade med byggåret och Alla energiindikatorer (värme, elektricitet och total) minskade med arean. Första beror på att nya byggnader tenderar att ha högt elkonsumerande mekaniska ventilationssystem, men eftersom de återvinner värme minskar energiprestanda trots de ökande elanvändningen. Area korrelationen kan bero på att större skolor har olika användning av area och därav lägre intensitet.

Skillnaden i förhållande mellan yta och volym kan eventuellt förklara 73 % av skillnaden mellan skolans värmeförlöster från klimatskalet; skillnaden i U-värde för fönster kan förklara 22 % av uppvärmningsintensitetsgapet mellan skolorna.

Känslighetsanalysen resulterade i en rankninglista för båda skolorna där det mest inflytelserika faktorerna kan observeras vilket är; verkningsgrad för värmeåtervinning, börvärde för rumstemperatur, U-värde för fönster, SFP (Specific fläkteffekt) och dimensionering av ventilationsflöden. Verkningagraden för värmeåtervinningen är de mest intressanta faktorn eftersom den inte är känd för skolan med högst energiprestanda och är låg för den andra skolan.

Baserat på analysen av skolbyggnaderna kan dessa rekommendationer ges, högre verkningsgrad på värmeåtervinningsen, energieffektiva fönster, bättre fläktar med lägre SFP, balansering av ventilationssystem samt rekomenderas att ta hänsyn till S/V-ratio i projekteringsfasen

Keywords: Energiprestanda, skolbyggnad, IDA ICE, simulering av energiprestanda, modellering.

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Translation of terms*

Swedish	English
Energideklaration	Energy performance certificate (EPC)
Grundskolan	Primary and secondary
Lokalförvalningen	Local administration
Fjärrvarme	District heating
Fastighet	Property
Fastighetsel	Property electricity
Verksamhetsel	Tenant electricity
Fritidshem	After-school care center
Obligatorisk ventilationskontroll (OVK)	Obligatory ventilation control
Självdragssystem (S)	Natural ventilation system
Frånluftssystem (F)	Extract ventilation system
Från- och tilluftssystem med värmeväxling (FTX)	Exhaust and supply air ventilation with heat recovery
Boverket	The National Board of Housing, Building and Planning
Boverkets byggregler (BBR)	Boverket's building regulations
Standardisera och verifiera energiprestanda i byggnader (Sveby)	Standardization and verification of energy performance in buildings
Stadsbyggnadskontor	The city planning office

Acronyms and abbreviations

Abbreviation	Full name
WWR	Window to wall ratio
S/V-ratio	Surface to volume ratio
HR	Heat recovery
SFP	Specific fan power
HVAC	Heating, ventilation, and air conditioning
AHU	Air handling unit
Atemp	Interior area that is heated to above 10 °C

*In the event of any discrepancy between the Swedish words from the original version of EPC and English translation, the Swedish version prevails.

Contents

1 Introduction

1.1 Background

The Building and construction sector account for nearly 40% of global final energy consumption and CO_2 emissions, and it has a big potential to be improved [1]. To meet the Paris Agreement, this sector must decarbonize by 2050 [2]. School buildings account for 13% of non-residential building energy consumption in the US and 10% in the UK [3], therefore decreasing the energy consumption in the school buildings is vitally important.

In the Swedish Energy Agency annual report of energy use in residential and non-residential buildings, the total energy use for heating in 2019 is 77 TWh [4]. The heating used for school buildings is approximately 7% of the use of the building sector in Sweden [5]. According to Swedish Energy Agency annual report on energy use in non-residential buildings, the average use intensity per square meter is approximately 153 kWh/m^2 [6]. To put it into perspective, a newly renovated school from 1972 decreased its energy use from 180 kWh/m^2 to 54 kWh/m^2 [7]. Comparing the building types in Sweden, school buildings have the third highest energy intensity[8]. This indicated that there is room for improvement in energy performance, which makes school buildings practically important to study.

To tackle emissions and reduce consumption, the coverage of Energy Performance Certificate (EPC) and building codes expand in Sweden. EPC is an important tool to evaluate and compare building energy consumption. Swedish EPC is a valuable source of information because it shows measured energy use rather than calculated values for many other EU countries [9]. EPC can also be a useful tool to analyze the school buildings, but there has not been such analysis based on school EPCs, making this study important.

Most of the energy used in the buildings is used to maintain a comfortable indoor environment. Energy use in schools depends on many technical parameters, such as building envelope, HVAC system, and operation of buildings or the behavior of occupants, which may lead to significant differences in energy use between similar buildings. To propose energy-saving strategies for schools, it is important to determine the factors that have the greatest impact on their energy consumption.

1.2 Aim

The purpose of this study is to explore the main factors affecting the energy performance in a sample of school buildings. This is done through analysis of the EPC data for a sample of 23 schools in Gothenburg and further analysis of two case study schools in detail. The specific objectives of the project are:

- To investigate which school characteristics from those reported in EPCs are related to the schools' energy use and how
- To identify differences in energy use between schools that cannot be explained by basic building information (e.g., year of construction, ventilation system etc.) and select case studies for further analysis
- To identify the main factors contributing to the case study buildings' energy performance and their difference, through analysis of collected data, inspections, modeling and EPCs and through sensitivity analysis of known and unknown influencing factors.
- To propose appropriate energy-saving measures for the schools, based on the previous analysis.

1.3 Target users

The thesis will contribute to an ongoing research project focused on the relations between the indoor environment, building and system characteristics and energy consumption in school buildings. The thesis also helps practitioners who want to reduce energy use and operational issues for schools in a cold climate and consultants working with schools. The thesis will be interesting for the local administration, as they take care of the school buildings. The target users also include all the teachers, pupils, and operation personnel working and studying in schools.

2 Theory

This chapter will introduce background information and former studies conducted on the subject. It will outline the status of Swedish school buildings which includes their characteristics and energy use. The chapter also cover factors found contributing to energy use in Swedish schools and schools in other countries. Lastly, this chapter will cover what EPC is, studies made with EPC and what challenges can be found when using EPC in modeling.

2.1 Swedish school buildings

The Swedish energy agency and Boverket made a thorough inventory on school buildings called STIL2 [10] where they mapped the use of energy. 16% of the schools, were inventoried. The goal was to improve the statistics of the energy use efficiency and indoor quality of schools. No other mapping of energy use in schools has been made on the same scale. The annual statistical report from the Swedish energy agency for non-residential premises includes energy use in schools, but it only contains statistics and not qualitative or in dept analysis of the state of the school. Most of the property electricity use comes from fans. If electricity use for heating is excluded, 84% of electricity use comes from fans and the rest comes from pump, compressors, cooling machines, and elevators.

It states that the most dominating ventilation system in the schools is mechanical ventilation with both extract and supply flow and heat recovery (FTX) operating with constant airflow (CAV). The mean air exchange rate 2.3 1/h with a mean operation time of 3520 h/year. The mean specific fan power (SFP) for fans in the schools is 2.5 kW/m^3/s. The average U-value of schools is 0.53 W/m^2,K, but the standard deviation is large, which is 0.25 W/m^2,K.

The report gave a total overview of the energy use of schools in Sweden, but it was done in 2005, which is 16 years ago (2021), so the presented content may not be apply to today's building. The mean energy performance for schools studied is 177 kWh/m^2. This number includes energy for space heating, tap water, and property electricity. 87% of the energy performance comes from heating, and the remaining 13% is property electricity. To put into perspective, the corresponding value for energy performance today can be calculated from the annual energy agency report for non-residential buildings for 2020 and resulted in 153 kWh/m^2 [6]. The energy for heating has decreased by 24 kWh/m^2. 29% of bought electricity is property electricity according to the STIL2 report, and this ratio has been used to calculate 2020 property electricity use. This demonstrates that there may be some discrepancies in the report regarding its applicability to the state of today's school buildings. Maybe some of the recommendations have been implemented on schools which reduced the energy use, or new schools with better performances have been built.

Buildings built before 1940 have high ceilings and large windows with high U-values, which lead to higher energy use but better daylight. Fast forward to the 1940-1960, the ceiling height is lower. Other characteristics are similar. Buildings built in 1961-1975 have the same characteristics as older buildings apart from the reported moisture issues. The difference from older buildings is that maintenance has not been done. After the oil crisis in 1973-1979, the regulation for buildings became stricter, which means that buildings built at that time generally have more insulation and has smaller windows. The buildings built after 1990 have a low demand of maintenance of the envelope. Moreover, the windows perform better, which lead to larger windows.

2.2 Energy performance certificate

Energy performance certificate (EPC) was firstly introduced by the Energy Performance of Buildings Directive (2002/91/EC) with the objective of improving building energy performance, and is defined as "a certificate recognized by the Member State or a legal person designated by it, which includes the energy performance of a building calculated according to a methodology based on the general framework set out in the Annex" [11].

In the Energy Performance of Buildings Directive (2010/31/EU), the members of EU were inquired to present energy performance certificate for their buildings. The main outputs from the required certificate are energy performance grade and cost-effective measures. The goals are to incentivize energy efficiency in buildings and bring awareness of building energy performance. EPC is required to be presented in every building for sale, which urges the customer to be aware of the energy use and consequently put pressure on building's owner to take energy efficiency measures [12]. It also makes it easier for the building owner to take measures when the measures are presented in EPC. It can be made in a comparable way across Europe [13]. Furthermore, there is a high potential of EPC to provide insights on building stock performance and renovation guide. EU has funded projects which use the EPC and the data to characterize and prioritize buildings in need of renovation. This can later be used as a tool for investors and stakeholders to prioritize buildings in need of energy efficiency measures. This organization of data would not be possible if requirement of EPC did not exist.

2.3 Studies conducted with EPC

2.3.1 Data-driven and physical-based methods

EPCs are used in a wider way than intended, as Pasichnyi et al. outlined in a study in 2018 how EPC data is used in research [14]. It appeared that 34% of studies using EPC go under mapping energy performances, and it is mostly done as a preliminary investigation for future possible retrofitting of buildings. Another popular application of EPC is retrofitting study.

EPCs have been widely used through data-driven methods. Researchers got encouraging results through algorithms including Artificial Neural Network, Support Vector

Machine, Reduced Error Pruning Tree, Random Forest, D-vine copula quantile regression, Hierarchical, Density-based, K-Medoids [15] [16] [17] [18] [19] [20]. Recent state-of-the-art researches predict energy consumption when sufficient EPC sample are provided. Attanasio et al. [15] implemented algorithms on 90 000 EPC sample to predict heating and energy use, the best accuracy reached 85.67% by using the method random forest. Wenninger et al. [16] implemented various algorithms on extensive EPC data of 25 000 residential buildings to predict heating energy performance, among which the extreme gradient boosting performed the best. Lu et al. [17] integrated support vector machines and fuzzy c-means clustering method for predicting energy performance after retrofitting. EPCs are also analyzed for clustering. Ali et al. implemented several algorithms for making archetypes that could be reference buildings, among which K-mean performed the best [21]. Gangolells et al. also did a cluster analysis to define reference building sets using K-means [18]. De Jaeger et al. [20] brought up a building characterization method. They output U-values and window to wall ratios through quantile regression with 8 basic features from EPC. Apart from energy or building sectors, a data-driven method using EPCs can help with asset management [16]. It has been used for assessing the economic damage from floods in Belgium[22]. However, the data-driven method requires a large number of data; since it is a black-box method, some results are difficult to interpret by physical terms [23].

Few studies use EPC data as a source for simulating physical-based models. Badiei et al. [24] built reduced data dynamic models (RdDem) to predict the energy demands and indoor environment condition. Although the EPC XML database used does not provide all building information, their database did provide more information than standard EPCs, including property details and building part which were fed in RdDEM to get all inputs for later Energy Plus modeling. Therefore it does not apply to standard EPC. Through the physical-based method, results can be explained physically, but it requires more building information including geometry, construction, internal boundary conditions, and weather data [23].

But the above-mentioned data-driven researches are all done with sufficient level of data, which masks the fact that EPC data does not include enough data for physical models without further scrutiny. Data study on a small EPC sample, as in this case, has not been done before. It is also a novel approach to establish physical models based on preliminary results of EPC data analysis. The thesis combines data-driven approach and physical-driven approach, which would be an inspiration of using EPC data.

2.3.2 Challenges and expected outcomes of modeling with EPC

The physical-based model requires many input parameters. Even in the best-calibrated model, a deviation between predicted and actual parameters exists. In order to match the model with the actual building, the modeler will calibrate the simulation model. Some parameters can be obtained through observation, and the unobservable parameters depend on the knowledge and experience of the modeler. Therefore, the quality of the model is very dependent on the judgment of the modeler

[25].

And in this thesis work, several sets of input parameters can roughly approximate the performance of the buildings, but they can not be guaranteed to be reality. Heo et al. [25], Yu et al. [26] advocate the use of statistical inference to improve the parameter estimation, a Bayes-based method was proposed, so energy consumption can be quantified in the form of probability. Again, this requires enough sample.

Statistician George Box wrote the famous aphorism "All models are wrong, but some are useful" [27]. At least, practical models could give insights into optimization. One of the results of the calibration process can be the determination of fault. When large differences between results from input parameters and reality are observed, and unreasonable settings of the model are required to match the actual situation, it could be operational problems that were not discovered during the measurement and analysis process, and maybe be improved if the problems were verified in through building inspection [28].

2.4 EPC in Sweden

2.4.1 Introduction of Swedish EPCs

In most cases, Swedish EPC uses measured energy use to state the energy performance of a building and it is performed by an independent party [29]. EU requirements for setting the energy performance are either through calculation or measurement, which is either asset rating or-/and operational rating [30]. It is required that the performance should reflect the typical energy use. The difference between the two methods is that the calculated energy use values are standard assumption and theoretical input values, while the measured energy use values are real energy uses which can be affected by occupants, malfunction, etc. A new regulation was set in 2017 in Sweden claiming that the energy performance of buildings shall take into account the primary energy source through weighted factors [31]. This means that the Swedish energy performance takes into account both measured values and primary energy source, although only EPCs after 2017 have this feature. 14 of 28 Countries in the EU uses asset rating methodology and the rest uses a mixture of asset rating and operational rating.

The Swedish EPC for buildings is managed by the Swedish National Board of Housing Building and Planning (Boverket) [32]. It was first implemented in Sweden in 2006. The energy class presented in the EPC goes from A to G, where A represents a building with a low energy use, and G with a high energy use, see figure 1. The energy classes on the scale are based on the energy efficiency requirements of the new buildings built today. The requirements differ according to the location of the buildings in Sweden, the building types, and the heating methods.

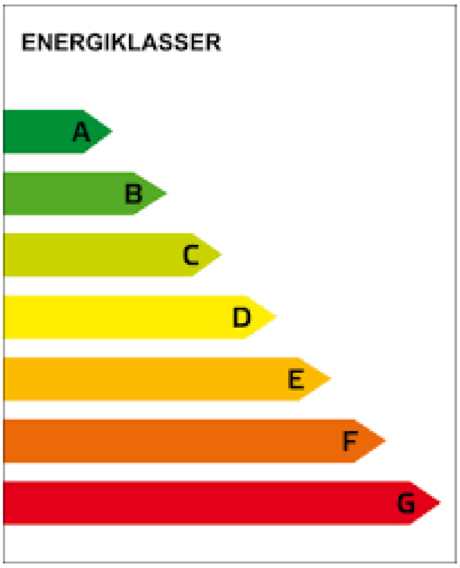


Figure 1: Energy classes stated on EPC

The annual buildings energy use is set in the EPC, which includes delivered heating energy, comfort cooling energy, hot water use and property electricity [29].Heating uses are normalized based on the difference between the local climate in a normal year and real climate during the period when the certificate is performed; the hot water use, internal heat gains and the indoor temperature are normalized [33]. If the measured indoor temperature is more than 1 °C lower than the required, additional 5% of heating use should be added for every 1 °C. This applies only if the low temperature caused by occupants' operation. The performance of a building is presented in kWh per square meter [kWh/m^2].

Heating energy is the energy for space heating and hot water. It can be distributed from district heating systems, heat pumps and fuel heat, oil boiler and more.

The electricity use accounting for the energy performance is the building's property electricity [34]. The property electricity is the electricity for operating the building, independent from its tenant. It includes permanent lighting in public areas and operating spaces, electricity used for pumps, fans, elevators, control, and monitoring equipment both installed internally or externally. The electricity for heat pumps is not included in property electricity but in heating energy instead.

Electricity used for household and business purposes, such as the lighting in the classrooms and computers is also not included. But the heating released by the household appliances is considered as internal heat sources when calculating the heating energy consumption.

Apart from energy-related data, there is also other important information about the building. It includes information about the building type, construction year, building complexity, heated area, overall floors, number of stairs, average hygienic outdoor airflow rate and whether it is protected for its heritage value. The energy information presented is usually the measured value for the specific year. Values that are stated normalized are total energy use per square meter. Furthermore, it presents information on obligatory ventilation control, type of the ventilation system is stated. Lastly, it proposes a list of recommended cost-effective measures. EPC experts raise their cost-effective recommendations and give estimations of potential reduced energy and costs for the measures [35]. Information such as U-value, window type, renovation status and s/v-ratio is not presented.

2.4.2 EPC based studies in Sweden

Hjortling et al. [8] outline the energy performance of 186 021 Swedish buildings through their EPC in 2017. The energy performance concerns building code, year of construction, climate zone, and building type. This is particularly interesting because school buildings are part of the study. Therefore, the difference between school buildings and other building types can be compared. Some of the building types studied is one- and two-dwelling buildings, multi-dwelling buildings, farms, schools, sports, healthcare facilities, industries, hotel and restaurants, and offices. The mean energy performance for schools was 171.8 kWh/m^2, compared with hotels and restaurants, resulting in 175 kWh/m^2, and farms with 138.3 kWh/m^2, which corresponds to the highest and lowest. School buildings have the third-highest energy consumption compared with the other categories. Another report states approximately 30% of the non-residential buildings are school buildings and 30% of the energy consumption from non-residential premises comes from school buildings [36]. Studies both show the importance of studying school building considering their energy use.

It could be concluded from Hjortling et al. [8] that the building codes for the years affected the energy use. For school buildings, the research found that the energy performance decreased from 178 kWh/m^2 to 155 kWh/m^2 and to 97 kWh/m^2 for the year intervals of before 1979, 1980-2009 and after 2010. In those years, the oil crisis in 1970 increased the requirements for U-values of the envelope, then in 2006, there was a requirement set for the performance of 110-130 kWh/m^2 depending on zones. Also, it was found that there was no significant difference in energy consumption depending on climate zones, indicating that the buildings are well adapted to the climate. Some interesting parameters in EPC have not been included in the analysis, such as area and ventilation system. However, it states that these parameters are worth evaluating in future work.

2.5 Factors contributing to energy use

The STIL2 study on Swedish schools [10] lists various factors contributing to the high energy use. The factors include high air flows in some parts of the building, high room temperature, lacking of heat recovery and high U-value of the envelope up to 0.9 W/m^2,K. It also detected that the school with the highest energy use had a kitchen where food is made, which indicates the use of the building is very important. When it comes to low energy use, observed factors were installations of heat recovery system and heat pumps.

Bivariate correlations between the electricity use and factors that contributed to electricity were conducted in STIL2. The correlations found in the report were following,

- Operation hours significantly affect the building electricity use
- Higher U-value decreases the building electricity of fans and the total electricity
- The specific electricity of fan use decreases with a larger window area
- The specific building electricity use decreases with the area
- Specific electricity use decreases with the number of students

It would be interesting to look at ventilation systems and energy use, or heat recovery efficiency and energy use. It was also stated that the heating system did not need restoring in most cases neither the ventilation system; the schools with no heat recovery should urgently upgrade.

A lot of researches has been done to extract factors contributing to energy performances. Building properties are proved to be important. Cerquitelli et al. [37] reported U-values of the opaque and the transparent, and S/V ratio are important factors for buildings' heating energy performance. Attanasio et al. stated that significant factors contributing to heating are aspect ratio, U-values, and construction years [15]. Badiei et al. found internal temperature mainly explains the heating demand [24]. A study on British EPCs shows mechanical ventilation and electricity use are highly correlated, the location of schools attributes the heating degree days and the heating use [38].

Ouf et al. [39] investigated the energy performance more closely with a focus on electricity, gas, and total energy performance, with the factors of building age, floor areas, retrofits number of occupants, occupant density, and school type (primary-, secondary- and all grades school). This study was performed in Manitoba which is a cold climate province in Canada, which makes this study significant, although Gothenburg has heating degree days around 4000 and Manitoba has 6000. It showed that all factors showed a significant effect on electricity use, but only the construction year has a statistical significance on electricity, gas, and total energy consumption. It also showed that these factors can vary the output of electricity, gas, and total energy consumption by 63,6%, 52,7%, and 43,2%. Although an increase in energy use in all aspect has been seen in this study between schools built or retrofitted before 1990 and after 1990, for schools which have made HVAC or envelope retrofits during 2004 to 2013, decreases in total energy use ranging from 8-35% can be observed. This is seen in 7 schools and only 1 school had a statistical significance. 4 of the 7 schools also showed an increase in electricity use, but the decrease in gas use was large enough for the energy consumption to decrease. It cannot be stated that in this district the retrofit of schools has a significance to less energy consumption. Ouf et al. state in the discussion that the influences from retrofits could be minor, such as HVAC and boiler replacement; some retrofits increase the electricity load, such as an increase in classroom ventilation rates, window replacements, adding heat recovery system.

Another trend that could be observed in the study [39] is that the electricity use increased with the year while gas decreased. An explanation to this was stated that the more electronics are used in schools compared with before, which increases the electricity use. It was proposed that the decrease in heating use can be explained by internal heat gains from equipment.

Research conducted in school buildings in the United Kingdom evaluated the factors contributing to heating and electricity use using UK Display Energy Certificate (DEC-British EPC) [40]. The found factor that contributed the most to the heating use was compactness followed by construction year and floor area. Buildings compactness decreases its heat losses from the building [41]; Buildings built later are more likely to have been built during a time with stricter regulations thereby lower energy use; and Hong et al. explain that schools with the larger area are thought to have different use of area thereby lower intensity. According to Hong et al. the electricity use which seems to include both property and tenant electricity, the most dominant factor was the number of pupils followed by floor area. The number of tenants increases the electricity use due to more electric equipment used. furthermore, it was seen that the electricity use increases with the increased area, and is thought to be due to larger schools are more likely secondary schools and they have equipment such as computers or laboratory equipment. The electricity used by the tenant is included in the analysis. In the STIL2 from the energy agency of Sweden [10], a negative correlation between property electricity use intensity and tenants was found. It can be stated from two analyses that the number of tenants affects the property electricity use and the tenant electricity use differently. The more tenants, the less property electricity is used, the more tenants, the more electric appliances hence more tenant electricity. The difference is the objective. In this thesis, only property electricity use will be evaluated. Other factors which contributed to electricity use were: phase of education, surface exposure, glazing windows, compactness, glazing ratio[40]. Swedish EPC does not have as detailed information as British, for example, number and type of windows, site position, orientation, building depth ratio, roof shape, etc. is missing in the Swedish version. In conclusion, interesting factors are listed below.

- Building properties including U-values, compactness, glazing ratio, depth ratio, area, year of construction
- Operation condition including Indoor temperature, operation hours
- Building site position, orientation
- Occupants’ behavior, density, number
- Retrofits of boilers and HVAC
- Educational phase

2.6 Summary

This study will statistically investigate the energy use of a sample of building through EPC. The EPC analysis will be similar to the study by Hjortling et al. [8], but it only focuses on the sample of schools in Gothenburg, and it also taking account the area and ventilation system.

Factors contributing to energy use of the selected buildings will be presented similar to STIL2 [10], Hong et al. [40], and Ouf et al. [39], but the scope and methodology would be different. Hong et al.[40] gain their results from EPCs and Artificial neural network (ANN), and Cerquitelli [39] gains its results from local utility provider and regression analysis and STIL2 [10] gained its results from inventory and statistical analysis. This thesis will gain its results from statistical analysis based on EPC combined with modeling. If the energy use cannot be explained by the factors in the EPC through statistical ways, the factors will be evaluated by modeling for chosen cases. Since some information needed for modeling are not in the EPC, auxiliary data is needed in physical-based modeling for selected buildings. For this thesis, sensitivity analysis will give some information on how other factors contributes.

The factors that from previous studies have shown effect on buildings will be tested in the models to see if it affects this particular building.

3 Method

3.1 Overview of methodology

A literature study was conducted intensively in the initial stages but also throughout the project. It is presented in chapter 2. The literature study aims to get the background information about the subject and use it as the backbone of the modeling stages by providing support to make informed decisions.

The first stage includes a statistical analysis of the EPC data of the 23 buildings in Gothenburg, where the respective energy performance of the schools is compared with the available characteristics of the buildings. The characteristics from the EPC that were studied include construction year, ventilation system, heated floor area, building protection status and heating system. These characteristics were compared with the total energy performance as well as energy for heating and electricity separately.

