Probabilistic approach to the assessment of uncertain input parameters when energy renovating existing buildings

A case study of a building in Linköping, Sweden

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Lund University

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Keywords: Input Parameters; Energy Simulations; IDA ICE; Heat Recovery; Specific Energy Use; Sensitivity Analysis; Uncertainty Analysis; Monte Carlo Simulations

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Abstract

Since the building stock stands for significant part of the EU's total energy use, energy renovations are needed in order to lower the negative environmental impacts. In Sweden, only 1 % of the total building stock is newly built i.e. the focus should be directed upon existing buildings. Moreover, most of the buildings in the "Million Program" from 1970´s are in need of renovations in order to keep them operational. This makes for excellent opportunity to energy renovate these buildings at the same time, and follow up the work that can later be implemented to all other types of existing buildings. This project is about trying to determine an existing building total energy use over a year, which is the main question that needs to be answered when it comes to determining the viability of energy renovations on existing buildings. For this, computational simulations were performed as well as statistical methods such as sensitivity analysis and Monte Carlo simulations. The statistical methods are used instead of performing conventional expensive and time-consuming measurements, when obtaining the values of the input parameters used for the simulation tool. In addition, installing the heat recovery on the current ventilation system is also looked upon in order to see what additional energy savings could be made. The results show that the