Schools whose performance could not be explained by these characteristics given in the EPCs, or schools that are similar in terms of characteristics in EPCs but perform differently, will be considered eligible for the next stage, i.e. modeling and analysis using IDA Indoor Climate and Energy (IDA ICE).

IDA ICE is a buildings simulation software for modeling energy consumption and indoor climate. The information needed for modeling were extracted from documents provided by the city planning office and supplemented by in-situ inspections, regulations, the local administration, measurement and standardized inputs from Sveby [42] and BBR. Examples of data collected from the inspection are the use of the building, window type and size, temperature and other possible factors that helped to build the model in IDA ICE. Not all information to build a fully accurate model can be obtained due to uncertainties on tenants' behaviour and other limiting factors.

Through modeling, known and unknown variable can be assessed and evaluated in order to see their impact on the energy use of the school. The goal is to see which factors contribute the most to the system and if they can explain the actual energy use. If the known factors do not explain the energy use, the primary importance is evaluating the unknown factors.

A baseline model will be constructed with auxiliary data from local administration, standardized input data from Sveby and qualified assumptions, and dynamic load simulations are carried out and continuously analyzed. A sensitivity analysis will be conducted on all factors considered important, where forward uncertainty analysis is included. Forward uncertainty analysis is a methodology where uncertain parameters in a model are varied to assess its impact on the model. Since this thesis aims to investigate the difference between existing buildings this methodology is extended to evaluate both certain and uncertain factors. Furthermore, an inverse uncertainty analysis will be conducted on uncertain factors that have been found to affect energy use significantly from the sensitivity analysis to match the EPC data. In the same procedure, it is possible to predict the impact of energy-saving measures on building energy consumption based on the calibrated model.

3.2 Background information of the school sample

The research object is a sample of primary school buildings. There are 187 primary schools in Gothenburg[43]. Primary schools consist of grades from 0 to 9. The school year consists of a spring and winter term with summer breaks from the middle of June to the middle of August and winter breaks during Christmas for three weeks. The functions of schools are generally the same, and the target students are at a certain age range, typically from 7 to 15 years old. Although schools do not offer classes during breaks, the leisure centers usually keep open, where children participate in indoor and outdoor activities. In addition, during one week in July when the Gothia football cup is held, the whole school will be occupied. Schools usually have classrooms, staff's offices, toilet facilities, free-time room, gym and storage. In the presented thesis, the sample includes 23 educational buildings from 19 primary schools distributed throughout Gothenburg. The chosen schools account for 10.4% of all primary schools in Gothenburg and are selected to cover different locations, schools sizes, construction years, heating systems and ventilation systems. The locations of the schools are shown in figure 2. The sample of schools were received from a research group in Chalmers at the division of Building Services engineering investigating indoor quality air quality and energy performance, and the detailed methodology can be seen in their paper [44].

The climate in Gothenburg is temperate, with minimum and maximum average temperatures of -0.3°C in February and 17.3°C in July, and an annual average temperature of 8.1°C [45]. Cooling is not required in schools. Heating is consumed mainly from October to May. The construction of district heating plants began in 1954 in Gothenburg, and oil-boilers were quickly replaced. Today, district heating accounts for 90% of the city's heating [46], and buildings widely use district heating as the primary energy source. The dominant wind directions are south, southwest and west around the year. During the heating season, cold prevailing wind blows from the south [47].

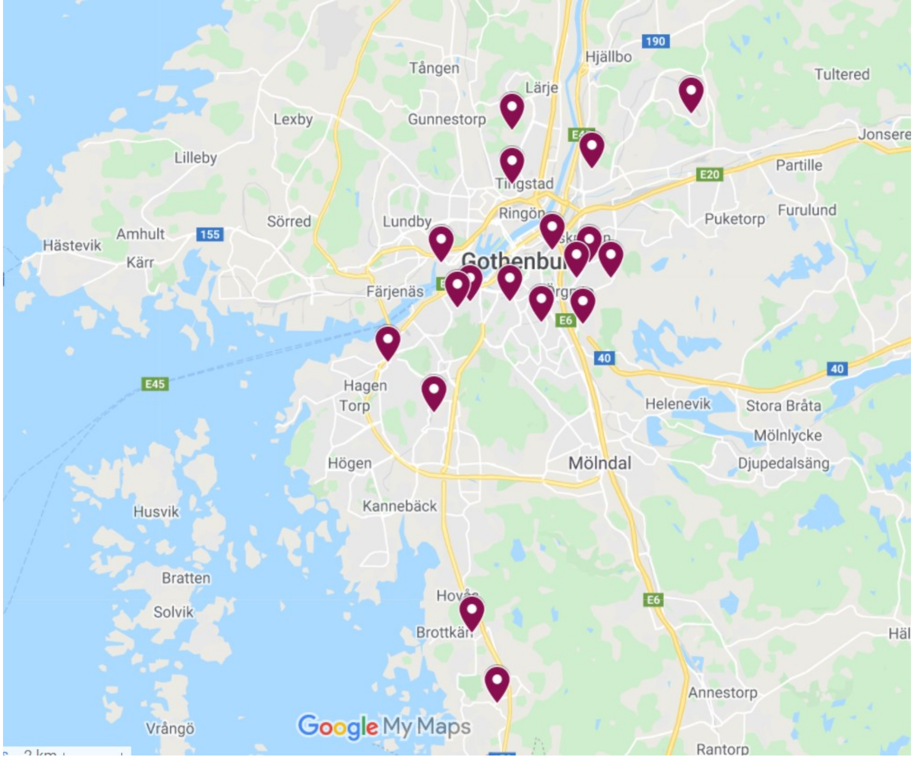


Figure 2: Location of the 19 selected schools

3.3 EPC analysis description

3.3.1 EPC data

The EPC analysis focuses on heating use intensity, electricity use intensity, energy performance and ventilation systems of each building. The energy performance values [kWh/m^2] and heated area A_{temp} [m^2] are taken directly from the EPC. The energy performance value covers the energy for space heating, hot water, and property electricity, and it is normalized to normal hot water use, tenants' behavior, indoor temperature, and outside temperature [48]. Electricity use intensity is derived from the property electricity (fastighetsel) value in EPC. The property electricity use includes the ventilation system energy, pumps, elevators, and facility lighting, and it is divided by the heated area. This value does not include heat pump electricity, as this part of the energy is classified as for heating purposes. It also does not include tenant electricity as it is not considered as the building's needs. The normalized heating use intensity values [kWh/m^2] are not provided in EPC. The heating use intensity includes both space heating and hot water use. It is derived by subtracting from the property electricity use value of the total energy use value and dividing it by the heated area. The heating use intensity is then compared with the described characteristics in the EPC like construction year, area, protection level, and ventilation system.

Almost all the EPC state the measured energy use of each term and the measured period and normalized use. But some EPCs only include the measured data, which are consistent with the energy performance result.

3.3.2 Ventilation information

Overall, the EPC provides insufficient information about the ventilation system. The ventilation information granted in EPC are: if obligatory ventilation control should be conducted and if it was conducted, the indication of the ventilation system types, the average flow rate, if a cooling system greater than 12kW is installed, and if a radon test has been conducted.

The classification of the ventilation system is not comprehensive. It only has 5 categories of systems: natural ventilation (S), extract only ventilation with and without heat recovery (FX/F), extract and supply ventilation with and without heat recovery (FTX/FT). But the 5 categories do not include all the possible cases. For example, two schools use window masters, but the installation of the window master system could not be categorized. The window master system is an intelligent ventilation mode that automatically regulates the window opening depending on indoor and outdoor air conditions. Additionally, EPC states all the ventilation systems in the schools, so the main one remains unknown in some cases. Due to this, the ventilation system has been extracted through auxiliary data provided by the local administration.

Also, EPCs may provide debatable data. The average ventilation flow in the EPCs is one example, which is in most cases 0 or 1 $l/s \cdot m^2$, which seem to be assumed values, or 0.35 $l/s \cdot m^2$, which is the minimum required value for non-occupied spaces. It is very likely that no measurements have been performed, and the value had been assumed. An additional uncertainty of the ventilation systems is that some schools have their ventilation systems renovated in recent years. However, the validity period of an EPC is ten years, and therefore the systems stated on the EPCs might no longer correspond to the actual system in use today.

Table 1: Categorization of ventilation system in two ways

Category	Ventilation systems	Number
For electricity analysis	Natural ventilation (S)	1
	Extract only ventilation (F)	4
	Window master	2
	Constant air flow with heat recovery (FTX_{CAV})	8
	Variable air flow with heat recovery (FTX_{VAV})	8
For heating and energy analysis	With heat recovery	16
	Without heat recovery	7
Total		23

Analyzing property electricity use intensity and ventilation system should be done according to the specific ventilation system. This is because different ventilation systems have varying property electricity depending on the properties of the systems.

For example, a school with a natural ventilation system (S) should not have a high property electricity use theoretically. If it does, it is interesting to look at why. Regarding heating use, it is interesting to investigate how schools with heat recovery perform compared with others without. Moreover, it is interesting to also look at the difference in energy performance among the schools with heat recovery. To have only two categorizations can be beneficial since the school sample is small.

To conclude, two different categorization systems will be evaluated in the analysis of the ventilation system. When evaluating the electricity use in buildings, the categories will be after the ventilation systems: natural ventilation (S), extract only ventilation (F), Window master, extract and supply constant airflow ventilation (CAV), and extract and supply variable airflow (VAV). The last two systems belong to FTX, which means there is a heat recovery system. When evaluating the heating performance and energy performance, it will be with two categories, i.e. with heat recovery and without heat recovery.

3.3.3 Analyzed factors in EPC analysis

Combining the conclusions from the literature review and the characteristics of this sample, the following parameters from the EPC data were selected for EPC analysis. Heating- and electricity use intensity and energy performance are analyzed with respect to

- Construction year
- Heated area (area heated to above 10°C)
- Whether the building is heritage protected
- Ventilation system

The analysis done on the EPC aimed to explain the buildings energy performance based on the provided information. This process leads to the selection of schools for the building simulation analysis. The choice is based on two factors: 1. The performances are not explainable by available characteristics in EPC, and 2. the schools are similar but performs differently.

3.4 Building energy simulation

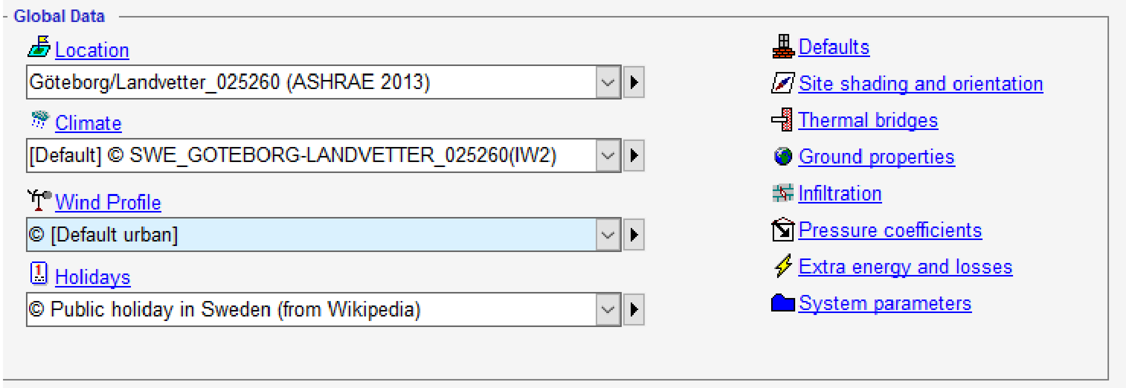
3.4.1 Collecting information of the selected buildings

The accuracy of the model relies on the input of parameters. The information of the input parameters comes from the building, measurements of indoor air quality from a research group in Chalmers University of Technology [44], local administration, city planning office and inspection of the selected buildings in April 2021. The details of the used input can be seen in chapter 5.

3.4.2 IDA ICE software

IDA ICE is a building simulation software developed by EQUA Simulation AB in Sweden which runs whole year dynamic multi-zone simulations for energy and indoor climate. The IDA ICE version used in this thesis is 4.7.1, released on September, 2016.

The input of global data of the models can be seen in figure 3. The location of the models is Göteborg Landvetter, which is the closest position chosen from the predefined database. The climate follows the location. The wind profile is urban default.



Global Data

Location

Göteborg/Landvetter_025260 (ASHRAE 2013)

Climate

[Default] © SWE_GOTEBORG-LANDVETTER_025260(IW2)

Wind Profile

© [Default urban]

Holidays

© Public holiday in Sweden (from Wikipedia)

Figure 3: Input of the global data

The models consist of several thermal zones. The sizes of each zones are determined according to the document provided by the city planning office. In one of the cases, the detailed sizes of the zones were given, so the sizes were entered by the modeler. In another case, the modeler imported drawings with scales since specific values were not found. Figure 4 is one of the floor plans from one school model.

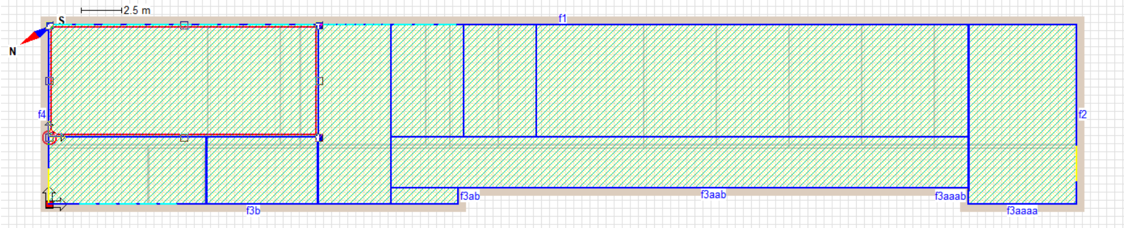
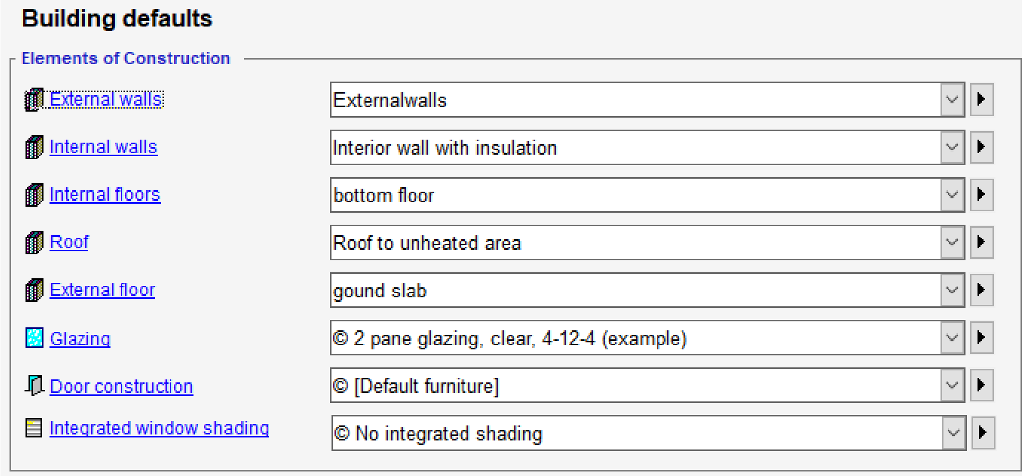


Figure 4: Example of one floor plan

The envelope defaults are demonstrated in figure 5. After the zones are correctly built, IDA ICE recognizes the envelope type of each surface automatically.



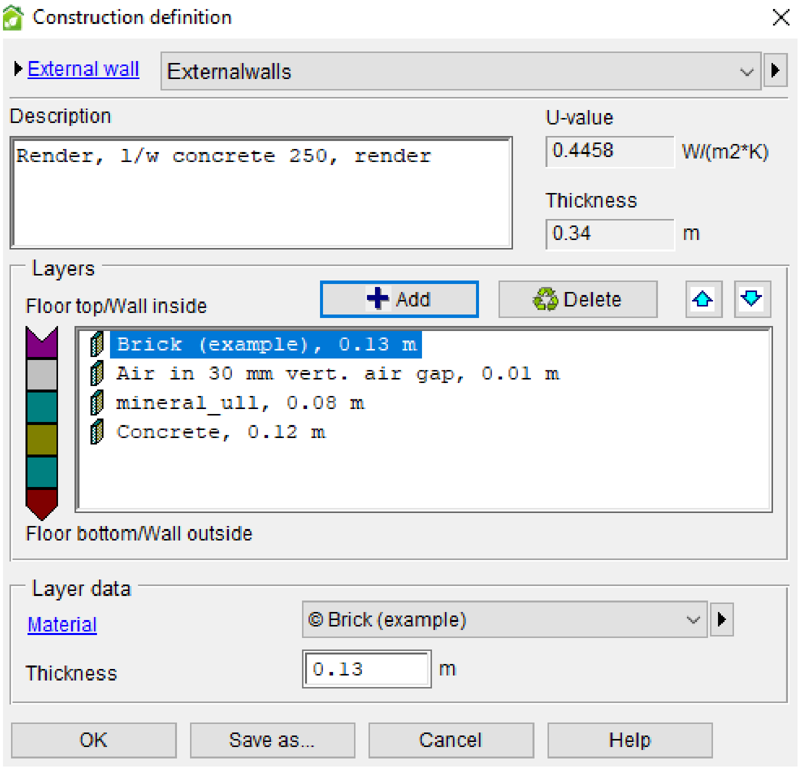
Building defaults

Elements of Construction

External walls	Externalwalls
Internal walls	Interior wall with insulation
Internal floors	bottom floor
Roof	Roof to unheated area
External floor	gound slab
Glazing	© 2 pane glazing, clear, 4-12-4 (example)
Door construction	© [Default furniture]
Integrated window shading	© No integrated shading

Figure 5: Building defaults

The U-values of the envelopes are calculated by IDA ICE, after defining the materials properties such as thermal transmittance and thickness of all the layers. One example of external wall is given in figure 6.



Construction definition

External wall: Externalwalls

Description: Render, l/w concrete 250, render

U-value: 0.4458 W/(m2*K)

Thickness: 0.34 m

Layers

Floor top/Wall inside

```
Brick (example), 0.13 m
Air in 30 mm vert. air gap, 0.01 m
mineral_ull, 0.08 m
Concrete, 0.12 m
```

Floor bottom/Wall outside

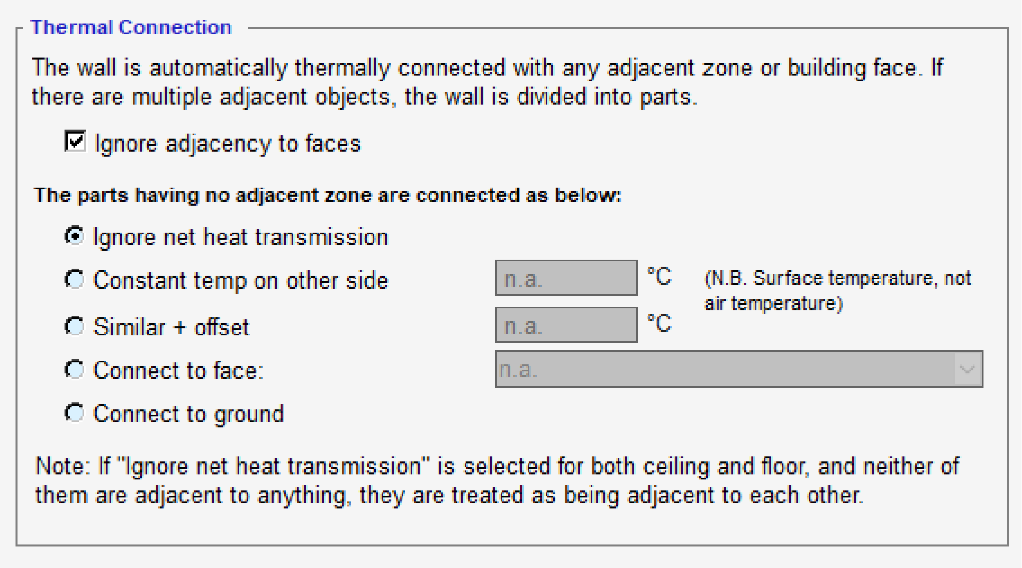
Layer data

Material: © Brick (example)

Thickness: 0.13 m

Figure 6: Construction definition

The walls connecting to the other buildings are non-exterior walls and the heat transmission should be ignored. This is done by manually change the thermal connection condition of the corresponding surfaces, see figure 7.



Thermal Connection

The wall is automatically thermally connected with any adjacent zone or building face. If there are multiple adjacent objects, the wall is divided into parts.

☑ Ignore adjacency to faces

The parts having no adjacent zone are connected as below:

● Ignore net heat transmission

○ Constant temp on other side n.a. °C (N.B. Surface temperature, not air temperature)

○ Similar + offset n.a. °C

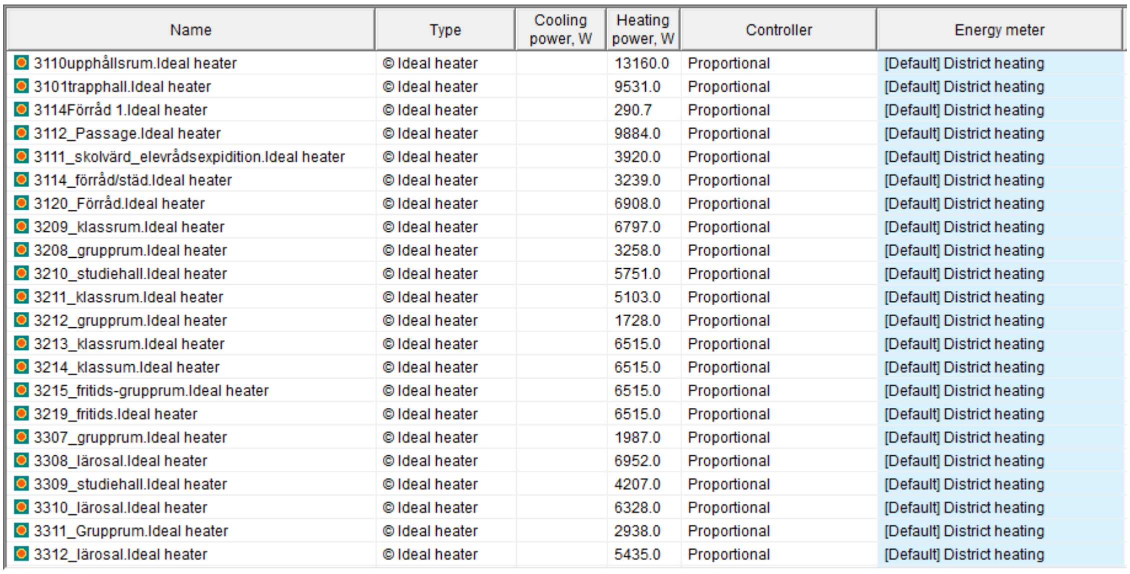
○ Connect to face: n.a.

○ Connect to ground

Note: If "Ignore net heat transmission" is selected for both ceiling and floor, and neither of them are adjacent to anything, they are treated as being adjacent to each other.

Figure 7: Building defaults

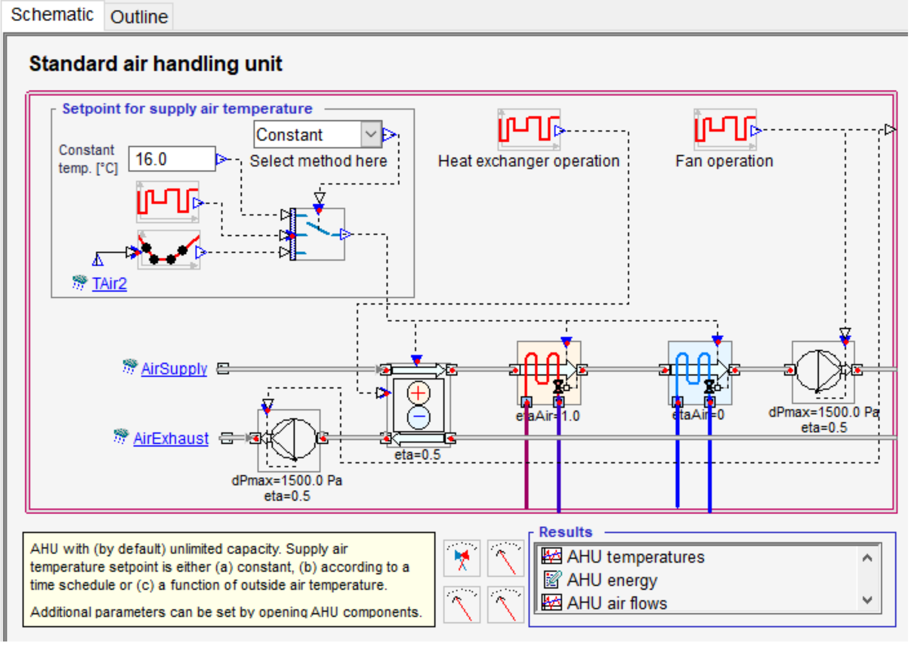
Ideal room units are used in models to model the heat source in the zones, since no detailed information or positions of the water radiators are given. The controllers are proportional controllers.



Name	Type	Cooling power, W	Heating power, W	Controller	Energy meter
3110upphållsrum.Ideal heater	© Ideal heater		13160.0	Proportional	[Default] District heating
3101trapphall.Ideal heater	© Ideal heater		9531.0	Proportional	[Default] District heating
3114Förråd 1.Ideal heater	© Ideal heater		290.7	Proportional	[Default] District heating
3112_Passage.Ideal heater	© Ideal heater		9884.0	Proportional	[Default] District heating
3111_skolvärd_elevrådsexpidition.Ideal heater	© Ideal heater		3920.0	Proportional	[Default] District heating
3114_förråd/städ.Ideal heater	© Ideal heater		3239.0	Proportional	[Default] District heating
3120_Förråd.Ideal heater	© Ideal heater		6908.0	Proportional	[Default] District heating
3209_klassrum.Ideal heater	© Ideal heater		6797.0	Proportional	[Default] District heating
3208_grupprum.Ideal heater	© Ideal heater		3258.0	Proportional	[Default] District heating
3210_studiehall.Ideal heater	© Ideal heater		5751.0	Proportional	[Default] District heating
3211_klassrum.Ideal heater	© Ideal heater		5103.0	Proportional	[Default] District heating
3212_grupprum.Ideal heater	© Ideal heater		1728.0	Proportional	[Default] District heating
3213_klassrum.Ideal heater	© Ideal heater		6515.0	Proportional	[Default] District heating
3214_klassum.Ideal heater	© Ideal heater		6515.0	Proportional	[Default] District heating
3215_fritids-grupprum.Ideal heater	© Ideal heater		6515.0	Proportional	[Default] District heating
3219_fritids.Ideal heater	© Ideal heater		6515.0	Proportional	[Default] District heating
3307_grupprum.Ideal heater	© Ideal heater		1987.0	Proportional	[Default] District heating
3308_lärosal.Ideal heater	© Ideal heater		6952.0	Proportional	[Default] District heating
3309_studiehall.Ideal heater	© Ideal heater		4207.0	Proportional	[Default] District heating
3310_lärosal.Ideal heater	© Ideal heater		6328.0	Proportional	[Default] District heating
3311_Grupprum.Ideal heater	© Ideal heater		2938.0	Proportional	[Default] District heating
3312_lärosal.Ideal heater	© Ideal heater		5435.0	Proportional	[Default] District heating

Figure 8: Example of ideal heaters

The ventilation system is implemented in the model by including air handling units. The supply air temperature, mode, SFP, the efficiency of the heat exchanger, the efficiency of the fan, the efficiency of the heating and cooling coil are defined. In both models, VAV systems are used to model the on and off of the CAV systems. The supply air temperature and the efficiency of the heating coil are the default values of 16°C and 1. The cooling coil has an efficiency of 0 and the supply air will not be cooled, since no cooling coil exists in buildings. Other school specific input parameters are presented in chapter 5.



Constant temp. [°C] 16.0

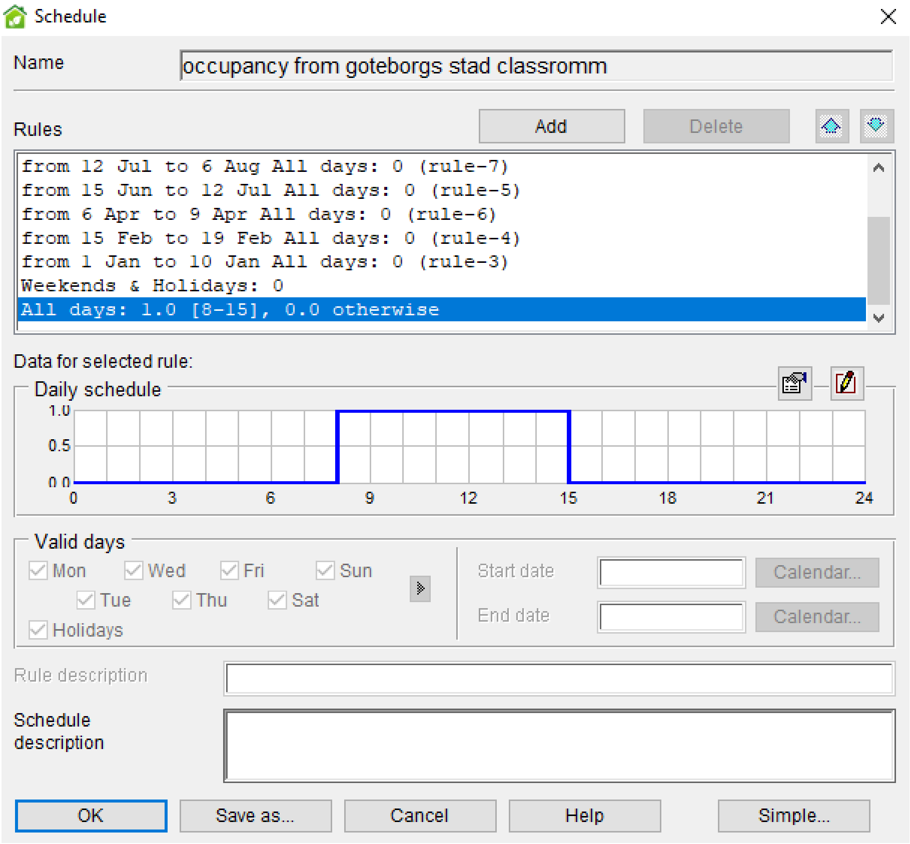
Constant

AHU with (by default) unlimited capacity. Supply air temperature setpoint is either (a) constant, (b) according to a time schedule or (c) a function of outside air temperature.

Additional parameters can be set by opening AHU components.

Figure 9: Air handling unit interface

IDA ICE allows schedules on multiple parameters which enables a more accurate implementation of user behavior and moreover makes sensitivity analysis on various scenarios possible. The days in a year, times in a day, input values can be precisely determined accordingly. One example can be seen in figure 10.



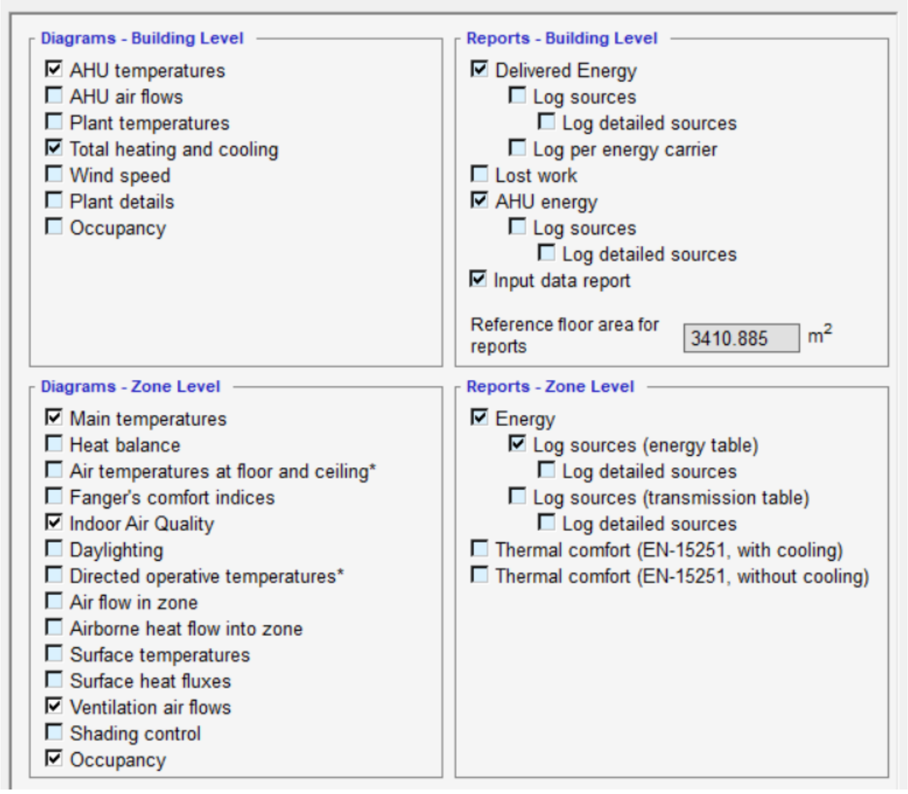
Name: occupancy from goteborgs stad classromm

```
from 12 Jul to 6 Aug All days: 0 (rule-7)
from 15 Jun to 12 Jul All days: 0 (rule-5)
from 6 Apr to 9 Apr All days: 0 (rule-6)
from 15 Feb to 19 Feb All days: 0 (rule-4)
from 1 Jan to 10 Jan All days: 0 (rule-3)
Weekends & Holidays: 0
All days: 1.0 [8-15], 0.0 otherwise
```

☑ Mon ☑ Wed ☑ Fri ☑ Sun
☑ Tue ☑ Thu ☑ Sat
☑ Holidays

Figure 10: Schedule interface

The possible output is listed in figure 11.



Diagrams - Building Level

☑ AHU temperatures
☐ AHU air flows
☐ Plant temperatures
☑ Total heating and cooling
☐ Wind speed
☐ Plant details
☐ Occupancy

Reports - Building Level

☑ Delivered Energy
  ☐ Log sources
    ☐ Log detailed sources
  ☐ Log per energy carrier
☐ Lost work
☑ AHU energy
  ☐ Log sources
    ☐ Log detailed sources
☑ Input data report

Reference floor area for reports: 3410.885 m^2

Diagrams - Zone Level

☑ Main temperatures
☐ Heat balance
☐ Air temperatures at floor and ceiling*
☐ Fanger's comfort indices
☑ Indoor Air Quality
☐ Daylighting
☐ Directed operative temperatures*
☐ Air flow in zone
☐ Airborne heat flow into zone
☐ Surface temperatures
☐ Surface heat fluxes
☑ Ventilation air flows
☐ Shading control
☑ Occupancy

Reports - Zone Level

☑ Energy
  ☑ Log sources (energy table)
    ☐ Log detailed sources
  ☐ Log sources (transmission table)
    ☐ Log detailed sources
☐ Thermal comfort (EN-15251, with cooling)
☐ Thermal comfort (EN-15251, without cooling)

Figure 11: List of outputs

Many outputs can be requested in the simulation such as zone temperatures, AHU temperature, indoor air quality, ventilation air flows, and more. The energy simulation generates the total heating use both for zone heating and air handling unit heating. The heating use intensity is also presented in the output. The HVAC electricity use is simulated and is estimated to be comparable to the property electricity use in EPC, although a small part of property electricity use in the EPCs is due to other purposes such as elevators or facility lighting.

3.4.3 Modeling procedure

A baseline model was conducted based on the input parameters which is more precisely described in chapter 5. It is based on a certain input variable, and the uncertain variable is set to a standard value, see 10. If standard values was not found for uncertain or unknown parameters a consultation with an expert was conducted and expert assumption was implemented in the model based on the experts long experience. In table 10, all the input parameters and their sources can be seen. The extracted output of the simulations are, S/V-ratio, WWR, heating use intensity and HVAC electricity use intensity. This enables a more detailed comparison of the building, it can be seen in 6.1.3. The layouts of the buildings were compared to see if there is a difference in use. Comparison of the buildings was also carried out through a scenario adapting deviant characteristics in one school to the other schools model, in 6.2. The goal was to evaluate if that can explain why the school performs differently.

Furthermore, a sensitivity analysis was conducted on the baseline, in 6.3. Both certain and uncertain factors were evaluated in the sensitivity analysis. Categories for factors is determined. Detailed information on the sensitivity analysis can be found in chapter 5. The result will also single out the critical factors when it comes to energy use. Based on that information and qualitative analysis a ranking is constructed, see 6.3.5. The results that are to be obtained from the sensitivity analysis done on the factors described in table 11 in chapter 5 can possibly also provide some information on what categorization is most important when considering the energy use of the building. Based on the results from the sensitivity analysis and qualitative conclusions, some factors of the baseline model would be adjusted trying to match with the performance stated in EPC. This is the inverse uncertainty analysis, in 6.4.

Lastly recommendations on possible measures is given based on the detailed comparison of the schools, sensitivity analysis and the inverse uncertainty analysis.

3.5 Limitations

The sample size is an important limitation for generalized conclusions. The investigated sample consists of only 23 buildings. After they are further divided into categories in the EPC analysis, some categories have a small number of samples. For example, there is only one school with a S ventilation system, making it hard to compare with schools with other ventilation systems. It is hard to state that a difference in performance is due to a certain factor in a small sample because they are more likely to have false-positive results and inflated effect size. Also, the study might not have high external validity and reproducibility when the result is generalized to other districts. On the other hand, it can be interesting to have a small sample, because it can show faults, information and details that would otherwise be hidden in analyzing larger samples.

Another limitation is the data quality. The reliability of some parts of EPCs can be discussed. EPC might contain non-reasonable information, which would lead to wrong conclusions [49], for example, regarding the airflow rate. The Swedish EPCs are also not definitely accurate [49]. Some data are assumed or missing, resulting in possible wrong conclusion if used. In addition, it is common to see the information missing for some EPC. Some missing data are about the buildings themselves, e.g., the house number, amount of the floors and stairs, whether it is protected; some are related to energy analysis, e.g., the way experts measured the heated area, whether the district heating value is from measured or distributed data, and the tenant electricity use. Another limitation is the inconsistency of the received data. As the validity period of an EPC is 10 years, some of the selected EPC are old. The indoor measurements taken by researchers are done in 2019. The local administration provides some other information, including the ventilation schedule and the holiday schedule, but the time when they collected that information is unknown. There is a possibility that renovations or changes have been made, then some data is out of date, while others are still valid.

The accesses to information were limited, due to lack of time, information not existing, and unavailability of the managing personnel of the school's operation. Due to lack of access to all building and operational information for modeling, standard values and qualitative assumptions have been made, which further challenges the model's accuracy. Nevertheless, there is a meaning in using standard value because it is possible to see the potential of energy use of the building. Assumptions were necessary due to limited time, e.g. thermal bridges were assumed because it would require too much time to measure and calculate them; ventilation operation times and SFP were assumed due to lack of building operation information and access to certain parts of the buildings. There will always be a source of error in the modeling stage. Even the best model has a deviation between predicted and actual parameters.

4 EPC Analysis Results

4.1 Basic information from EPCs

Each building in the investigated sample of 23 school buildings has its own EPC. The validity period of an EPC is ten years, and for the selected buildings, the EPCs cover a wide range of years. 22 out of 23 certificates have the date of issue registered. The average year is 2016. Among the 23 EPCs, 16 have energy classes on them. The following table 2 displays the classes of the 16 buildings.

Table 2: Energy classes of 16 buildings

Compared to the requirement	Energy class	Number
$\leq$ 50%	A	0
>50% - $\geq$ 75%	B	1
>75% - $\geq$ 100%	C	2
>100% - $\geq$ 135%	D	3
>135% - $\geq$ 180%	E	7
>180% - $\geq$ 235%	F	1
>235 %	G	2

The requirements refer to the energy performance indexes in kWh/m^2 that would apply for a similar building constructed today. 13 out of the 16 buildings own a class worse than C, which is the requirements for new buildings at the time of when the EPC was conducted. Only 3 schools meet the requirements for new buildings which indicates potential for improvements. Most of the buildings that do not achieve C typically use 35% to 80% more than their energy performance indexes.

Basic statistics of the main variable used from the EPC, i.e., construction year, heated area, energy performance, heating performance, and electricity use of the 23 buildings, are listed in the table 3.

Table 3: Summary statistics of main variables used from EPC

	Max value (oldest)	Min value (newest)	Mean value	Median	SD
Construction year	2016	1889	1955	1952	42
Heated area [m^2]	7776	590	3309	3216	2111
Energy performance [kWh/m^2]	221	54	123	123	39
Heating use intensity[kWh/m^2]	194	35	103	105	39
Property electricity use intensity [kWh/m^2]	29	4	19	18	7.5

The sample differs greatly concerning construction years. The oldest school was built 130 years ago, the year 1889. The newest one was built five years ago, the year 2016. On average, the schools are 66 years old, built 1955. The schools also vary significantly in terms of energy performance, with the best performing having a value of 54 kWh/m^2 and the worst performing a value of 225 kWh/m^2.

Most schools use district heating for space heating; only one school use oil boilers, another new school uses heat pumps, and lastly, some schools have a hybrid system of district heating and heating pumps. No cooling systems are installed. Before normalization of the hot water use, the hot water use ranges from 2%-21% of the heating use. A factor affecting the hot water use could be the use of the specific building. For example, some buildings only have classrooms and toilets while others have kitchens and gym halls with showers. The heating and electricity use intensities range between 35 to 194 kWh/m^2 and 4 to 29 kWh/m^2 respectively.

4.2 Energy performance with respect to construction year

In figure 12, 13, 14, the heating use intensity, electricity use intensity and energy performance of the school buildings are demonstrated in relation to their years of construction.

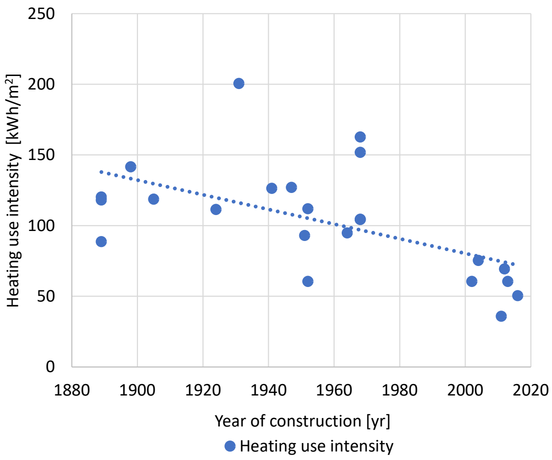


Figure 12: Heating use intensity in the school buildings with respect to construction year.

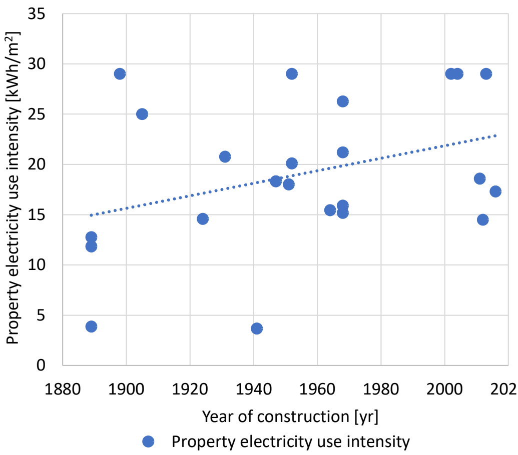


Figure 13: Building electricity use intensity per square meter is presented with respect to construction year.

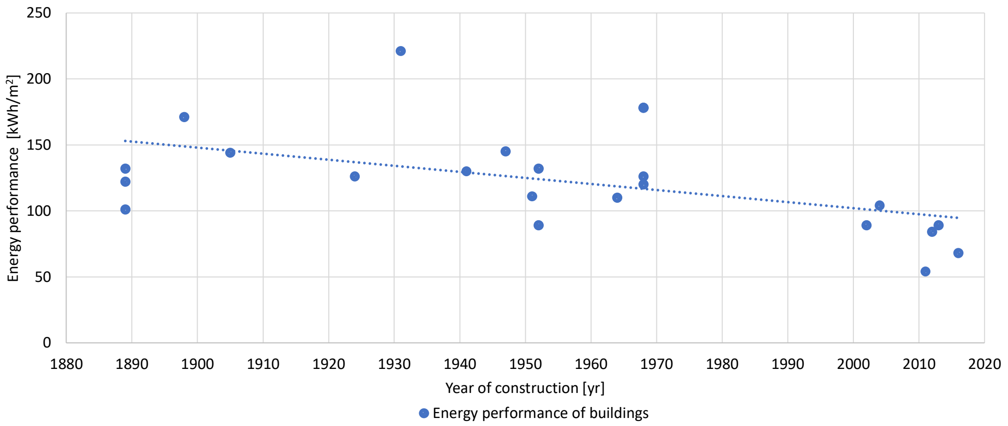


Figure 14: Energy performance of the building with respect to construction year.

It can be concluded from figure 14, that there is a negative correlation between the construction year and energy performance with r=-0.50 (p-value=0.015<0.05). The negative correlation between construction year and heating use intensity shown in figure 12 is clearer and significant with r=0.56 (p-value=0.006<0.01). The electricity use data in figure 13 provide statistically non-significant results of r=-0.35(p-value=0.1), although a certain relationship can be seen.

Looking at the trend line displayed in Figure 14, there is an average difference of about 50 kWh/m^2 from oldest to newest school. A trend can be noted; new schools have lower energy use than older schools. Many reasons can explain this. First, newer schools have heat recovery units installed which cover part of their heating demand. This will be further investigated in the analysis of ventilation systems. Also, the newer the building, the better insulated materials are used due to stricter regulations and newer technologies. It can also be seen that some old schools built around 1890 perform well considering the years, which could indicate that there has been a renovation. This matches with the information stated in the STIL2 report about the state of buildings built before 1940 [10], that they are more likely to have been renovated. Other studies on school buildings also confirm the correlation between energy use and construction year [8] [39] [40]. The electricity use intensity is considered closely related to ventilation and will be analyzed together with the ventilation system, but based on figure 13, newer buildings in the sample have higher electricity use.

There are some schools built around 1960-1970s which have high energy use compare to schools built before and after. They were built before the oil crisis, so the stricter regulations implemented after have not been applied to them, but the magnitude of the difference is so large, which makes them stand out. The worst performing school is constructed in 1930 with energy performance of 221 kWh/m^2. To heat the building, the school uses an oil boiler which is most likely the reason why it is performing worse than the corresponding schools. The school is located quite far away from the city and probably outside other district heating nets, which makes the school impossible to connect to. The high heating use intensity might result from the efficiency of the oil boiler. Considering individual boilers began to be replaced by district heating systems in the 1950s, the boiler is most likely to be an old one with an annual fuel utilization efficiency of 56% to 70% [50]. This corresponds to 124 to 155 kWh/m^2 if it is using district heating, which follows the trend line. Another possible reason its performance is deviating is that it has not been renovated. Due to it being the only school operated by an oil boiler, it is not comparable to the rest of the schools. Hence it is not a good candidate to further investigation.

4.3 Energy performance concerning heated area

Research found that floor area affects heating use [40]. The possible explanation is that larger schools may have larger areas used for more than just education. This results in reduced intensity. The heated area is interesting to examine, as it can reveal whether there is a trend between the heated area and energy performance.

Heating use intensity, electricity use intensity, and energy performance concerning the buildings' heated area are illustrated in figures 15, 16, 17.

In these figures, the heated areas are compared with the energy performances. Buildings are divided into old schools built before 1952 and newer schools built after 1952. 1952 is about the median value of this sample in terms of time, and it just divides the sample into two halves. After 1952, there are only systems with heat recovery, so analysis on the new batch would show how the heated area affects energy use on building equipped with heat recovery systems, and the old batch shows how area effect energy use on old schools that have a mix of ventilation systems. This is done by comparing more similar buildings.

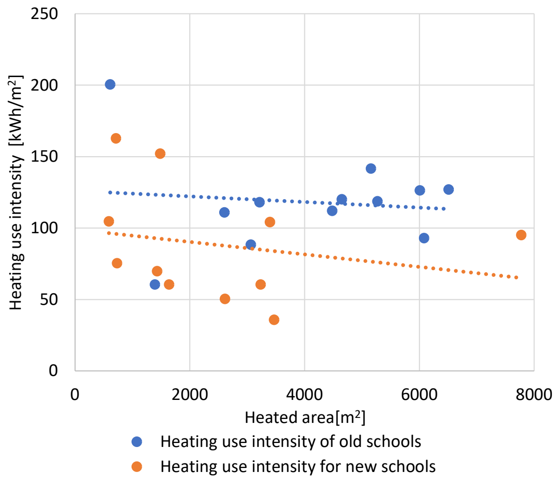


Figure 15: Building heating use intensity with respect to heated area. The old schools are built before 1952 and the new after 1952.

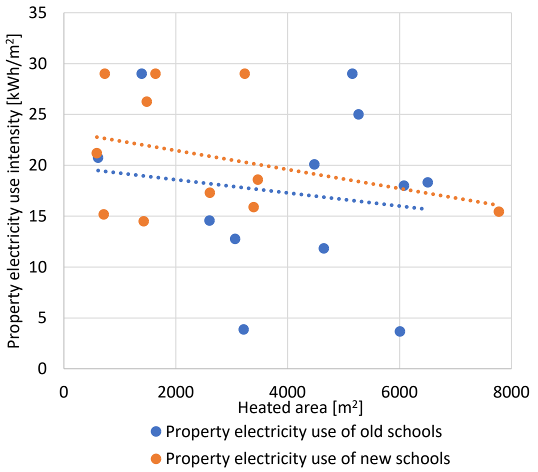


Figure 16: Property electricity use intensity with respect to heated area. The old schools are built before 1952 and the new after 1952.

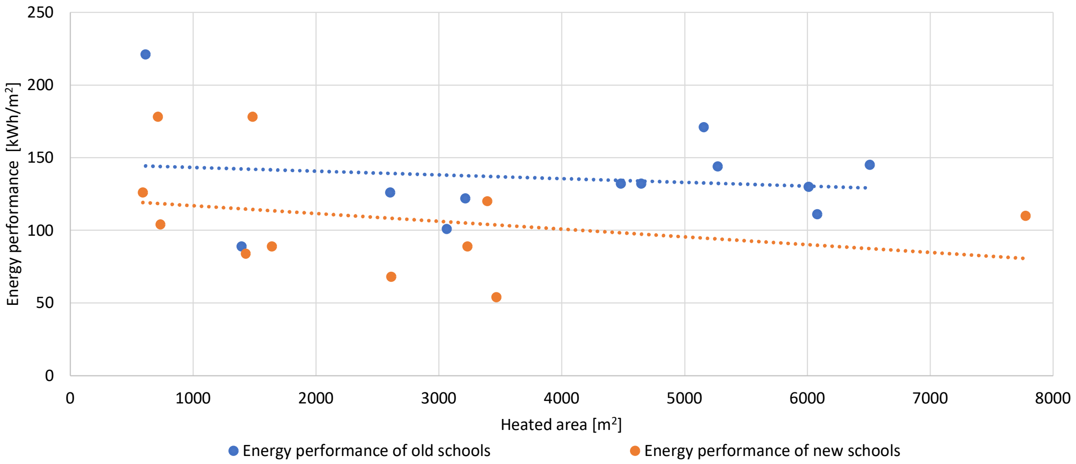


Figure 17: Building energy performance use with respect to heated area. The old schools are built before 1952 and the new after 1952.

The trend lines indicate that new buildings have a higher electricity use intensity and lower heating use intensity and energy performance, confirming the results of the previous section. In figure 15 describing the heating use intensity, r are -0.11 and -0.22 for old and new buildings respectively; in figure 16 describing the electricity density, r are -0.14 and -0.31; in figure 17 describing the energy performance, r are -0.14 and -0.28. Overall, for all energy indicators investigated, there is a decrease with the increasing heated area, but the relationships are weak. It can be seen in this sample of schools, the heated area had a weak negative effect on the heating and electricity use intensity and energy performance, but all the p-values are far from the range to be considered significant. In all the figures, the correlations are stronger for newer schools, maybe due to new schools being more similar in all aspects, and there are fewer variables affecting them other than their area. However, there is a gap in the sub-sample of the newer schools between 3500 m^2 and nearly 8000 m^2, which may have influenced the results. Therefore, further conclusions cannot be made with confidence.

4.4 Energy performance with respect to building protection status

It can be assumed that if a school is protected due to its heritage value, it is harder to conduct any renovations. Thereby their energy use might be higher than buildings constructed during the same time but are renovated [51]. In this sample, most schools are not protected, and protected schools do not show very high performances. Only 4 buildings are protected, accounting for a small part. It cannot be determined if the protection of schools has an impact on energy performance.

4.5 Energy performance with respect to ventilation system

The average heating use intensity, property electricity use intensity, and energy performance, and year of construction by ventilation type are given in table 4.

Particularities of the ventilation and heating system of the oil boiler and heat pump school are not wanted when calculating averages, so they are excluded in table 4. The systems without heat recovery are F and window master systems. The systems with heat recovery are CAV and VAV. The electricity use intensity listed below largely depends on the SFP of the fan.

Table 4: Average electricity use intensity, heating use intensity, and energy performance of the sample by ventilation systems

System	Number	Heating use intensity [kWh/m^2]	Electricity use intensity [kWh/m^2]	Energy performance [kWh/m^2]	Year
F	4	113	11	124	1906
Window Master	2	101	29	130	1925
FTX$_{CAV}$	8	103	21	123	1961
FTX$_{VAV}$	7	89	19	108	1984
Without heat recovery	6	109	17	126	1912
With heat recovery	15	96	20	115	1972

The box plots of heating and electricity use intensity of mechanical ventilation systems are shown below in figure 18 and figure 19. Window master and S systems are not included due to limited samples. However, the heat pump school is included in the VAV sample.

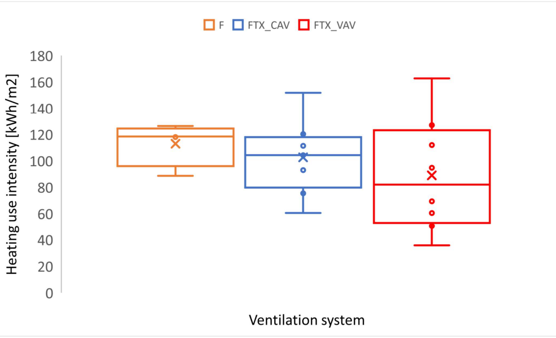


Figure 18: Heating use intensity in the school buildings with respect to construction year and ventilation system

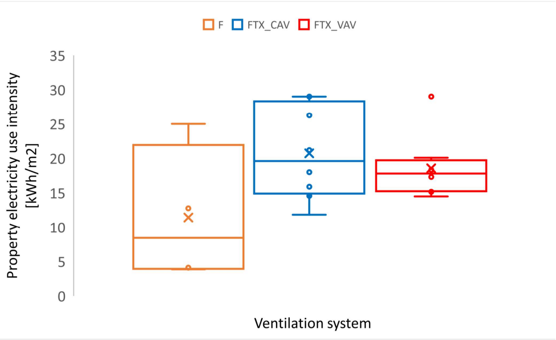


Figure 19: Property electricity use intensity with respect to construction year and ventilation system

In terms of heating, VAV has the most extended interquartile range and whiskers range which means the data disperses and scatters the most, then follows the CAV. The dispersion of CAV and VAV might be due to the difference in the efficiency of the heat exchangers. The efficiencies might vary from 25% to 80% depending on types and operation conditions [52]. The wider range for VAV results from the complex operating condition of VAV. A good working condition leads to a good efficiency, but due to its complexity, operation errors may occur leads efficiency reduction at different levels. Among the known factors, one building with VAV uses heat pumps instead of district heating like other buildings, which is an exception where heating use is very low. Another interesting observation is that a VAV school that should be energy efficient consumes as much as 162 kWh/m^2 heat. It uses the most electricity among its category, as much as the highest CAV, and the reason can not be confirmed but it can very likely be operation error or malfunction. In terms of electricity, the F system has a wide interquartile range. This indicates the data is spread out, possibly due to varying fan performances.

Figure 20, 21, 22 are plots of heating and electricity use intensity by heat recovery category and ventilation category, against construction year. The oil boiler and heat pump schools are not included in the figures.

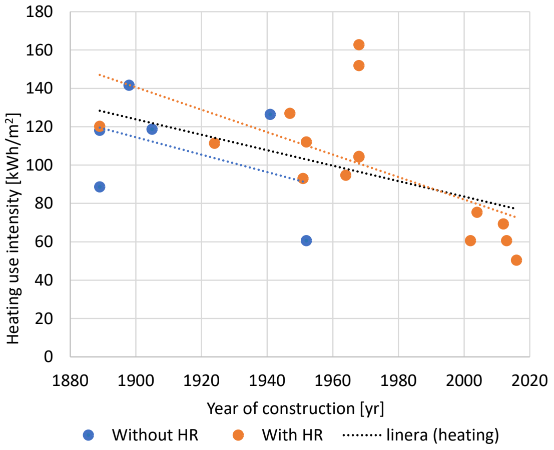


Figure 20: Heating intensity with respect to the construction year and ventilation system.

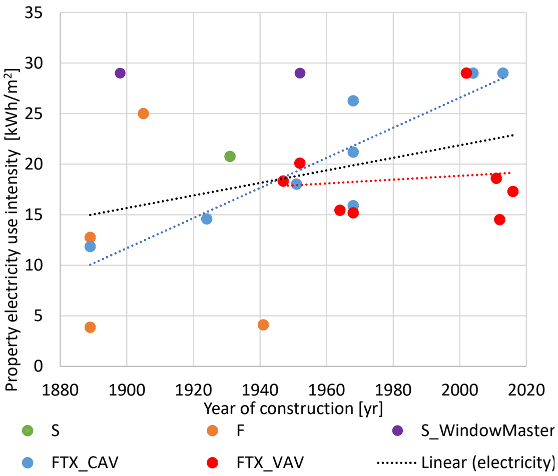


Figure 21: Property electricity use intensity with respect to the construction year and ventilation system

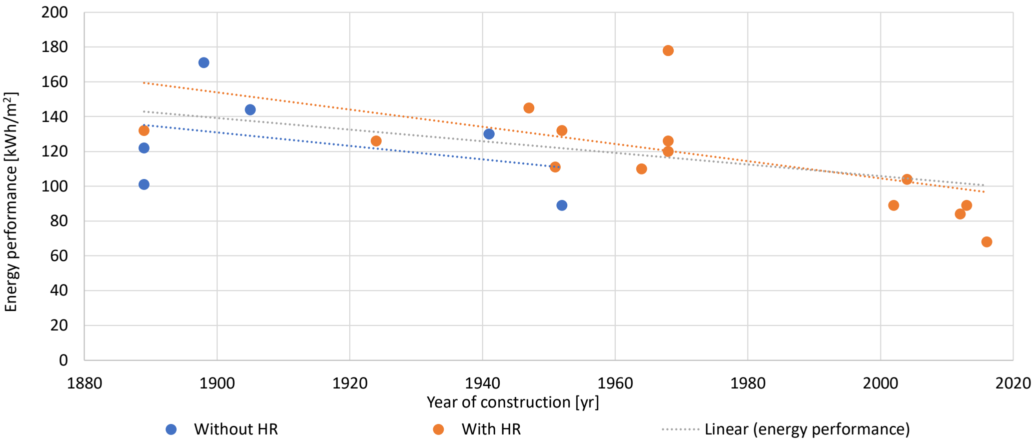


Figure 22: Energy performance per square meter with respect to energy use

Heating use intensity for all the buildings is categorized by heat recovery system (HR) as given in figure 20, since heat recovery has a big impact on heating use. The schools with oil boiler and the heat pump are excluded since it is desired to compare among district heated schools. For buildings with HR, the correlation between heating use intensity and year of construction is stronger than for the entire sample, with r=-0.63 (p-value=0.011<0.05) compared to r=0.54. The relationship would have been stronger had it not been for two buildings built in 1968. The correlation for buildings without HR is r=-0.42 (p-value=0.4), but not statistically significant and with a widespread of the data points.

Property electricity use intensity for all the buildings categorized by ventilation systems is given in figure 21. All the buildings are included. The correlation coefficient for the whole sample is r=0.35, but the p-value=0.1 indicates a non-significant relationship. The trend line for CAV systems clearly shows that for these schools, newer buildings are more likely to consume more electricity with r=0.89 (p-value=0.003<0.01). The samples of the window master are not enough to run the correlation. The schools with F and VAV do not provide statistically significant results. Although the overall trend for the sample is weak, table 4 still shows that average electricity use is increasing with the years. Old schools with natural or extract only ventilation do not use much electricity. Some old buildings have been renovated, and they should be energy-efficient ones. However, high electricity use intensity can be observed in very recent buildings, which should be energy efficient.

Figure 22 shows the energy performance of buildings categorized by whether they have heat recovery or not. Again the oil boiler and heat pump buildings are excluded, as heating use intensity is dominant in energy performance. The strong relationship can be observed for the whole sample, with r=-0.46 (p-value=0.035<0.05) and for buildings with HR, with r=-0.55 (p-value=0.03<0.05). The correlation coefficient for buildings without HR r=-0.36 (p-value=0.5) is not statistically significant. This because both F and window master systems are included, which might not be comparable themselves.

Some schools use more energy than expected; the only school with simple natural ventilation has high property electricity and heating use. Although it does not have a mechanical ventilation system, the school operating oil boiler consumes electricity. The furnace usually includes a burner motor, fuel oil pump, and burner; the burner by-products elimination system includes blower fans; the control mechanism includes switches and thermostats [53], which can explain the high electricity use.

Different generations of ventilation systems are observed. The development of ventilation systems is in line with a reduction in energy performance. As it can be seen in figure 21, S and F are only found in old buildings built before 1941. After that, schools mostly use CAV and VAV that have heat recovery units. CAV covers a wider range of years, as it is a simple and economical choice. Window masters, which are new inventions, are installed in two rather old buildings. It indicates that some renovations have been done to old schools.

Differences in heating and electricity use intensity among mechanically ventilated schools are observed. Those having heat recovery systems consume more electricity than those who do not. Among buildings equipped with HR, on average, buildings with VAV systems use 10% less property electricity than CAV systems. Considering there is other electricity accounted in property electricity, the percentage of ventilation electricity use gap between CAV and VAV should be higher. In terms of heating, VAV uses 14% less heating than CAV. The differences are in line with information that VAV systems use less fan electricity and save fan power than that of a comparable CAV system [54]. That laboratory study found that compared to the investigated CAV systems, VAV systems generate savings in fan power by 20-48% and heating use by 14-20%. The difference found in the statistical analysis of this sample is smaller.

According to table 4, on average, buildings equipped with heat recovery units consume 14% less heating and 15% more electricity than buildings with heat recovery. The most prevalent system in Swedish buildings is rotary heat recovery system, and it is possible for those schools to have such a system. The system has a high efficiency – above 80% is not uncommon [55], but the heating savings are not high as expected, the sample buildings are believed to have less efficient heat recovery systems with efficiency lower than 80%.

The two schools with window masters are interesting to look at. The electricity use intensity is high. One of the reasons for that is that they have complicated control systems, including sensors, actuators, and processing units that are powered by electricity [56]. This only reason is insufficient to justify the high electricity use intensity, and the information is inadequate to draw more speculations.

The heating use intensity for these two schools diverse from 60 kWh/m^2 for the newer building to 142 kWh/m^2 for the older building. One school uses the least among buildings at its age. In contrast, the other one uses the most, which is not consistent with the very energy-saving gimmick promoted by window master's producer [56].

Differences between reality and the expectation of the window master could result from different choices of operators. The system allows several modes in addition to auto mode, including closed, manual control, pulse ventilation, slit ventilation, etc. And the schools could perform differently under different modes [57]. If the settings allow enough airflow to meet the indoor air quality requirements, the energy consumption may be high due to lack of heat recovery, which might be the case of the older school. For the newer school, it possibly has a modest mode where the air change rate is lower than the older school and having a worse indoor environment. The differences might come from the same auto mode as well. Errors of auto mode were documented in the OVK report from another school; the air change rate was only 15% of the recommendation [57]. Also, the difference could be caused by errors in operations due to a lack of customer operating training. Last, the system allows manual override, so the opening and closing of windows in two buildings differ on occupants' behaviors. Windows in other schools are not encouraged to open since they already have mechanical ventilation systems. Compared to those schools, occupants' preferences have a bigger impact in schools with window master systems. No solid conclusions are drawn, as many uncertainties exist in the window master system. There are only 2 samples, and no further measurements are done.

4.6 Conclusions from EPCs

4.6.1 Selected schools for case study

For the case study, it is desirable to find buildings built in similar years and with new ventilation systems having different performances. School building 16 A (VAV,1968) and school 2 (CAV,1968) are equipped with new ventilation systems but have high energy use; in contrast, school buildings 1 A, D (CAV,1968) and school 15 (VAV,1964) also have heat recovery ventilation systems. However, the consumption is much lower, which would be interesting to look at. There is no other indicator in the EPC analysis that could explain the deviation in energy use. The question arises, why do these schools with a heat recovery system have such high heating use intensities? And one of the bad performing schools also has high electricity use. The basic information of the 4 buildings is listed in table 5. The building varies in terms of area, which might have an impact on energy use. Therefore, school 1 A and school 2 are the selected buildings as they are close in terms of heated areas. School 2 is the building that has the highest energy use intensity after the oil boiler school. School building 1 A is chosen over school building 1 D for its slightly lower energy use since a solid contrast to school 2 is desired.

Table 5: Interesting schools to study based on their EPC information

School name	Heating use intensity kWh/m^2	Electricity use intensity kWh/m^2	Energy performance kWh/m^2	Area m^2	Ventilation
School 16 A (1968)	152	15	178	713	FTX_VAV
School 2 C (1968)	163	26	178	1484	FTX_CAV
School 15 (1964)	95	15	110	7776	FTX_VAV
School 1 A (1968)	104	16	120	3395	FTX_CAV

4.6.2 Measures proposed in the EPCs for the 2 chosen schools

The school 1' EPC suggests LED lighting, new radiator thermometer, to check the hydraulic condition of heating and ventilation systems. The highest expected energy reduction is from changing the current windows to 3-pane windows, with an expected saving of 11 kWh/m^2. Although the buildings had changed to 3-pane windows in 1991, the windows might not be considered efficient enough compared to today's 3-pane windows. At the time of inspection, the windows were not in very good condition, indicating great degradations since installation.

The expert who performed the school 2 EPC states that the energy use is high and questionable considering it has a heat recovery system. A measure proposed is adjusting the heating and ventilation system, and that will be saving approximately 25000 kWh for the whole school per year. This corresponds to approximately 17 kWh/m^2 if taking the A_{temp} given in the EPC, which will decrease the performance to

161 kWh/m^2. If the measures were implemented, the energy performance would still be higher than expected considering the construction year and ventilation system. Therefore a further analysis on why it performs so odd is interesting.

5 Selected school buildings

5.1 Information from documents

The city planning office provided archived information on the history of the selected buildings. The folder contained information about the building construction, HVAC-system, OVK-protocols, renovation decisions and so on. Useful information was extracted from the files. Dimensions of the building as well as construction materials of the building could be extracted from the given drawings. The U-value of construction elements and their layers can be found in Appendix 2 [8]. The U-values were set based on the library of IDA ICE and regulations that applied when the schools were constructed [58]. If a material was not found in the library of IDA ICE or the IDA ICE values did not follow the regulations, the thermal transmittance of the material's was extracted from the regulations. The OVK-protocol is a protocol on the mandatory ventilation inspection on buildings. Several protocols were found from different years. Information was extracted from the latest valid protocol. The third information extracted from the archive is the renovations made on the buildings. Standard input values for normal use were retrieved from Sveby document of user data for educational buildings. [42], e.g. indoor temperature and internal heat gains.

5.2 Data from measurements

Measurements conducted by a research group at the division of Building Services Engineering at Chalmers linking indoor air quality and energy performance of which this study is an extension, have been obtained. The measurements included operative temperature, relative humidity, CO_2 concentrations. The measurements were taken in two classrooms in each school building during a week and at 5 minutes intervals. From the CO_2 measurements, the occupancy schedules were determined as well as the average air exchange rate [1/h] and average classroom temperature. In this thesis, the mean temperatures of both classrooms have been used in the baseline models. The air exchange rate [1/h] was converted to airflow [l/s,m^2] for both schools. The measured airflow rate was compared with the requirements for ventilation from the local administration for the given maximum occupancy in the classroom, and an operation of max flow was set in the model. The value is stated in table 10 under operation percent.

5.3 Information from building inspections

Inspection to the schools were conducted to gain additional information which could not be obtained from the archived data. Site visit and field measurements in two schools were done in April. During the inspections, the physical properties of buildings including nearby environment, location and sizes of windows and doors, patterns of blinds, use of some spaces got confirmed. Instantaneous temperature measurement were taken to confirm whether the basements were heated or not.

The surrounding environments are confirmed during the inspections as figure 23 and 24 show. As it can be seen in figure 23 which displays the surrounding of school 1, the east side is a playground which would not block the sun, and the buildings on the north side do not affect solar radiation. In contrast from school 1, school 2 has trees and hills on the east side which are very likely to create shadings as can be seen in figure 24

Figure 23: Surroundings of school 1

Figure 24: Surroundings of school 2

The east facades of the two schools are shown in figure 25 and 26. Opening of windows are observed in both schools.

Figure 25: East facade of school 1

Figure 26: East facade of school 2

The west facades of the two schools are shown in figure 27 and 28. Openings of windows are seen in school 1, but for school 2, windows on the west facade can not be opened due to them being connected to the corridor.

Figure 27: West facade of school 1

Figure 28: West facade of school 2

The opening and shadings of windows can be seen in detail in figure 29 and 30. Both schools have blinds between panes. The left small part of school 1' windows are sometimes open. Less windows are open in school 2, but the degree of opening could be higher.

Figure 29: Windows and shadings of school 1

Figure 30: Windows and shadings of school 2

Unfortunately, occupancy density and daily schedule, equipment and lighting capacity and schedule remain uncertain due to lack of access.

5.3.1 School 1 A

School 1 is located in the southwest of the city, with about 450 students from grade 0 to grade 6. Among the six buildings, one building is investigated, which is building A, see figure 31. The building's long walls approximately align on the north-south axis. There are small hills on the north and west sides of building A, and there is a lower building to the west. The east side of the building is a playground, and the south side is connected to other buildings and modeled as no net heat transmission.

Figure 31: Map of School 1 and the A building

The building is composed of 4 floors; the basement with storage rooms and air raid shelters, and the upper floors with classrooms, offices, leisure center, and toilets. There are 16 classrooms in total, occupying around 33% of the heated area. The basement is used as shelters and warehouses, and it is smaller than a normal floor. The building has three U-shaped staircases, one entrance door on the west and three on the east side. The building has many windows on its east and west facades. As shown in table 6, several renovations have been done, windows and ventilation systems have been updated in 1994 and 1996.

Table 6: Construction and renovation history of school 1 A

Year	Measures
1968	Construction of the building.
1991	Replacement of windows.
1994	Change of floor layout.
1996	Changes in heating and ventilation.
2008	Construction change, e.g, entrance doors.

5.3.2 School 2 C

School 2 is located in central Gothenburg and has 690 students from classes 4 to 9. The selected building is building C which can be seen in 32. The school is U-shaped, but the shape of the building investigated is long and it is aligned with the NNE-SSW (North northeast-south southwest) axis. The school is in a residential area and is surrounded by buildings. The chosen building to study, Building C has a wooded area opposites its ESE (East- southeast) facade where also all the windows of the classrooms are located. Not all of the facades are shaded by the trees. On the opposite side, the building has a playground.

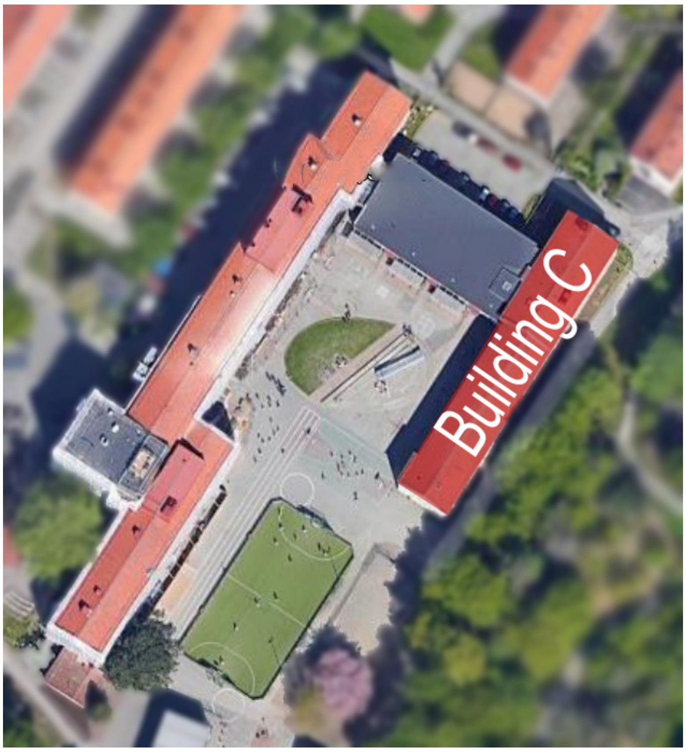


Figure 32: Map of School 2 and the C building

The building has 3 floors and 1 basement which is not fully underground. In the model it has been assumed that half of the basement is below ground and half above, based on the observation during the site inspection. The building is connected to another building as can be seen in figure 32. The heat transfer in this connection is neglected in the model. The classrooms, toilets, after-school care centers and teachers rooms are located in floor 1 and 2. According to observations in the inspection, the basement seemed to have some after school activity, while other parts were shelter rooms and storage area, thereby they seemed unused. 46% percent of the basement is assumed to be heated in the model. There are windows on the facades of the long side of the building but the density differs significantly. All the classroom windows are on the ESE-facade, which is the most window dense facade. Every classroom has 6 windows. There are 8 classrooms in total, which is around 35% of the heated area. The corridors which are facing WNW-facade have smaller and more scattered windows. The most common entrance to building C is at the linking building, which was observed in the in-situ inspection. The building has two own entrances in the short sides of the building, where only one of them seemed to be used. The shape of the roof has not been modeled, only the materials of the roof were modeled.

Transferring the dimensions of the building from drawings to IDA, the size of the zones where determined by outer measurement. Some renovations have been performed, see table 7.

Table 7: Construction and renovation history of school 2

Year	Measures
1968	Construction of the building.
1994	Facade renovation.
2006	Ventilation system replacement.
2014	New fans

The most recent one is in in the ventilation system. FTX-system was installed in 2006. The facade renovation was minor, with thin plaster put on the facades.

5.4 Input data for school 1 and school 2

Bought heating and electricity records for the year 2017, 2018 and 2019 are provided by the local administration and used in the building comparison part. The geometries of the models are obtained according to the drawings and documents provided by the city planning office which can be observed in table 8.

Table 8: Basic geometry properties of the buildings

Geometry property	School 1 A	School 2
Basement floor	1	1
Floors above ground	3	2
Basement room height to ceiling/roof [m]	2.45	3.38
Room height to ceiling/roof [m]	3.11	3.52
Ground area [m^2]	896.5	675.7
Heated area [m^2]	3395	1587

The most important U-values of opaque and non-opaque envelopes are listed in table 9. The detailed composition of the envelopes and the properties of the materials are listed table 8 in the appendix 2.

Table 9: Input U-values of the main envelope elements

Element	U-values [W/m^2,K]	
	School 1	School 2
External walls	0.45	0.45
windows	1.9 (3-pane)	2.8 (2-pane)
roof	0.27	0.2
ground floor slab	0.4	0.6

The various model input data are divided into 7 categories, including ventilation system, openings and shadings, internal heat gains, heat losses, percentage of internal gains, schedules and heating system, see table 10. The sources of the input data are also presented in table 10.

Table 10: Detailed input information of the two building models and the sources

	School 1 A	Source	School 2	Source
		Ventilation system		
Efficiency of fans	Approximated to 0.5	Experts assumption	Approximated to 0.5	Expert assumption
Maximun air flow [1]	6200 [L/s]/6200*1.3 [L/s]	Opeartion personnel	3440 [L/s]	Assumed
Operating percent	75%	Local administration	65%	Air flow measurements
Power	2*11 [kW]	OVK 2014	2X9.2 [kW]	OVK-2017-01-09
SFP	2.7 kPa	OVK 2015	3 kPa	Expert assumption [2]
Heat exchanger efficiency	40%	School caretaker	50%	Expert assumption
Airflow for basement [3]	0	Inspection	0	Inspection
Airflow for unoccupied spaces	0.35 [l/m^2]	Sveby	0.35 [l/m^2]	Sveby
Airflow for occupied spaces[4]	Scaled 0.35 [l/m^2] + 7 [l/s,p]	Sveby	Scaled 0.35 [l/m^2] + 7 [l/s,p]	Sveby
		Shadings		
Shading	Without	Default	Without	Default
Shading from trees	-	Inspection	East; transparency of 0.5	Inspection
		Internal heat gains		
Light	5 [kWh/m^2]	Sveby	5 [kWh/m^2]	Sveby
Equipment	5 [kWh/m^2]	Sveby	5 [kWh/m^2]	Sveby
Occupant	According to drawings	City planning office	According to drawings	City planning office
		Percentage of heat gains		
Equipment heat gains percentage	70%	Sveby	70%	Sveby
Occupants heat gains percentage	70%	Sveby	70%	Sveby
Light heat gains percentage	70%	Sveby	70%	Sveby
		Heat losses		
Opening of doors and Windowss	4 [kWh/m^2]	Sveby	4 [kWh/m^2]	Sveby
Thermal bridges	20% envelope loss	Boverket [59]	20% envelope loss	Boverket
Infiltration	0.8 [L/m^2,s]	[60] [61]	0.8 [L/m^2,s]	[60] [61]
Infiltraion pressure coefficient	Autofill; semi-exposed	Default	Autofill; semi-exposed	Default
		Schedule		
Occupancy classroom	1092 [h/yr]; 8:00-15:00; 1h break	CO2 measurements	1092 [h/yr]; 8:00-15:00; 1h break	CO2 measurements
After-school care center	1450 [h/yr]; 13:00-18:00	Assumption	1450 [h/yr]; 13:00-18:00	Assumption
Ventilation schedule	1615 [h/yr]; 6:00-18:00	Local administration School caretaker	1615 [h/yr]; 6:00-18:00	Local administration School caretaker
Light and equipment schedule	1092 [h/yr]; 8:00-15:00; 1h break	CO2 measurements	1092 [h/yr]; 8:00-15:00; 1h break	CO2 measurements
		Heating system		
Source	District heating	EPC	District heating	EPC
Room units	Ideal heater, proportional	Water radiators	Ideal heater, proportional	Water radiators
Schedule	24/7		24/7	
Temperature set point	20.55℃/22℃	Measured/EPC	19.8℃/22℃	Measured/EPC

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[1] School 1 has a Swegon Weiss system. School 2 has Ecopilot, an overall control system.

[2] Expert suggested use 3 KPa although 5 KPa is the calculated value, and using 5 KPa results deviating electricity intensity.

[3] The unused part of the basement, including shelters and storage.

[4] Firstly, the airflow is calculated according to the regulations with the occupancy given by drawing. The flows for school 1 A were scaled by the total airflow provided by personal, the flow for school 2 was scaled by measurements done in 2 classrooms.

The input parameters are used to build a baseline model which will be used later in the sensitivity analysis, as stated in chapter 3. Since there are many uncertainties and assumptions in the models, the default values for the unknown factors were used. The models are not calibrated to have output values really close to the EPCs. The baseline models property electricity use intensity and heating use intensity deviates from the EPCs with +14% and -26% for school 1 and -18% and -21% for school 2, respectively. Although there are still some gaps between EPC values and the modeled outputs, the models can be considered valid for the subsequent sensitivity analysis, and the modeled output can reach EPCs if the uncertainties is varied.

5.5 Sensitivity analysis

Table 11 lists the factors which will be evaluated in the sensitivity analysis under their respective category. The factors are divided into 4 categories: occupant-related factors, operational controlled factors, building characteristics and HVAC-characteristics. The table presents a description of the input range, and the reasons will be presented under the table.

Table 11: Description of tested inputs in sensitivity analysis

	Describtion of tested inputs and input range
	Occupant-related factors
Shading*	1. Sun controlled shading : All windows Occupancy& sun controlled shading: 2. All windows 3. 50 % of windows
Window openings*	Magnitude of window opening is 30% in all three scenarios: 1. 20 min two times a day, 1 window per classroom 2. 20 min two times a day, all windows 3. 60 min two times a day, all windows
Occupants*	Occupants density: 0.08-0.26 occupants/m^2
	Operational controlled factors
Temperature set point	19-22℃
Ventilation flow*	1. Operation percentage of max flow varied from 20% less to 20% more 2. Ventilation on during summer time 3. Schedule 8h/day, on school days
Night time set back	Lower temperature between 6 pm-5 am with 1-4 ℃ lower operative temperature during occupied hours
	Building characteristics factors
Thermal bridges*	Accounting for 10%-40% of the transmission heat loss
U-value of exernal walls	Varying the U-value of the external walls: 0.18-0.75 W/K,m^2
U-value of windows	Changing window to a lower U-value: 3.14 W/m^2,K - 1.2 W/m^2,K
	HVAC characteristics factors
SFP*	Ranging from 1.5-5.4 kW/m^3,s
Heat exchanger efficiency* for HR	0%-80%

The factors marked with a star are uncertainties in the model, which is especially important in the sensitivity analysis. Some uncertainties are only for one school.

Occupant-related factors

In table 11 the tested inputs are presented for occupant-related factors, which are; shading, window openings and occupancy. Sveby recommend the g-value (solar factor) 0.65 [42]. Observation from visiting the school showed shadings in the studied schools, thereby it is of interest to test the sensitivity to the model. The baseline do not include shading, since it is a factor hard to determine and highly occupant controlled. These scenarios is tested:

- The first scenario is that all blinds are controlled merely by the sun, which means the blinds are drawn when the solar radiation is above 100 W/m^2 [62].
- The second scenario is that all blinds are sun and occupancy-controlled. During occupied hours, i.e., from 8-11 and 12-15 o'clock, blinds can be drawn if the radiation reaches 100 W/m^2.
- The last scenario investigates when only half of the blinds can be drawn. The last scenario is investigated since blinds are totally occupant controlled.

In the baseline model, the standard input value for window openings of 4 kWh/m^2 from Sveby is adapted. However, it is true that the window opening is hard to determine in these buildings. Thereby some window opening schedule which seems reasonable has been set to test the sensitivity and the impact it has, see table 11.

The occupancy is set in the building from the max occupancy in drawings and information received by the local administration. The real occupancy might differ from the maximum value, therefore a variance of occupancy is tested.

Operational controlled factors

Measured temperature for two classrooms in each school showed there is some difference, see table 10. Thereby it becomes interesting to evaluate the impact of the temperature on the heating use in the building. Sveby [42] recommend 22 °C for good indoor environment but it can vary by 2 °C. The lowest temperature (19 ° C was chosen because one of the schools classrooms operative temperature was below 20 degrees, thereby a lower temperature was seen to be interesting to evaluate to see the models sensitivity to lower indoor temperature.

Since EPC for one of the schools states that the ventilation system needs balancing, it is interesting to investigate its effects, thereby the first scenarios testing the dimensions of ventilation system, where it is varied from -20% to +20% of the baseline. The measured bought electricity received from the local administration between the years 2017-2019, indicated that the electricity use is at the same level during summer as occupied days, therefore modeling a scenario with ventilation in the summer is interesting. Also, Sveby suggests scheduling 8h/day for primary and secondary schools, and this is the third scenario.

A nighttime setback can be implemented in schools to optimize operation, although its implementation in schools is not usual. This can indicate some saving potential.

Building characteristics factors

Since the thermal bridge was a standard input for energy modeling, it is interesting to evaluate the impact on the results. 30% and 40% were set to see the impact on the extreme side.

Although the U-value is not an unknown variable, the U-value might differ based on the input of thermal transmittance value. Thermal transmittance of insulating material was retrieved by regulations at construction time [58] and from the library in IDA ICE, for the given material. The exact thermal transmittance for the building is not known furthermore the level of deterioration is not known. For example, there existed three qualities of materials with slight difference in thermal transmittance and the one in the middle was chosen in the baseline. The models sensitivity to the choice between the three qualities is tested. The extreme case 0.75 W/K,m^2 demonstrates the deterioration of the walls, while the middle value represents the uncertainties of the exact U-value. Another aspect that is interesting to evaluate is how can retrofits in external walls can affect the energy use, thereby the scenarios with significantly lower U-values were built. 0.18 W/K,m^2 is chosen since it today's standard [63]

Due to the renovation of windows in one of the schools, the U-value of windows differs. Investigating the school's sensitivity to window U-value and if that could be the reason why the schools perform differently are meaningful. Furthermore, the potential savings with having windows following today's regulations are modeled [63].

HVAC characteristics factors

BBR recommends SFP to be 1.5 kW/m^3s for FTX-ventilation systems [63]. The highest tested value is 5.4 kW/m^3s since it was calculated from the OVK documents for one of the schools but seemed unreasonably high, and therefore rejected in the baseline model. 3 kW/m^3s was assumed for that school. This is an unknown parameter for one school but still interesting to investigate in both schools.

A heat exchanger can have up to 80% efficiency, which is a standard value used in the design of new school buildings in Gothenburg [64]. The efficiency is known for one school which is 40% but assumed to be 50% for the other. It is interesting to evaluate what effect heat recovery has on thebuilding energy use thereby a scenario with no heat recovery was built. In the EPC of the worse performing school, the experts states that it is abnormal for a school with a heat recovery system to have this high energy performance. This makes it particularly interesting to study the heat efficiency effects on the model. The lowest value chosen was 0 % efficiency to see how much the HR saves and how important it is.

6 Analysis of selected school buildings

The school buildings studied are school 1 A and school 2 C, but they will be referred to as school 1 and school 2 for simplification from now on. If nothing else is stated, the electricity use refers to property electricity use, its introduction can be found in the Method part.

6.1 Comparison of school buildings

6.1.1 Energy use

In this section, the EPC data as well as data of bought heating and electricity for the year 2017-2019 will be presented and compared. The bought energy is interesting because the value is the source of EPC. Table 12 shows the energy performance values from EPCs.

Table 12: Energy performance from EPC branched into heating and electricity

	School 1	School 2
Heating use [kWh]	353 559	225 615
Hot water use (included in heating) [kWh]	7 396	9 877
Property electricity use intensity [kWh]	53 946	38 955
Total energy use [kWh]	407 505	264 199
Heating use intensity [kWh/m^2]	104	152
Hot water intensity (included in heating) [kWh/m^2]	2	7
Electricity use intensity [kWh/m^2]	16	26
Energy performance value[kWh/m^2]	120	178
Total heated area [m^2]	3 395	1 485

From table 12, it can be noted that school 2 has higher energy performance value, heating use intensity, electricity use intensity, and hot water use intensity. The hot water use intensity is three times higher for school 2 compared to school 1. The absolute value of hot water use for school 2 is significantly higher despite the fact that school 1's heated area is more than twice as large. Hot water use should be normalized for normal use according to Boverket [33]. It is unclear whether this difference results from normalization, different water use in the building, or a different hot water distribution system that generates higher losses. The difference of use of the building will be evaluated under building characteristics. The two values of hot water use have been directly adopted in the models in order to simulate the known parameters, although it is unclear why the difference exists. The heated area A_{temp} for school 1 is just over double of school 2. The accuracy of heated area A_{temp} is critical since it is what is determining the energy performance value of the building.

The EPCs for all the buildings of school 1 were received. The performance is the same for almost all buildings except for one building which has 6 kWh/m^2 more in electricity use intensity. For school 2, the performances for all buildings differ, where the studied building C has an energy performance of 178 kWh/m^2 and the other buildings have 176 kWh/m^2 and 161 kWh/m^2, respectively. The mean energy performances for the schools are 122 kWh/m^2 and 172 kWh/m^2 respectively.

The values of bought energy are not only for the selected buildings but for the whole school. This includes additional 4 buildings for school 1, and additional 2 buildings for school 2, which contains 5 buildings for school 1 and 3 buildings for school 2.

The energy use intensity for different buildings in one school vary. When intensity for a specific building is taken from performance for the whole school, there could be errors. This can lead to an in-comparability between bought energy use intensity for the whole school, and the specific building's analyzed energy performance. Since the EPC for all buildings has been assessed and found not to differ significantly, it is valuable to study the bought energy. One advantage of analyzing the received bought energy data from local administration which are measured values, is that the bought heat and electricity are given monthly. This enables monthly comparison. The EPC is developed by this kind of data but it states the annual energy use. Another advantage is that the data of two schools are from the same year, and since the schools are located in the same climate district, they are more or less comparable.

The EPC measurements were done in 2016 and 2014 by different experts, so there is room for differences when the performance is calculated. Although EPC has been normalized, it is of value to see the difference in bought energy in the same year and during the whole year for both schools. The total heated areas are taken from the EPCs. The accuracy of this analysis is dependent on the accuracy of the area; a smaller area than actual will overestimate the energy intensity and, vice versa.

The bought heat for three years can be examined for school 1 in figure 33 and school 2 in figure 34.

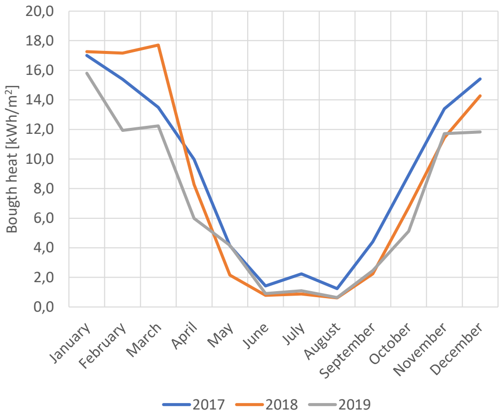

Figure 33: School 1 bought heating energy [kWh/m^2] for the years 2017-2019.

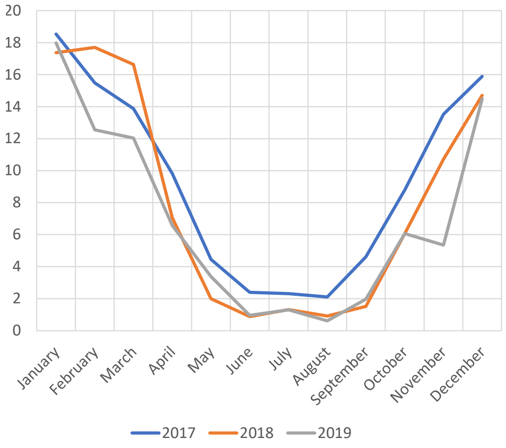

Figure 34: School 2 bought heating energy [kWh/m^2] for the years 2017-2019.

It can be noted that there are discrepancies among years due to differences in outside temperatures, i.e. 2018 had clearly a colder winter (January-April) while 2017 was a colder year overall. In general, the heating use is the highest in October-April period, and low during the rest of the year. Comparing both schools, the heating use per square meter heated area is very close to each other. The bough heat concerning the heating area is presented in table 13.

Table 13: Bought heat per square meter for three years and the average

Year	School 1 [kWh/m^2]	School 2 [kWh/m^2]
2017	107	112
2018	100	97
2019	84	84
Average	97	97
EPC value (normalized)	104	152

Compared to school 2 which had a significantly higher energy use in EPC than measurements, school 1 get closer energy use per square meter, as table 13 displays. The average bought heat for both schools for the three years is exactly the same. The average bought heat intensity for school 2 is 55 kWh/m^2 lower than the normalized heating intensity in EPC. Since the two schools are in the same climate zone and the data is collected from the same years, correction of energy use can be overseen.

The difference in heating use intensity in EPC between the schools is 48 kWh/m^2, whereas no difference in bought heat can be observed in table 13. The performance is not necessary the same if the bought heat is the same since one school may have different indoor temperature or uses. If this is the case in the two schools can not be established. An other possible reason to explain the discrepancy between bought heat and EPCs for school 2 can be that some renovation measures have been performed between the years when the EPCs measurements were conducted and when the bought energy was documented, i.e., 2014 and 2017-2019. The EPC of school 2 recommends balancing the heating and ventilation system as a renovation measure, and suggests that it would save 17 kWh/m^2. That measure may have been conducted between 2014 and 2017. Other measures have not been seen in the archived files for the schools, except for fan change which probably affects the electricity use intensity. The measures cannot explain the full gap between the results from the bought heat from the year 2017-2019 and the EPC.

The bought electricity for three years can be examined for school 1 in figure 35 and school 2 in figure 36.

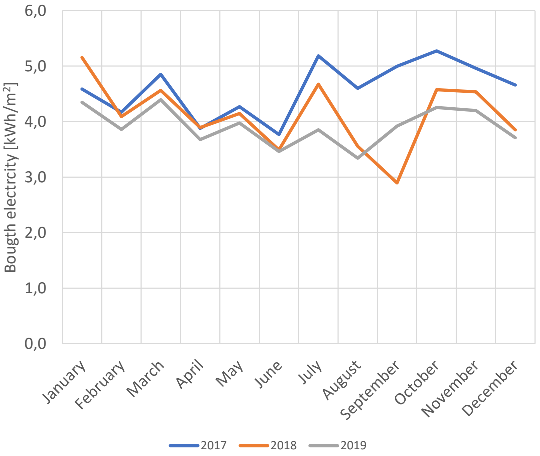

Figure 35: School 1 bought electricity [kWh/m^2] for the years 2017-2019.

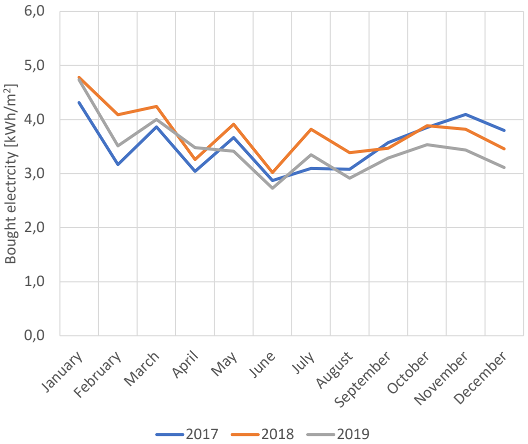

Figure 36: School 2 bought electricity [kWh/m^2] for the years 2017-2019.

Contrary to the EPCs, the bought electricity use includes the tenants' electricity use, thereby it is not fully comparable to the electricity use intensity investigated in the EPCs. Nevertheless it is still interesting to see the trends between the schools when it comes to bought electricity. The electricity use intensity holds a very steady level throughout the year where peaks and lows can be noted every other month. This trend can be seen in both schools. The information obtained by the local administration is that the ventilation system is off during the summer and there is no other use than possibly 1 week in summer when the school is occupied for a football cup. The reason why the electricity use is as high during the summer could not be explained by the local administration. The after-school care centers are open during June and August but they only account for a small part of the buildings. The classrooms are not used during the whole summer. The reason why the schools still purchase electricity during this period could not be clarified. If the ventilation or lighting was on, it could explain the electricity use.

Table 14: Bought electricity per square meter for three years and the average

Year	School 1 [kWh/m^2]	School 2 [kWh/m^2]
2017	55	42
2018	49	45
2019	47	42
Average	51	43
EPC value (normalized)	16	26

It can be noted from the average bought electricity in table 14 that school 1 consumes more electricity per square meter than school 2, which seems is opposite to the trend EPC discloses, although EPC only considers property electricity. Since the bought electricity includes both the tenant electricity use and the property electricity use, it can not be concluded that this result contradicts the EPC. Hong et al. [40] showed the larger the school is, the more electricity is used, and the reasoning behind that is that larger schools are often secondary schools and they have higher electricity use intensity. Both examined schools have students from years 7-9 (secondary school), but it is unknown how much of the schools are occupied by older students who need more electrical equipment. The EPC for school 2 provides the tenant electricity use intensity; thereby, a fraction can be derived for property electricity use intensity and total electricity use intensity. This information could not be obtained in school 1. Thereby the same faction, 42%, is used for both schools. The estimated property electricity use intensity is 21 kWh/m^2 and 18 kWh/m^2 for schools 1 and 2, respectively. School 1 has lower estimated property electricity use in the EPC compared to estimated while school 2 has a higher value.

In addition to the trends in the figures 33, 34, 35 and 36 and values from table 13 and 14, trends for the schools within the same year can be further and more closely seen in figure 37, 38 for 2017. The bought heating is basically the same, while the electricity use intensity for school 1 is higher.

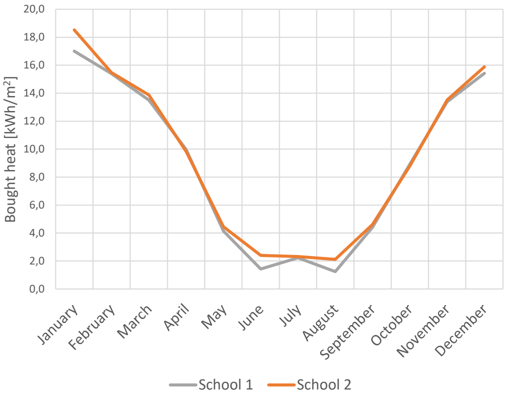

Figure 37: Bought heating energy [kWh/m^2] for two schools in 2017

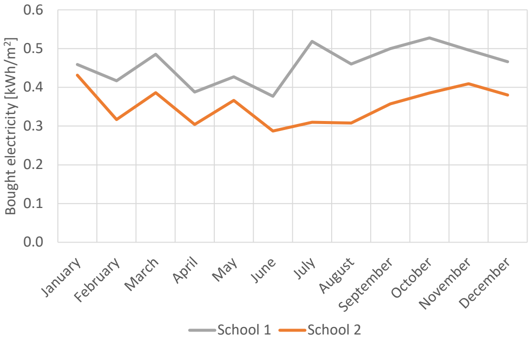

Figure 38: Bought electricity [kWh/m^2] for two schools in 2017

6.1.2 Modeled energy use

Input values of known variables were put in the IDA ICE to model, and for the unknown values standard value were inserted, see table 10. This information generates baseline models where the results can be observed in table 15. Since the modeled heated area diverged from the EPC heated area for school 2, the modeled output will be compared with the energy use in kWh instead of kWh/m^2 in the EPCs. The modeled HVAC electricity use is compared with the property electricity use.

Table 15: Building simulation results - Energy use generated by baseline model in IDA ICE compared with EPC values and the average of measured values

	School 1	Deviance to EPC	Deviance to average measured value	School 2	Deviance EPC	Deviance to average measured value*
Heating use [kWh]	288 347			183 576		
heating use intensity [kWh/m^2]	84	-19%	-13%	116	-19%	+20%
Property electricity use intensity [kWh]	62 099			30 302		
Property electricity use intensity [kWh/m^2]	18	+14%	-	19	-21%	-
Total energy use [kWh]	350 447			213 878		
Energy performance [kWh/m^2]	103	-14%	-	135	-19%	-

The results state that there are some deviances between the modeled results and the EPC results as well as the average measured bought values between the years 2017-2019. The average measured bought values is marked with a (*) in table 15 because they have not been normalized, therefore it should be taken with caution. Electricity has not been compared with average measured bought value since tenant electricity is included in measurements, and a comparison of that would be misleading. School 1 has -19%, +14%, and -14% deviance from EPC for heating use intensity, electricity use intensity, and energy performance, respectively. This can be compared with school 2 deviance to EPC, which is -19%, -21% and -19% for heating use intensity, electricity use intensity and energy performance, respectively. What is interesting with school 2 is that the modeled heating use intensity is 20% lower than EPC and 20% higher than the average bought heating in 2017-2019. Comparing the modeled results of the two schools, it can be seen that models underestimate heating, electricity and energy use intensity compared with the EPCs in most cases, except the electricity use intensity for school 1 which is overestimated. School 1 has a smart ventilation system which has not been adapted in the model due limitations, which can explain the overestimation in the model. Both schools have similar modeled electricity use intensity, but the EPC electricity use intensity is notably greater for school 2, which needs further investigation. It is clear in table 15 that school 2 deviates more from the EPC. Most of the property electricity comes from the fans [10], and new fans were installed in late 2014, thereby the electricity use could have been reduced. Also, the ventilation system was proposed to be adjusted according to EPC; it may have been adopted.

6.1.3 Comparison of building characteristics

Information about the building characteristics is presented in table 16 which has been extracted from building simulation, drawings and measurements conducted by a research group at the division of building services Engineering at Chalmers linking indoor quality and energy performance. U-values, WWR and S/V-ratio were retrieved from building simulation results. Building geometries and maximum occupied density and occupied area compared to heated area, are from drawings. Average measured classroom temperature and air exchange rate are retrieved from measurements conducted by research group mentioned above. The light color highlights are especially interesting characteristics of the buildings where they align with each other and the grey marked rows are where they deviate from each other.

Table 16: Building simulation results and layout comparison-Building characteristics

Building characterictics	**School 1**	**School 2**
U-value external wall [W/m^{2}K]	0.45	0.45
U-value roof [W/m^{2}K]	0.27	0.20
U-value external floor [W/m^{2}K]	0.40	0.60
U-value windows [W/m^{2}K]	1.9 (3-pane)	2.80 (2-pane)
U-value of building [W/m^{2}K]	0.61	0.61
WWR [%]	12.8	7.3
Area of windows [m^2]	473	211
Direction windows [m^2]	E: 219.15 W: 253.85	ESE:176.67 WNW: 34.81
Heights of classrooms [m]	2.8	2.8
S/V-ratio[m^2/m^3]	0.34	0.42
Average measured temperature classroom [°C]	20.5	19.8
Average measured air exchange rate classroom [1/h]	2.55	2.35
Maximum occupied density [occupants/m2]	0.19	0.14
Occupied area /tot area	0.60	0.66
Classroom area/heated area	0.32	0.35
Heated area A$_{temp}$ [m^2]	3410	1578

The overall U-values of buildings are the same, although there are some differences in the building component U-values. School 1 has 3 pane windows with a presumed U-value of 1.9 W/m^2,K, which were installed in 1991, while school 2 keeps the original windows since 1968. The U-values for roof and external floor differ slightly; school 1 has a higher U-value for roof and school 2 has higher for the external floor, and they stand for 12.9 % and 13.3 % of the transmission heat losses, respectively.

School 1 has a significantly lower window U-value but still manages to have the same average building U-value. It can be explained by the window to wall ratio (WWR), of which school 1 has almost double compared to school 2, see table 16. Both long sides of school 1 building are window dense, unlike school 2, which only has one window dense side. This can be observed in figure 28 taken during the inspection, a quantitative description can be seen in table 16 in "direction windows" where the window areas are distributed to their respective facade. School 1 has 219 m^2 and 254 m^2 facing east and west, while school 2 has 177 m^2 and 35 m^2 facing east-southeast and west-northwest. Whether the window is the factor or one of the factors to why the energy performance is different will be further evaluated in later chapters.

Both schools have their windows facing east and west, although school 2 has a slight shift to the south-north axis, it is mostly facing the east and west side. The most prevalent wind direction during heating season is from the south side, so both building have an advantage when it comes to window direction. School 2 might have a small disadvantage.

In table 16 the occupied area by the total heated area A_{temp}, classroom area by heated area and maximum occupied density are investigated to see if the use of the building varies. For example, if one school has significantly larger corridor areas compared to classrooms, it might be a reason to believe the energy performance gets affected. According to a British study on schools, it could be concluded that larger schools tend to have lower heating use and, this is explained by the author that it could be due to larger schools have different use and thereby lower intensity in some places [40]. The three variables can be seen in table 16, from which it can be concluded that there are no large differences between the schools.

School 1 is approximately twice as large as school 2 and it has 16 classrooms while school 2 has 8. The ratio between occupied area and heated area differs by 0.06 and and classroom and heated area differs by 0.03. These ratios have been obtained by comparing the layout of the buildings from drawings. The building drawings further state maximum people in each room so that was compared, and the maximum density of the schools was 0.19 and 0.14 respectively for school 1 and school 2. This is the max occupants given in the drawings so it doesn't necessarily give the actual occupancy today. For both schools, the real occupancy in each classroom was not possible to check. Assuming the same amount per classroom in both schools, it could be stated that it doesn't differ significantly. Generally, the number of students in classrooms does not differ between schools, and is around 20. In that case, the occupancy densities are 0.1 pp/m^2 for both schools.

Since this analysis indicated there is no difference of use in the buildings, the difference in hot water use stated in table 12 can be further questioned.

In table 16, the modeled heated area can be obtained. It can be noted that, when compared with the information given by EPC, the modeled area is different. For school 1 it differs marginally, 0.4% and it can be said that the EPC area is aligned with what is obtained from the drawings. In school 2 the modeled area is 6.3% larger from the EPC. The modeled area was derived from the drawings of the building together with observation during the inspection. It was assumed that 56% of the basement was unused thereby unheated, since it looked like a storage area. Since no measurements could be done due to lack of access, it is not certain if it was heated or not. However, based on the observations made during the inspection, it did not seem to be used. A temperature measurement was taken in the accessible parts to evaluate if it was close to the temperature in other heated rooms.

The heated area affects the energy performance value. If the whole basement was included in the heated area the modeled heated would be 2026 m^2. If the same A_{temp} was to be used in the EPC the energy performance would be 167 kWh/m^2 instead of 178 kWh/m^2. There is a possibility that the modeled area is overestimated or the

EPC area is underestimated, but either way it affects the intensity significantly.

In table 17 the contributions of the energy losses in the building can be seen, based on the baseline model simulation results. Envelope component and thermal bridge losses are shown in percentage of the total heating losses.

Table 17: Building simulation results - Heat losses of the two buildings and their envelope components heat losses

Heat loss	School 1	School 2
Envelope and thermal bridges	55%	70%
-*External walls*	*12%*	*21%*
-*Windows*	*22%*	*23%*
-*Thermal bridges*	*12%*	*15%*
-*Roofs*	*6%*	*5%*
-*External floors*	*3%*	*4%*
Mechanical ventilation	37%	22%
Window opening and infiltration	6%	6%
Hot water use	2%	2%
Total heat loss	100%	100%

What is interesting with school 2 is that envelope heat losses are significantly higher for school 2 where most of the energy losses come from the windows followed by external walls. Additionally, the energy performance value for school 2 from the EPC is higher. Although the U-values for both schools are the same for the external walls, the heat loss contribution from external walls for school 2 is significantly higher. The total heat loss is also higher for school 2. The reason for the higher percentage of external wall heat loss for school 2 could be a higher wall ratio and higher S/V-ratio. S/V-ratio can be one of the factors describing the difference in energy use, and it will be further assessed in later chapters.

The details of envelope and thermal bridges heat losses are interesting. Figure 39 and figure 40 draws the fractions of each source of contribution to envelope heat losses for both schools in pie charts.

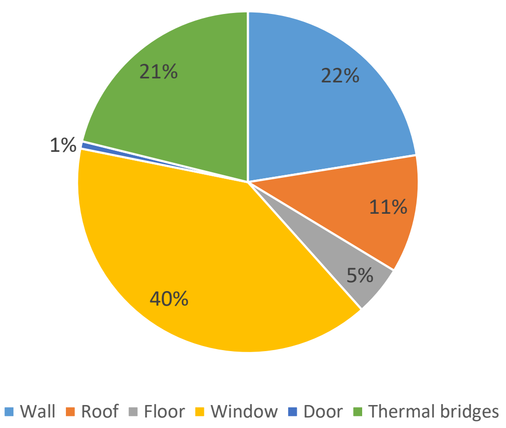

Figure 39: Building simulation results- Heat loss from envelope divided by their respective envelope component contribution for school 1

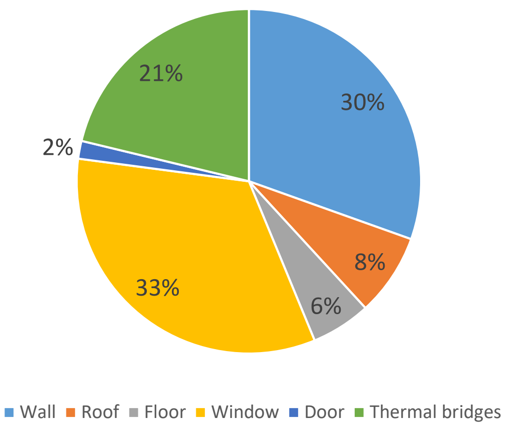

Figure 40: Building simulation results- Heat loss from envelope divided by their respective envelope component contribution for school 2

As listed in table 16, the S/V-ratios of the buildings differentiate. And that may explain why the schools perform differently. School 1 has S/V-ratio of 0.34 m^2/m^2 while school 2 has 0.42 m^2/m^2. Hong et al. [40] found that one of the most important factors contributing to energy use is compactness which is determined by S/V-ratio. Smaller S/V-ratio indicated more compactness of the building which generates less envelope losses. School 1 has lower energy use than school 2 so it is inline with the finding. However, it can not be said that this is the reason why it performs differently.

The S/V-ratio is an interesting factor to discuss, but the units for energy indicators are usually kWh/m^2, making quantifying the influence from the S/V-ratio more difficult. In order to explain in a physically meaningful way, envelope area to floor ratio is discussed. This ratio is closely related to S/V-ratio because the volume of the building is largely dependent on the floor area. It could be seen as an indicator of the compactness of the buildings.

The heating losses in table 17 are divided into two categories based on their origins in table 18. Envelope, thermal bridges, window openings and infiltration are categorized as envelope-related losses because they are directly related to envelope area. Mechanical ventilation and hot water use are categorized as floor-related losses because they are related to indoor activities.

The extract airflow for school 1 is 30% higher than the supply, and heating loss because of the unbalanced flow is categorized as ventilation losses, although it seems to come from infiltration. This is because if imagine a balanced ventilation system where the supply is 30% higher, that part of heat losses would be undertaken by the ventilation system. The supply or extract flows for school 2 are unknown due to lack of information, which is an added uncertainty; thereby, the airflow is defined according to Sveby requirements together with airflow measurement.

Table 18: Building simulation results - Heat losses categorized by floor-related and envelope-related

	School 1	School 2
Total heat loss (per floor area) [kWh/m^2]	88	112
Heat losses related to floor area (per floor area) [kWh/m^2]	35	27
Heat losses related to envelope (per floor area) [kWh/m^2]	54	85
Heat losses related to envelope (per envelope area) [kWh/m^2]	50	46
Envelope to floor ratio ([m^2/m^2])	1.08 (3698/3410)	1.85 (2912/1578)

The heat losses from envelope per envelope area of two schools are very close, which can be explained by their close overall U-value, as mentioned in table 16. However, if heat losses are divided by floor area, school 2 has a much larger value. This is due to their different envelope to floor area ratio, with school 2 having a higher ratio of the envelope area than school 1. When comparing the energy performance, however, all energy is divided by floor area. Each square meter of floor in school 1 undertakes 1.08 m^2 of the envelope, while each square meter of floor in school 2 undertakes 1.85 m^2 of the envelope.

6.2 Effect of differentiating factors in energy use

To investigate where the difference in performance between the two schools comes from, stated differentiating characteristics of the school buildings are adapted to the other school building. The results of this analysis will give some ideas of if the difference can be explained by these factors. Investigated factors are windows, S/V-ratio and setpoint temperature.

The U-values of windows are 1.9 W/m^{2}K and 2.9 W/m^{2}K for the two schools, respectively. This baseline will be compared with two scenarios: first, if school 2 renovated its windows to school 1 windows and second, a scenario before the renovation of school 1 to see if worse windows could explain school 1's performance. The results are listed in table 19.

Table 19: Building simulation results: Window U-value scenarios compared to baseline

W/m^{2}K	Heating use intensity school 1 [kWh/m^2]	Heating use intensity school 2 [kWh/m^2]	Differences in between [kWh/m^2]	Gap change
Baseline (U_1=1.9, U_2=2.9)	82	118	36 (44%)	-
Renovate school 2 (U_1=1.9, U_2=1.9)	82	110	28 (34%)	-22%
Before renovation (U_1=2.9, U_2=2.9)	89	118	29 (33%)	-20%

The comparison of 3 scenarios shows the difference of window may be one of the factors explaining the difference of performance. It can explain 8 kWh/m^2 out of 36 kWh/m^2 difference. This closes the gap between the schools heating use intensity with 22% .

As the setpoint is very sensitive and the difference is large in between, a comparison between schools where they have the same temperature is listed in table 20. School 2 has a lower temperature in the room but higher heating use intensity. The difference becomes even more prominent when they have the same temperature setpoint.

Table 20: Scenarios when schools having the same set-point temperature, and the heating difference in between

°C	Heating use intensity school 1 [kWh/m^2]	Heating heat loss school 2 [kWh/m^2]	Differences in between [kWh/m^2]	Gap change
Baseline (T_1=20.55, T_2=19.8)	82	114	32 (39%)	-
Case 1 (T_1=21, T_2=21)	85	128	43 (51%)	+34%
Case 2 (T_1=19, T_2=19)	74	106	32 (43%)	0%

It is interesting to investigate whether S/V-ratio explains the varied energy performance. The S/V-ratio is higher for school 2. Also, it could be noted that school 2 had a higher envelope losses percentage than school 1. This was investigated by reforming the corridors of school 2, so that the width of the building is increased, which would increase the S/V-ratio and make the building more cube-like. In scenarios 1 and 2, corridors are 4 m and 7 m longer respectively. The investigated output is the heat loss from the envelope. The heating use intensity is not used since it is dependent on many other factors except envelope losses, such as supply air heating and occupancy. Other factors are not considered in the analysis for simplification. The results are demonstrated in table 21.

Table 21: Scenarios when schools having close S/V

S/V ratio	Envelope heat loss school 1 [kWh/m^2]	Envelope heat loss school 2 [kWh/m^2]	Differences in between [kWh/m^2]	Gap change
Baseline (S/V_1=0.34, S/V_2=0.42)	48	78	30(63%)	-
Scenario 1 (S/V_1=0.34, S/V_2=0.37)	48	65	17(35%)	-43%
Scenario 2 (S/V_1=0.34, S/V_2=0.34)	48	56	8(17%)	-73%

It can be noted that decreasing the S/V ratio shrinks the gap between the envelope losses per square meter of the two buildings. This indicates that the S/V ratio can be one of the factors contributing to the difference in performance. It can be seen that the gap between the envelope heat loss between the schools decreased by 73% when adapting the same S/V-ratio. One detail noted when investigating this issue is that these changes in the model changed other variables such as WWR. Consequently, the overall U-value of the building was affected. The U-value of the building was 0.61 W/m^{2}K in the baseline, and in scenarios 1 and 2 it decreased to 0.56 W/ m^{2}K and 0.53W/m^{2}K. This would also have an effect decrease of heat loss. The WWR decreased from 7.3% to 6% and 5.3% respectively for the scenarios.

6.3 Sensitivity analysis

In order to understand the impact of each input parameter on heating use-, electricity use- and energy use intensity in the selected buildings, sensitivity analyses was conducted. Furthermore, it helps to understand the difference in performance between the schools. For the development of scenarios to be simulated, the input parameters were divided into 4 categories: HVAC factors, occupant-related factors, operational factors, and building characteristics factors. Some factors are uncertain and some factors are known.

In order to match with the EPC values, the IDA ICE model of schools 1 should have 26% higher heating use intensity and 12% lower electricity use intensity; school 2 should have 23% higher heating use intensity and 27% higher electricity use intensity%. The input of baseline can be seen in chapter 5. Different horizontal bars are marked in the figures in this section, see figure 41 and 42, indicating deviations of the baseline from the EPC. Blue and orange horizontal lines stand for electricity use intensity goal and heating use intensity goal from EPC, respectively. Heating use and electricity use written in this chapter refer to building heating use intensity and property electricity use intensity for short, especially in the figures. The red marker on the x-axis demonstrates where the baseline is.

6.3.1 HVAC factors

Analyzed HVAC factors include SFP and heat exchanger efficiency. In both cases the baseline values are assumed for school 2. See figure 41 and figure 42 for school 1 and 2 respectively.

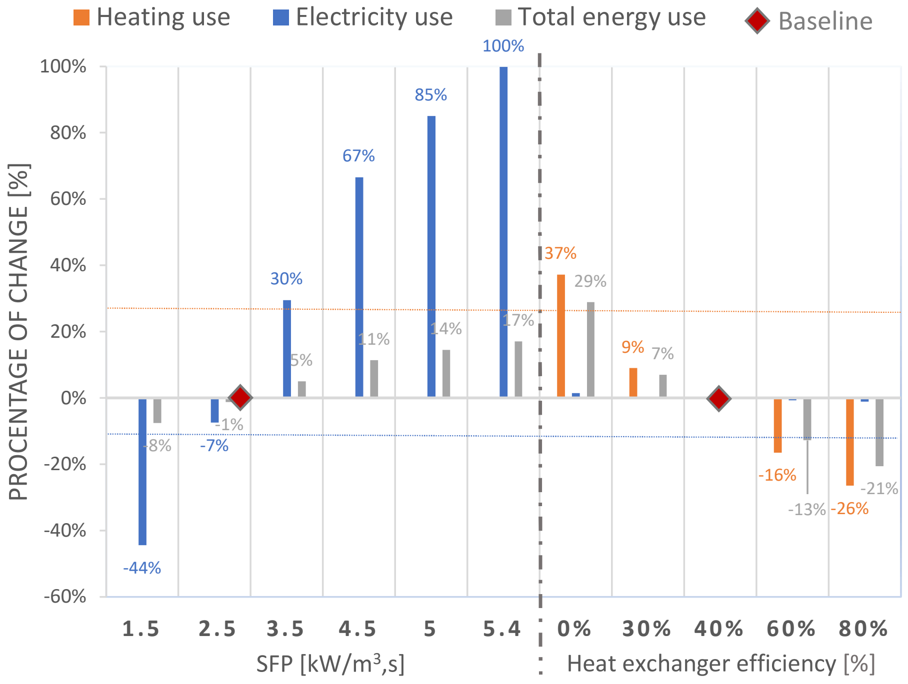

Figure 41: Sensitivity analysis on HVAC factors of school 1.

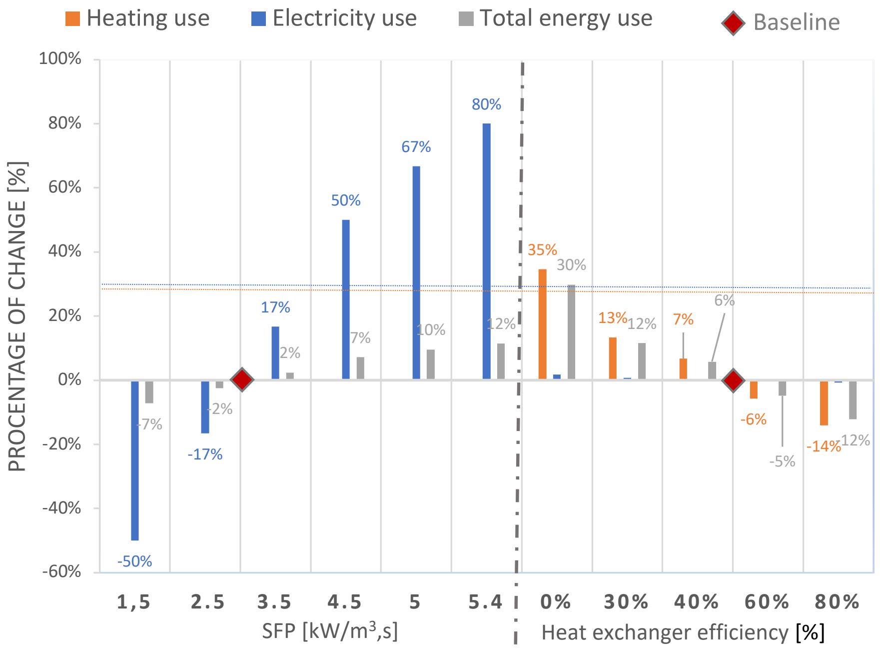

Figure 42: Sensitivity analysis on HVAC factors of school 2.

Tested SFP values range from 1.5 kW/m^3.s to 5.4 kW/m^3.s. 1.5 kW/m^3 is the highest possible value according to BBR for new buildings [65], which is in this analysis an indicator for possible renovation target value. 5.4 kW/m^3 is the value calculated from school 2's OVK, and it can be noted that the modeled electricity use intensity with this value would be much higher than the electricity use intensity in EPC, as can be seen in figure 44. The value of 5.4 is anyway too high, suggesting possible issues with data provided in the OVK.

Both figures 41 and 42 show a clear sensitivity for electricity use intensity to SFP. According to STIL2 report, [10], SFP is the dominant part in electricity use intensity. Reductions of more than 30% electricity use is possible to be achieved in both schools if a fan that is 1 kW/m^3,s more efficient is used. 2-2.5 kW/m^3,s is the common value for renovated buildings, which would lead to promising energy savings.

Efficiencies of heat exchangers are tested from 0% to 80%, from no installation of heat recovery unit, or non-functioning unit, to the standard value used in the design of new schools in Gothenburg city [64]. School 1 has 40% efficiency while it is assumed to be 50% for school 2. Efficiency has a very important influence on heating use. The heat recovery systems already save 35% and 37% heating in these schools, indicating their importance. This can be seen in figure 41 and 42 when the heat recovery is set to 0%. School 1 could save 26% heating if an 80% heat exchanger could be installed, while school 2 could save 14%. The difference of savings between the schools is dependent on the baseline setpoint, school 2 has an assumed efficiency of 50% since no data is available for the ventilation system. If the actual heat recovery efficiency is lower than assumed, more saving can be gained.

6.3.2 Operational factors

The following operational factors are discussed: temperature setpoint, ventilation system setpoint, and nighttime setback temperature. See figure 43 and figure 44 for school 1 and 2 respectively. The ventilation system setpoint for school 2 is unknown. Other factors are known.

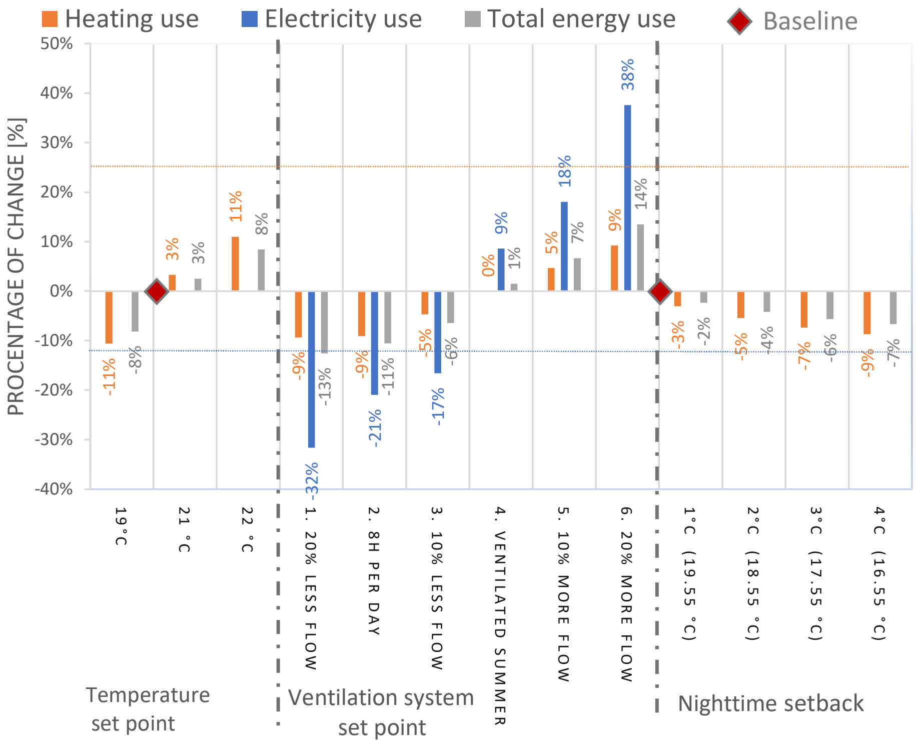

Figure 43: Sensitivity analysis on operational factors of school 1.

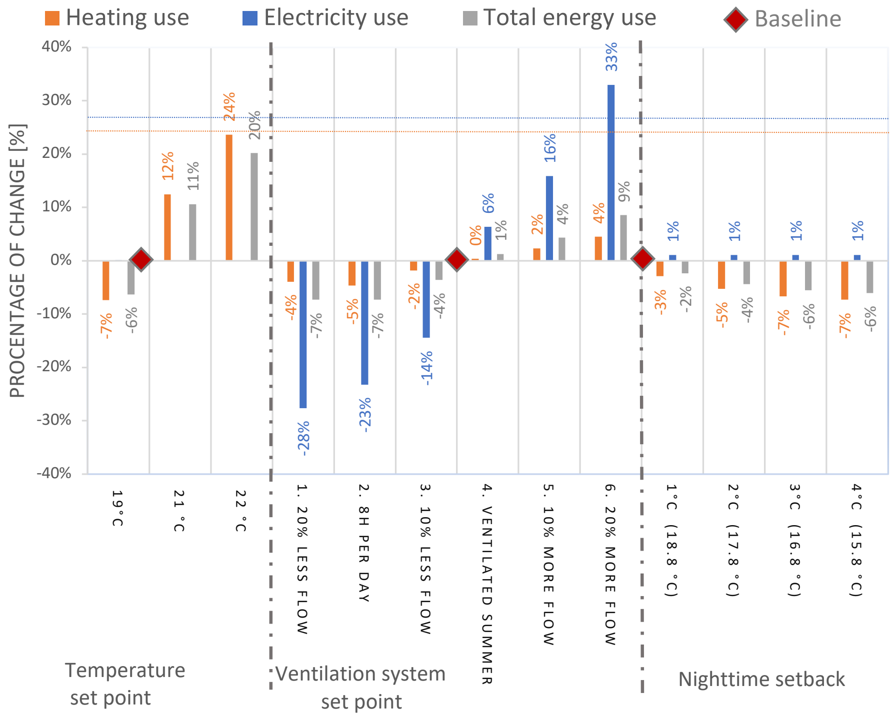

Figure 44: Sensitivity analysis on operational factors of school 2.

The heating set temperature is tested from 19°C to 22°C. 20-22°C are the temperature required in schools and universities; 22°C is required for primary schools [66]; since school 2 has a measured value lower than 20°C (see table 10), 19°C is added to see the energy performance in a theoretically less comfortable condition. The result shows that in both schools, the setpoint temperature is positively related to heating use intensity. 1°C higher setpoint induces around 7% more heating in school 1 and 12% for school 2. This difference is possible because school 2 has a higher S/V ratio, and heat losses through the envelope are more dominant regarding the envelope heat losses.

The tested scenarios regarding the ventilation system air flow dimensioning or scheduling include, different dimensions of flow rates ranging from -20% to +20% of the set air flow in the baseline, reduced ventilation time to 8 hours, and adding ventilation schedule in the summer. Varying the flow rate is interesting because the flow rate for school 2 is uncertain, and EPC states that a balancing of ventilation system is needed. It can be seen in figure 43 and 44 that the flow contributes to the increase of heating use, and it has a higher impact on school 1, which might be explained by its less efficient heat exchanger. The ventilation flow is a sensitive parameter for electricity, as the increases of electricity are significant for both schools. The changes of electricity in percentage are around the same.

Adding ventilation in summer is to simulate the influence of possible summer activities. From the bought electricity in figure 38, it could be observed that the consumed electricity does not have a significant drop during summer, which seems to conflict with the information from school personnel that the ventilation is off most of the time during summer. After adding about 1-month ventilation, the heating does not increase while the electricity use intensity increased 9% and 6% respectively. Ventilation in summer does not impact the heating use, since summer is not a heating season.

A reduced ventilation schedule is modeled to investigate the possible strategy for saving energy. This is especially interesting since Sveby user data for school buildings [42] suggest scheduling 8h/day. When ventilation reduces from 12 hours to 8 hours, i.e., 33% reduction of time, schools have 21% and 23% lower electricity use. Schools have 9% and 5% lower heating use respectively, the difference comes from the heat exchanger efficiency. Such a measure however should be carefully evaluated with respect to potential negative effect on indoor air quality.

The third part is the nighttime setback analysis. It is very unlikely that those schools have such an operation scheme. In Sveby standards, it is stated that night time could occur to optimize the operation [42], therefore it could be an suggestion for these buildings. In modeled scenarios with nighttime setbacks, the thermostats are set to be several degrees lower after school time and turned back to the setpoint temperature 3 hours before schools begin. Buildings are not used during the night, so it will not cause any discomforts to occupants. The values in the brackets correspond to room setpoint temperatures. In both schools, 1 °C setback can reduce heating use by 2%. The setback temperature is remarkably less of a sensitive factor compared to the room setpoint temperature. The nighttime setback duration is around half of the day, but the influence from 1 °C nighttime setback is less than half of the influence from 1 °C heating setpoint change. This is due to the absence of ventilation during the setback time, which means that the heating need at night is lower.

6.3.3 Occupant-related factors

Occupant-related factors include shading, window opening schedule and occupancy density. Figure 45 and figure 46 illustrate the analysis for the two schools. For both schools, the first two are unknown factors, the third is inferred from the drawings.

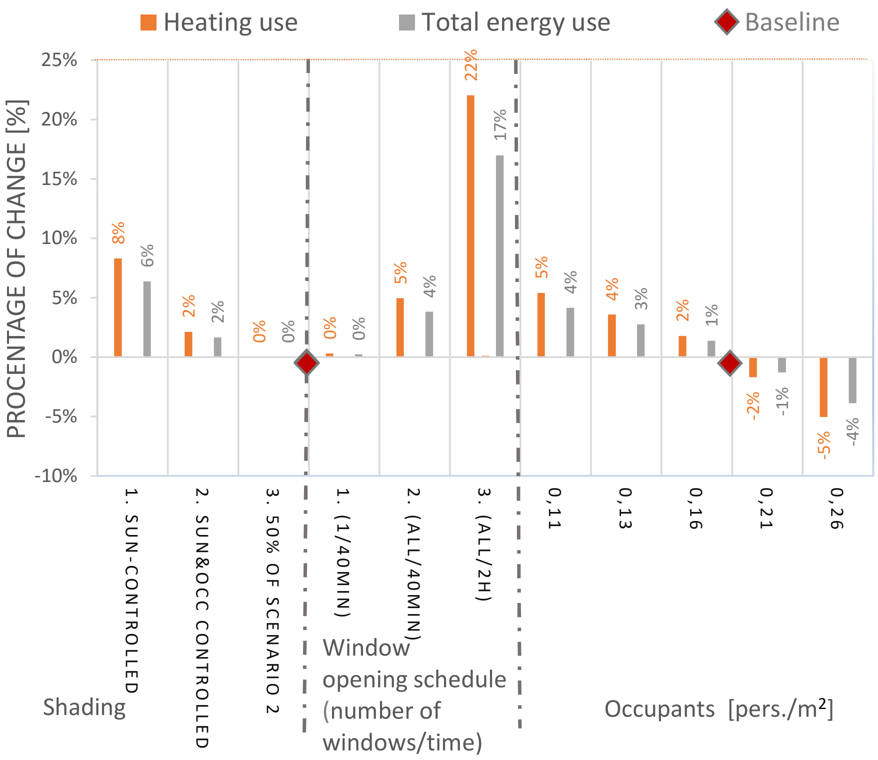

Figure 45: Sensitivity analysis on occupant-related factors of school 1.

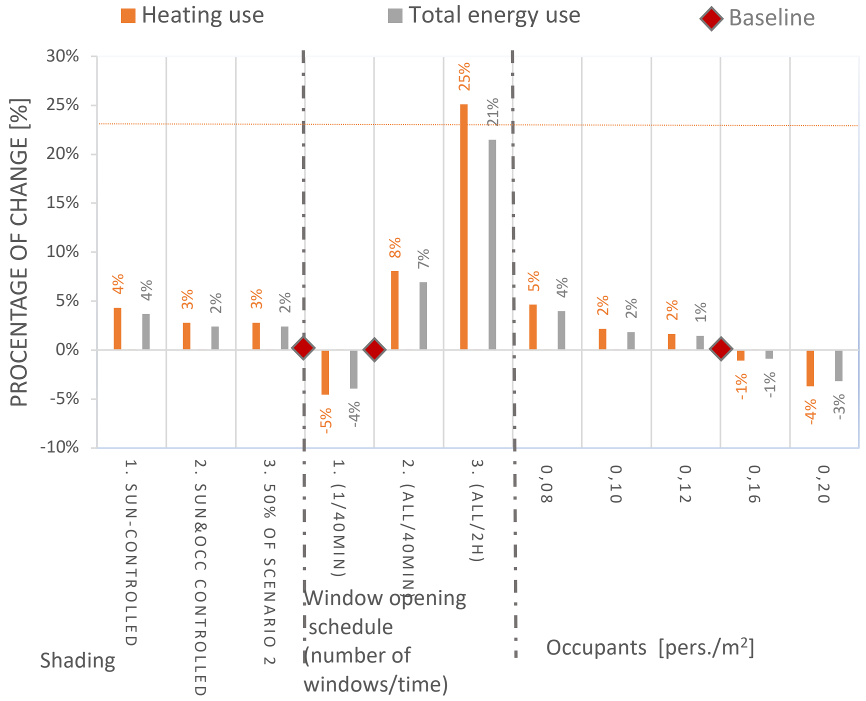

Figure 46: Sensitivity analysis on occupant-related factors of school 2.

Proper shading could provide visual comfort as well as lower peak heat gains. There are observed shadings between panes in both schools, but the control is unpredictable. There are uncertainties of how and when people use blinds. In the inspection, it was apparent that blinds were not drawn entirely. Three shading scenarios are simulated:

- The first scenario is that operation of all blinds is controlled merely by the sun, which means the blinds are drawn when the solar radiation is above 100 W/m^2 [62].
- The second scenario is that all blinds are sun and occupancy-controlled. During occupied hours, i.e., from 8-11 and 12-15 o'clock, blinds can be drawn if the radiation reaches 100 W/m^2.
- The last scenario investigates when only half of the blinds can be drawn. The last scenario is investigated since blinds are totally occupant controlled.

Regarding the first scenario, it can be seen the heating use of school 1 is more sensitive regarding the shading. The solar radiation is a more important heat source for school 1. The reduction of solar gain due to shading is more significant because school 1 has more windows.

For school 2, occupant control plays a more important role in shading. This is related to the orientations of the building. School 1 has big windows on the east and west facade, so in the early morning and late afternoon, i.e., before 8 and after 15, the school receives much solar radiation when blinds can not be controlled due to the absence of people. Furthermore, school 2 has fewer windows generally, especially in the west facade. Since the east facade is east-south to be exact, it receives radiation later than school 1's east facade. So when the school 2 is receiving the sun, it is mainly during occupied hours, i.e., 8-15 o'clock. In scenario 3, school 1 has nearly no increase of heating use while school 2 has a close value as in earlier cases, which emphasizes again that school 1 mainly gets solar radiation when people are not there.

The second part of occupant-related factors analysis is focus on window opening where three window opening schedules are studied. The opening degree of every window assumed to be 30%. The number before the slash indicates how many windows are controlled per room. The number after the slash is the total opening duration in one day. The fenestration times are divided into two and distributed during the day. The three scenarios are:

- The first scenario is that one window opens per room for 40 minutes everyday.
- The second scenario is that all the windows are open for 40 minutes everyday.
- The last scenario is that all the windows are open for 2 hours everyday.

It is interesting to see the output of the first scenario for school 1 corresponds to the window-induced heat losses value from the recommended input by Sveby [42], which is 4 kWh/m^2; while for school 2 it is lower than the recommendation. This may be due to school 1 having smaller rooms, hence 1 window per room corresponding to more windows and the percentage of opened windows were higher in school 1.

In the second and third scenarios, school 2's heating use intensity is a bit more sensible than school 1's. Overall, window opening is a sensitive factor. During the inspection,it was observed that opening of the window is very common in school 1, but not for school 2. It is, therefore, reasonable to assume a higher duration of window opening for school 1.

The third part of the analysis includes the variances of occupancy density. The estimated occupancy density is close between the two schools. The densities in person per square meter are stated in the axis. The occupancy density is around the same sensitivity for both schools; every 1/7 of change in input induces around 1-2% of heating change.

6.3.4 Building characteristic factors

The three building characteristic factors analyzed in this part are thermal bridges, U-values of windows and of walls. The first factor is unknown, the rest are known. The figure 47 and figure 48 are the results for school 1 and 2. It can be seen that only the heating use is affected.

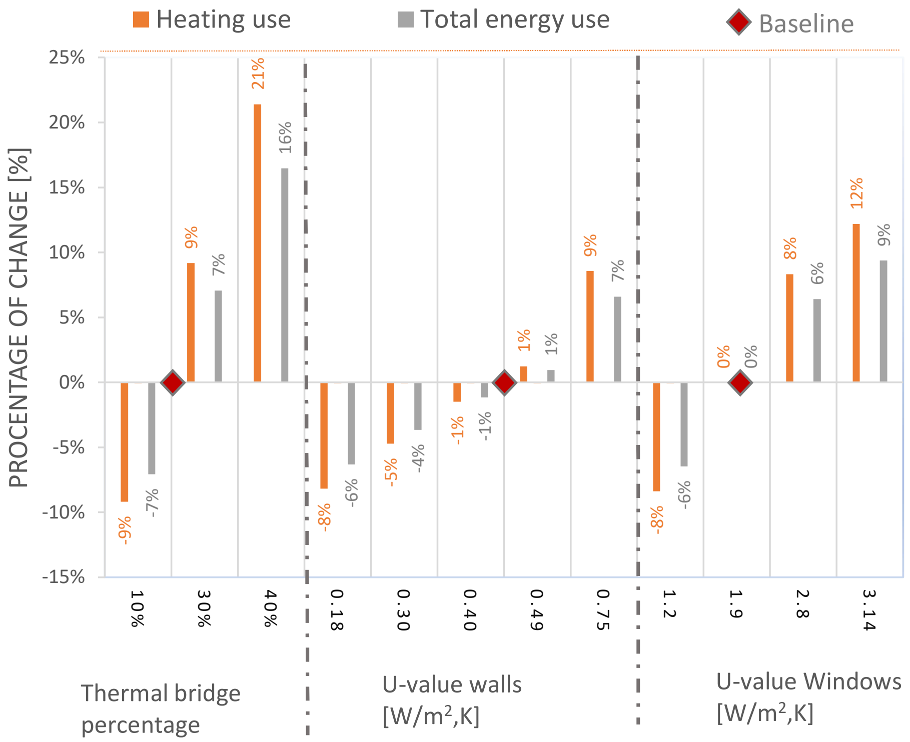

Figure 47: Sensitivity analysis on building characteristic factors of school 1.

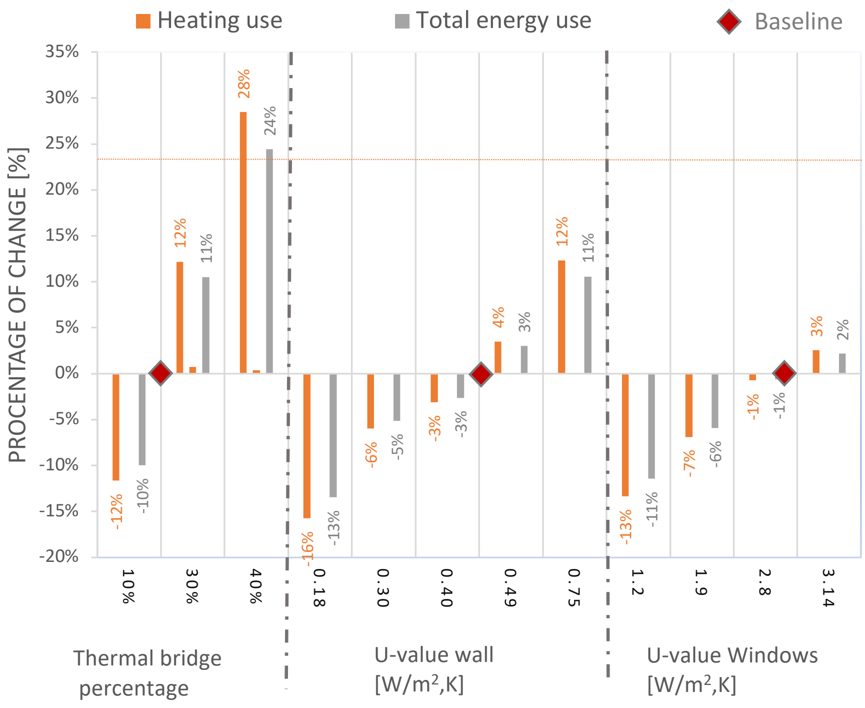

Figure 48: Sensitivity analysis on building characteristic factors of school 2.

The presumed baseline value for thermal bridges is 20% of the envelope heat losses [59], which is normally used for modeling. The degradation degree of the buildings is unknown and therefore tested. The U-values of when thermal bridges are 10%, 20%, 30%, 40% of the envelope heat losses are obtained from iterative input thermal bridge U-value. It can be seen that thermal bridges make a remarkable impact on energy use. The correspondence of the extreme value 40% to reality could be questioned. For both schools, the U-value of thermal bridges would have to reach 0.32 K/m^2 to be 40% of the envelope heating loss, which is significantly higher than 0.21 K/m^2 which gives 20%. Since further measurements are not done, and no information is available, it is better to keep the thermal bridge ratio not far away from the typically implemented.

Several U-values of walls are tested, from 0.18 W/m^{2}K [65], the standard recommendation according to BBR for today's new building, to 0.75 W/m^{2}K which represents a bad wall condition. It can be seen that school 2's heating is more sensible to the U-value of the wall. This can be explained by the higher heat loss percentage from walls. The original U-values are the same for the 2 schools. No further measurements are done, and no documentation of envelope renovation is received, but it is possible for the schools to have the same degradation since they are built in the same period. The U-value of 0.4 W/m^{2}K and 0.49 W/m^{2}K is tested to see the impact of chosen insulation since there were 3 qualities of that material. It showed to have only 1% change. It can be noted from the figures 47 and 48, that there is a saving potential of -8% or -16% is possible if the external walls are renovated to today's standards, or even better.

The U-values of windows range from 1.2 W/m^{2}K, which meets today's standard [65], to 3.14 W/m^{2}K [58], the worst windows possible during the time when schools were built. Window U-values are very sensitive, especially for school 1, which has more windows. 1 W/m^{2}K lower U-value could save around 7% heating for school 2 and higher than 8% for school 1. This parameter is very interesting because it is sensitive and different between these schools.

6.3.5 Summary

In order to differentiate among important factors, a list has been constructed with the factors which quantitatively contribute the most to the output. This is highly dependent on the range of input and it has been decided based on different factors; they are not necessarily comparable. Therefore, a qualitative assessment needs to be executed additionally. Nevertheless, the table gives some indications of essential factors. This list is exclusive to the analyzed buildings given the input, not giving a general ranking of factors. Only the factors that have the most effect are presented. The ranking for heating use intensity is listed in table 22.

Table 22: Ranking of factors for heating ordered by per unit

Important factors	**School 1 Heating**	Approximate change per unit compared to baseline	Category	**School 2**	Approximate change per unit compared to baseline	Category
1	**Heat recovery efficiency**	*8,3% output change per 10% HR-efficiency [1] change*	*HVAC factor*	**Temperature setpoint**	*7% output change per 1 °Cchange*	*Operational factors*
2	**Temperature setpoint**	*7% output change per 1 °Cchange*	*Operational factors*	**Window opening**	*8% increases % for 40 min all windows*	*Occupant related factors*
3	**U-values windows**	*5% change per 0,5W/m^2, K*	*Building characteristics*	**Heat recovery efficiency**	*6,3% output change per 10% HR-efficiency change*	*HVAC factor*
4	**Window opening**	*5% increases % for 40 min all windows*	*Occupant related factors*	**Thermal bridge**	*6% change in output per 5% change*	*Building characteristics*
5	**Thermal bridge**	*4,5% change in output per 5% change*	*Building characteristics*	**U-values walls**	*5% change per 0,1 W/m^2,K*	*Buildings characteristics*
6	**Ventilation flow**	*4,5% change per 10% change in ventilation setpoint*	*Operational factors*	**U-values windows**	*4% change per 0,5W/m^2,K*	*Building characteristics*
7	**U-values walls**	*3% change per 0,1 W/m^2,K*	*Buildings characteristics*	**Ventilation flow**	*2% change per 10% change in ventilation setpoint*	*Operational factors*

The ranking has been done where the input has been adjusted to the input unit, although the input range has not been standardized this can show some information of how the different factors affect the buildings respectively. For example the heat exchanger efficiency is the most important factor for school 1 while for school 2 it is the third. This is might be due to higher flows in school 1, thereby higher heating use of AHU, or due to the lower heat recovery efficiency. School 1 is operating with a heat exchanger efficiency of 40 %, therefore there is high potential for saving specially since the model is mostly sensitive to heat recovery efficiency. An exact saving cannot be calculated since not all building information is available, but it shows the possible impact. School 1 is more sensible to window U-value which is not unexpected due to their higher WWR. For school 2 the most important

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[1] The output change refers to the absolute value, for example, the baseline HR efficiency of school 1 is 50%, and the output is compared to scenario of having HR efficiency of 60%.

factor seen in table 22 is the heating setpoint temperature and can be due to that school 2 has lower temperature to begin with and maybe the high S/V-ratio makes it more sensible to indoor temperature. The next highest factor is window openings which is an unknown factor. Depending on the users' activities, it can vary significantly. The simulated extreme cases are to illustrate the users' impact and are with reason. Although these scenarios may be less reasonable for schools equipped with mechanical ventilation, it may be possible for schools with a poorly functioning system or lacking mechanical ventilation. The third most important factor is the heat recovery efficiency and since this is unknown for school 2 it is specially interesting. According to the conducted EPC on school 2 it questions the heat recovery systems property since it is abnormal to have as high energy performance with a heat recovery system for buildings built in the same period. U-value of walls and thermal bridges have higher impact on school 2 than school 1 which can be explained the difference of S/V-ratio. Since the thermal bridge was assumed for both buildings the only conclusion that can be drawn is that it is more important to remedy thermal bridges in school 2 generally. The same applies for the U-value of the walls; increasing insulation will give more savings in school 2 although other factors gives better effect.

The input variation for both windows and walls is not as extreme as other categories, like heat recovery efficiency from 0% to 80% or window openings scenarios. This is due to that the materials and U-values of the building are known, which means that they cannot differ much, also because the U-values are not as bad as the HR efficiency (compared to maximum possible). Since the aim of thesis is finding the factors contributing to energy use and the difference of energy in the buildings, there is more value of varying unknown variables. If the materials were not known, it would be more important to test a larger variation of U-values, which consequently could lead to another ranking. The values are based on the worst-performing windows or walls during construction year [58], except for 1 scenario where the potential deterioration of the wall is tested. The best-case U-value scenarios are from today's regulations [65] for new buildings. The interesting part of this analysis is to see the potential of having U-values that meet today's regulations. This choice of input value affects the ranking.

To summarise, it can be seen in table 22 that all four influencing parameter categories have a significant effect on heating use. From the top 3 factors, the common categories are HVAC-factors and operational factors. When investigating the difference between the performances of buildings, if it cannot be explained by known parameters, uncertain factors becomes particularly important and they can vary greatly between the schools since some parameters are known for one building but not for the other. In table 23 the electricity use intensity ranking has been made where the output ranges are for per unit of input.

Table 23: Ranking of factors tested in sensitivity analysis based on their generated output range of percentage of change per unit input compared to baseline for electricity use intensity

Important factors	**School 1**	Output range compared to baseline	Category	**School 2**	Output range compared to baseline	Category
1	**SFP**	*37% output change per 1 kW/m3,s*	*HVAC factors*	**SFP**	*34% output change per 1 kW/m3,s*	*HVAC factors*
2	**Ventilation system (dimensioning)**	*18% output change per 10% flow change*	*Operational factors*	**Ventilation system (dimensioning)**	*15% output change per 10% flow change*	*Operational factors*
3	**Ventilation system (operation time)**	*21% output change every 4 operation hours*	*Operational factors*	**Ventilation system (operation time)**	*23% output change every 4 operation hours*	*Operational factors*

Among factors contributing to electricity use intensity, SFP is found to be the most dominant. The ventilation system dimension is also an important factor. The ventilation flow is simulated from -20% to +20% of maxflow, which shows more changes compared with changing the operation time in summer or decreasing operation time during the day to 8h/day. Category-wise, only HVAC factors, and operational factors contribute to the electricity use intensity among the 4 categories.

6.4 Inverse uncertainty analysis

Inverse uncertainty analysis are performed so that the modeled energy use comes close to EPC. Since the model contains many uncertainties, a calibrated model may not be totally representative of reality, but should get as close as possible.The schools will be presented separately since they have different uncertainties.

6.4.1 School 1

The baseline model should have 26% higher heating use intensity and 14% lower electricity use intensity to meet the EPC value.

Scenario 1

In this scenario, for heating, the setpoint temperature is changed to 22°C in the model to meet the required value. This scenario is useful in case in other years the temperature in classrooms is not 20.55°C.

The electricity is firstly calibrated because there are less uncertainties. The ventilation is on in the summer according to the history of bought electricity from table 14. This seems to violate the electricity consumption value which is being already higher. But the additional information from the operation personnel reveals the existence of Swegon Weiss systems and the possibility of controlling the airflow based on temperature and CO_2. The percentage of flow to maximum flow is very possible to be lower than 75%, which is the maximum percentage suggested. According to the measured air flow rate in two classrooms, the air flow is possibly 65% of the maximum flow.

The occupancy is now 0.1 pers./m^2, assuming there are 20 students and 1 teacher per classroom. The remaining gap would be filled by window U-value and window opening schedule. The window U-values are set to be 20% higher, considering the bad condition of the windows, see figure 49 and 50. Opening schedule is 40 minutes for every window with a degree of 30%, since there are constant window openings observed during the inspection in April afternoon, when it was not hot.

Figure 49: Interior window condition in school 1

Figure 50: Exterior window condition in school 1

Scenario 2

The second calibrated model has the setpoint temperature as measured 20.55°C, and another 7.5% would be added on the modelled heating use intensity as a normalization procedure, according to Boverket [33].

For electricity, same has been done as in the first scenario, i.e., reduce 10% the flow and add summer ventilation. The window opening schedule is also same, 40 minutes for every window with a degree of 30%. U-value for the window is 10% higher than the baseline. The results of each scenarios are presented in table 24. In addition to comparison of energy, the outputs of IDA ICE models are compared with the measured temperatures and indoor CO_2 concentration, so that no big errors are made.

Table 24: Comparison between calibrated models and EPC

	Heating use [kWh/m^2]	Deviance EPC	Electrcity [kWh/m^2]	Deviance EPC	Energy performance [kWh/m^2]	Deviance EPC
Scenario 1	104	0	16	0	120	0
Scenario 2	102	2%	16	0	118	2%

6.4.2 School 2

School 2 deviates from EPC with -18% lower heating use intensity and 21% lower electricity use intensity. In total, the energy performance is 19% lower.

The expert performing the EPC states that it is questionable that the school has such high energy use with heat recovery, which indicates that there might be dysfunction or a low performing heat recovery efficiency. Therefore the lower heat recovery efficiency can be a factor that influence the energy use. The energy expert stated that the ventilation and heating system should be balanced, which indicates that there might be higher ventilation rates than needed in some areas. It is common as stated in STIL2 as well. Since the measurements were only taken in chosen classrooms, it remains unknown if this is the case for school 2.

According to Boverket [33], when conducting the EPC, the heating use intensity is normalized. School 2 has more than 2 degrees lower temperature in two classrooms, this temperature is assumed in all heated areas. The measurements were performed in 2020, but the EPC was conducted in 2014. It might be a source of error to assume that the indoor temperature is the same in 2020 and 2014. So it is interesting to have a higher operative temperature in the calibration. According to the sensitivity analysis, SFP has a high impact on electricity use intensity. Since higher SFP is assumed for school 2, a higher SFP is tested as well. In baseline, the occupancy was calculated by having 25 students in each classroom as was indicated in drawings as max occupancy and having 5 students in the group rooms. Now a more realistic occupancy has been inferred. It is assumed to have 21 occupants per classroom (20 students and 1 teacher) and 1 occupant per group rooms, since the students from the classroom occupy the group rooms. The thermal bridges have a great impact on energy use, but since we have no information and only value given by BBR for modeling, it is not changed in this school. U-values are calculated according to information from the drawings and regulations and are not considered as an unknown factor. Therefore they are not calibrated. 3 scenarios have been conducted as the following shows. Since the modeled area is larger than EPC, the output has been matched with normalized total energy use from the EPC.

Scenario 1

In scenario 1, the heat exchanger is assumed to be as efficient as school 1's, which is 40%. The airflow is increased from 65% of max flow to 85% of max flow since the ventilation system was unbalanced when EPC was conducted. Fewer occupants were assumed. The energy use was normalized according to BBR, 10% increase since the operative temperature was 2% less than the wanted. In this case, it is assumed that the low temperature is due to occupants, not operational errors.

Scenario 2

In scenario 2, the temperature was set to 22°C to investigate what the energy use would be if the operative temperature was 22°C as Sveby recommends. SFP is set to 3.5 kW/m^2. Summer ventilation is on according to the bought electricity history. This scenario is run with a reduced occupancy as in the first scenario.

Scenario 3

Scenario 3 is a mix of scenario 1 and 2. Heat exchanger is set to have 40% efficiency, summer ventilation is on, SFP is 3.5kW/m^2. This scenario is run with a decreased occupancy.

Table 25: Comparison between calibrated models and EPC fro school 2

	Heating use intensity [kWh/m^2]	Deviance EPC [%]	Electrcity use intensity [kWh/m^2]	Deviance EPC [%]	Energy performance [kWh/m^2]	Deviance EPC [%]
Scenario 1:	143	0%	25.5	+4%	167	1%
Scenario 2:	143	0%	24.0	-2%	162	0%
Scenario 3:	137	-4%	25.5	+4%	167	-3%

The results of the scenarios presented in table 25 show that all scenarios come close to EPC. This indicate that these factors can match the energy performance and at the same time explain why the performance is as high.

6.5 Recommendation for measures

Based on the sensitivity analysis, the inverse uncertainty analysis and comparison of school characteristics some recommendations can be made. Since not all information of the building is known, the savings are based on the model and assumptions thereby not necessarily applicable to the real buildings, only indicates possible savings.

First, the heat recovery system should be looked at, since school 1 has 40% recovery efficiency which is low compared to the highest tested 80% and school 2 where it is unknown. The assumed value for school 2 is 50% which has a significant saving potential, specially if it is lower. If presuming the efficiency is the ones set in the baseline, the saving compared to the baseline could be 22 kWh/m^2 and 16 kWh/m^2 for school 1 and 2 respectively. If the efficiency is lower than the assumed the savings can be larger for school 2.

Since school 2 has the same windows as in the construction a change of window is beneficial for them. There is a large difference between the U-values of windows in regulations from when the building was constructed to today, which is 1.1 W/m^2,K. School 1 is more sensitive to window U-value, therefore a retrofit there is also beneficial. The savings compared to the baseline is 7 kWh/m^2 and 15 kWh/m^2 for school 1 and 2 respectively. It should be noted that school 1 already has a lower U-value due to the former retrofit. Evan more can be saved if a window with a lower U-value is set.

When it comes to the electricity use intensity, SFP and the dimension of ventilation flow gave the most effect. Both schools have significantly higher SFP than the recommended for today according to Boverket. Changing SFP to 1.5 kW/m^3/s generates the saving compared to baseline: 8 kWh/m^2 and 10 kWh/m^2 for school 1 and school 2 respectively.

Since it is unknown whether the schools need to balance the system and how much it is needed, it is hard to determine a target value for measures. If taking the scenarios tested which are a total of 10% and 20% reduction of the flow, the saving from that could be 3 kWh/m^2 and 6kWh/m^2 for school 1 and 3 kWh/m^2 and 5 kWh/m^2 for school 2. School 2's EPC states that it needs balancing of the ventilation system and since it is a comparable cheap measure it should be looked at.

Lastly, since it has been seen the S/V-ratio of the building could be one of the reasons for the energy use difference between the buildings, it should be taken into consideration when designing a building.

7 Discussion

7.1 Results from EPC analysis and modeling

Statistical analysis was conducted on 23 school buildings in Gothenburg. Their energy performance, heating use intensity and electricity use intensity were analyzed with respect to construction year, area, whether it is heritage protected and ventilation system. The following statistically significant correlations were found:

- Construction year of all school buildings significantly affects the energy performance negatively ($r=-0.50$, $p=0.015<0.05$)
- Construction year of school buildings with HR significantly affects the energy performance negatively ($r=-0.55$, $p=0.03<0.05$)
- Construction year of all school buildings significantly affects the heating use intensity negatively ($r=-0.56$, $p=0.006<0.01$)
- Construction year of school buildings with HR significantly affects the heating use intensity ($r=-0.63$, $p=0.011<0.05$)
- Construction year of the school building with CAV ventilation system significantly affects the electricity use intensity ($r=0.89$, $p=0.003<0.01$)

All the significant correlations found were with the buildings' construction year. Energy performance and heating use intensity are negatively correlated to the construction year. Stronger correlations were generally found for newer schools. Electricity use intensity was found to have a positive correlation with construction year. The reason why the newer and more efficient buildings have high electricity use is worthy of investigation. Weak negative correlations between heating use intensity, property electricity use intensity, and energy performance with the heated area were found for new schools with R=-0.22, 0.-31, and 0.28 respectively. The heating intensity decreasing with the area was found in a study on British schools using EPC [40], where it is explained by that larger schools tends to have areas with different use other than classrooms, hence decreasing the intensity. The STIL2 report also found a negative correlation between property electricity and area. The reason is worthy of investigating. The same energy modeling approach as has been used in this thesis could be used.

Two schools were chosen based on certain similarities in building characteristics, but having 58 kWh/m^2 difference in energy performance. Both of the schools were built in 1968, operated with CAV, unprotected for heritage reasons. The only differentiating factor seen in the EPC is the area, still, their areas are similar compared to other candidates for further analysis.

Data such as archived building information, OVK, bought heat and electricity from 2017-2019 and measurement was received. After obtaining information on the building, the models are built in IDA ICE, calibrated and validated through comparison with the EPC values. The calibration was conducted and assessed through varying unknown input parameters to reach the energy use from the EPCs. 2 and 3 scenarios were conducted for respective schools. Many more scenarios could be conducted to match the values in the EPCs, but the chosen ones seemed reasonable enough to validate the school models.

The results from building energy modeling conducted in IDA ICE shows some difference in the characteristics of the building:

- The better performing school, school 1, has a window U-value of 1.9 kWh/m^2 while the worse performing school has 2.9 kWh/m^2.
- S/V-ratio was smaller, 0.34 m^2/m^3 for better performing school, while the worse performing school has 0.42 m^2/m^3.

Analysis of bough heat between the years 2017-2019 showed that the difference between the bought heat between the schools did not differ. It could not be explained with certain. Possible reasons can be renovations measures between the year EPC was conducted and 2017 although nothing has been reported in the archived files, and errors either in the EPC or monitoring procedure.

A sensitivity analysis was conducted where possible factors were evaluated for their impact on the buildings' energy use, and it showed that heat recovery efficiency together with thermal bridges, temperature setpoint, ventilation dimensions and window openings were the top factors affecting heating use intensity. For electricity use intensity, SFP, ventilation flow properties and schedule were found to be the three predominating factors.

7.2 Recommended measures

The first recommended measure, especially for the worse performing school, is evaluating what factors that are the most important to that specific school. It has been seen that this can vary. The heat recovery efficiency should be overseen since it can affect energy performance significantly. Change of windows could be done for both schools since both schools have window U-value higher than today's regulations and energy-efficient windows. Since school 2 EPC states that the ventilation system should be balanced, that should be done, if it has not been conducted already.

Also, the nighttime setback could not only be limited to nights. Furthermore, a trial could be made to explore the possibilities of applying setback temperature during the weekend since the schools are not used. Although the sensitivity analysis results show 1 °C setback is not very sensitive, lower setback temperature and longer time duration could be promising.

7.3 Limitations

EPC is a very useful source of data for analyzing building related energy, but some limitations have appeared. The data of tenant electricity in EPC has low credibility. Only less than half of the EPCs state this value. Also, the values are widely scattered and dispersed. Some EPCs might not differentiate buildings within the same school. Some EPCs of different buildings in the same school have the same result. Schools 12 A, D and E are built in different eras which the gap is over 60 years; their ventilation systems are not the same. Perhaps these buildings shared meters, and then experts arbitrarily allocated consumption to the three buildings based on the building area. Errors and inconsistencies found in EPC data have opened up for studying for EPC data validation and quality assessment [14].

From the IDA ICE modeling results, it can be seen that every 1°C increase of indoor temperature causes approximately 7% and 10% more heating use in school 1 and school 2 respectively, compared with the normalization Boverket suggest which is 5%. This shows that normalization might not fully be adaptable to all buildings.

Possible factors contributing to performance difference that is found from modeling are the U-value of window and S/V-ratio. This data would be useful in analyzing EPCs. Other characteristics which could enrich the dataset of EPCs are opaque-area, HX-efficiency, ventilation system, air-exchange rate, WWR, and envelope U-values of opaque and transparent areas. Since the application of EPC has been found to be larger than intended, adaptation to the use is important. There are substantial potential benefits to gather such information so that it is possible to compare buildings internally and externally between countries, especially in the climate today.

The modeling accuracy of the building characteristics affects the continuing analysis. One important factor is the heated area, i.e., A_{temp}. Both IDA ICE models are constructed based on the drawings from the city planning office. However, it is not possible to reach 100% close to the A_temp in EPC. For school 1, the Atemp is 3395 m^2 in EPC and 3410 m^2 in the IDA ICE model, which has a difference of less than 1%. The model for school 2 was also rigorously produced according to the size given in the drawings. Nevertheless, the total area is not close to 1485 m^2 as stated in the EPC. The total A_{temp} is 1578 m^2 including a basement and 1523 m^2 if the basement is excluded. At least parts of the basement should be included as it is heated up above 10° C. It is unknown if the EPC includes this part of the area. The differences still exist if 1523 m^2 is taken. There are many sources of difference in the area. It is possible that when the expert executed the certificate, this part of the basement was not heated, or the expert did not add this part of the area due to other considerations. It is also possible that experts underestimated the area. As stated in the literature review, underestimation of the area is very common [49]. At the same time, it is also possible that the building model is not accurate. The errors caused by these deficiencies will more or less affect the results of the sensitivity analysis.

The ranges of input values in the sensitivity analysis can be misleading, to either too small or too big changes in output. For example, the heat exchanger efficiency ranges from 0% to 80%, which results in +35% to -14% output range. This might be too big for those schools, but it was tested like this due to a lack of information. If all factors for the whole sample are given, it would be possible to normalize the input ranges first and better prioritize them.

Evaluating S/V-ratio in modeling was found to be tricky since changing the parameter changes automatically other parameters such as WWR and U-value, thereby the results of the evaluation do not 100% depend on the input value. S/V-ratio is a parameter easier evaluated statistically via e.g. parameterization for the existing building, although the results from modeling gave meaningful information.

To summarize, the benefit of combining the statistical and modeling methodologies using a smaller set of data is that limitations such as errors, factors and information lacking in EPC can be localized, as has been done in this thesis. Further improvements of data can be suggested.

Continuing on this project evaluating the proposed factors and measures applicability on the building is of value. Furthermore, studies combining EPCs and modeling investigating different topics in building energy simulations could be further investigated.

8 Conclusion

This study explored the main factors affecting the energy performance of a sample of school buildings and analyzed two case study schools in detail. The study added to the rapidly expanding field of building energy performance analysis, and has been one of the first attempts to combine EPC with physical based analysis.

EPC data was statistically analyzed concerning the construction year, heated area, protection status, and ventilation system. The analysis found that energy performance and heating use intensity are negatively correlated to construction year.

This project continued to find out why similar schools have different energy consumption. Two schools with the same year of construction, ventilation system and other similar building characteristics were selected, one of whose energy performance was higher than comparable schools. The two schools were modeled in IDA ICE and known and unknown factors were evaluated in a sensitivity analysis. The findings indicate that that differences in U-values of windows and the S/V-ratio are the possible reasons for their difference in energy performance. The gap between the heating use intensity between the schools decreased by 22% when adapting the same U-value in school models. The gap between the envelope heat loss between the schools decreased by 73% when adapting the same S/V-ratio in school models. The study further identified heat recovery efficiency, heating setpoint, and SFP to have significant effect for both schools by 8.3% and 6.3% change in heating use intensity per 10% HR-efficiency, 7% and 12% change in heating use intensity per degree difference, and 37% and 34% change in electricity use intensity per kW/m^3,s respectively.

The findings of the study provided some implications for future practice, based on the models constructed. Taken together, these findings support recommendations on renovation and designing with possible savings based on the baseline models for respective school including:

- Retrofit: Higher heat recovery efficiency. Possibly save 22 kWh/m^2 and 16 kWh/m^2.
- Retrofit: Energy efficient windows. Possibly save 7 kWh/m^2 and 15 kWh/m^2.
- Retrofit: Better fans with lower SFP. Possibly save 8 kWh/m^2 and 10 kWh/m^2.
- Retrofit: Balancing of ventilation system.
- Design of buildings: Taking compactness into consideration at the design phase.

Further investigation might explore the relation between indoor air quality and EPC, it would establish a greater degree of accuracy on identifying differentiating factors and raising renovation strategies.

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[66] Per Levin and Branschstandard för energi i byggnader (Sveby), "Brukarindata undervisningsbyggnader: preliminär version," 2015.

Appendix 1

Summary of all buildings

School name	**Year**	**Electricity** [kWh/m^2]	**Heating** [kWh/m^2]	**Energy performance** [kWh/m^2]	**Area** [m^2]	**Ventilation**
School 1 A	1968	16	104	120	3395	FTX_CAV
School 1 E	1968	21	104	126	590	FTX_CAV
School 2	1968	26	152	178	1484	FTX_CAV
School 3	1889	4	118	122	3216	S_F
School 4	1889	12	120	132	4647	FTX_CAV
School 5	1889	13	89	101	3063	S_F
School 6	1898	29	142	171	5157	S_WindowMaster
School 7	1905	25	119	144	5269	S_F
School 8	1924	15	111	126	2604	FTX_CAV
School 9	1931	21	200	221	612	S
School 10	1941	4	126	130	6010	S_F
School 11	1947	18	127	145	6508	FTX_VAV
School 12	1951	18	93	111	6081	FTX_CAV
School 13 A	1952	29	60	89	1393	S_WindowMaster
School 14	1952	20	112	132	4480	FTX_VAV
School 15	1964	15	95	110	7776	FTX_VAV
School 16 A	1968	15	163	178	713	FTX_VAV
School 13 D	2002	29	60	89	1640	FTX_VAV
School 17	2004	29	75	104	733	FTX_CAV
School 18	2011	19	36	54	3468	FTX_VAV
School 16 F	2012	14	69	84	1428	FTX_VAV
School 13 E	2013	29	60	89	3233	FTX_CAV
School 19	2016	17	50	68	2611	FTX_VAV

Appendix 2

U-values of envelope elements

	Material	Thickness [cm]	U-value [W/m^2,K]		Material	Thickness [cm]	U-value [W/m^2,K]
	School 1				***School 2***		
External wall				**External wall**			
	1) Facade brick	1) 12	1) 0,58		1) 1/2 yellow facade brick	1) 13	1) 0,58
	2) Air gap	2) 1,5	2) 0,17		2) Air gap	2) 1	2) 0,17
	3) Min board 331.	3) 8	3) 0,052		3) Mineral wool	3) 8	3) 0,052
	4) Brick	4) 12	4) 0,85		4) Concrete	4) 16	4) 1,7
	5) Plastering	5) 1	5)0.08				
Total:		34,5	0,45	Total:		38	0,45
Roof				**Roof**			
	1) Mineral wool	1) 3	1) 0,0465		1) Mineral wool	1) 12	
	2) Mineral wool blankt	2) 10	2) 0,0465		2) Plaster board	2) 1,3	
	3) Concrete	3) 20	3) 1,7		3) Mineral wool	3) 3	
	4) wood wool board acustic	4) 5	4) 0,0814		4) Concrete	4) 30	
Total:		38	0,27	Total:		49,3	0,20
External floor				**External floor**			
	1) Coating	1) 3	0,8		1) Concrete	1) 16	1) 1,7
	2) L/W Concrete	2) 20	0,15		2) Mineral wool	2) 5	2) 0,05
	3) L/W arb.platta	3) 5	0,15		3) overconcret	3) 5	3) 1,7
Total:		28	0,53			26	0,60

Appendix 3

Building models

The appearances of the building models are shown below.

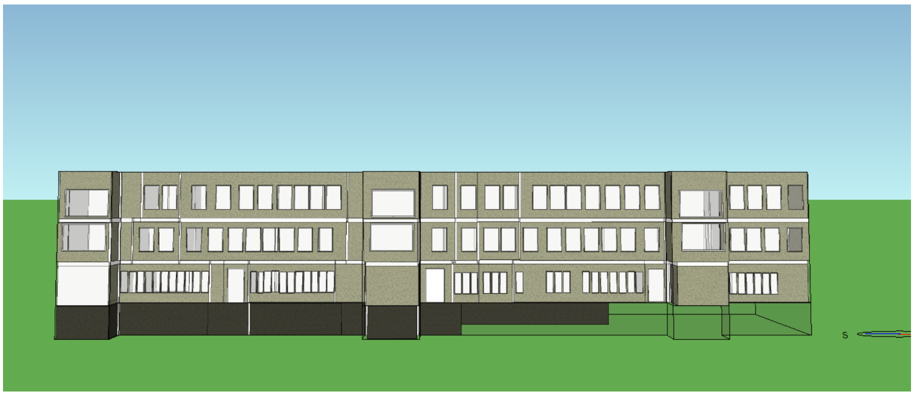

Figure of school 1 model: east

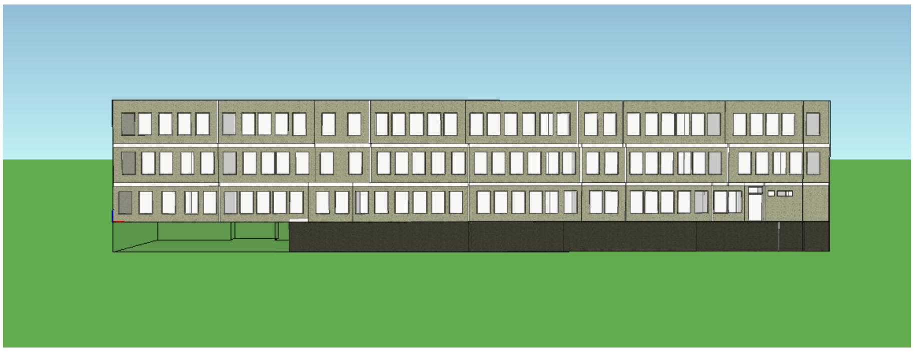

Figure of school 1 model: west

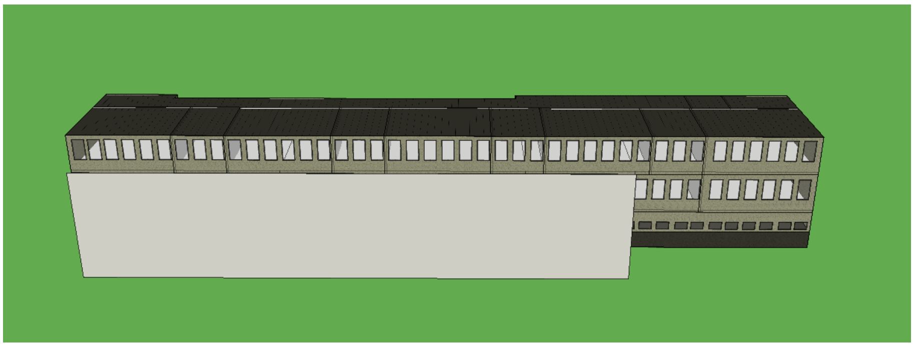

Figure of school 2 model: east

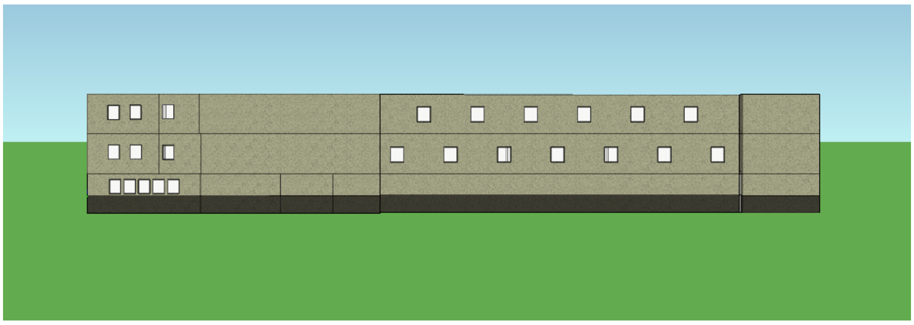

Figure of school 2 model: west

Appendix 4

Measurements in 2 classrooms of the chosen schools

	Average (operative) temperature during occupied hours (°C)	Air change rate (1/h)	Average CO2 during occupied hours (ppm)
School 1 room 1	20.6	2.63	680
School 1 room 2	20.5	2.47	744
School 2 room 1	19.5	2.31	687
School 2 room 2	19.8	2.38	605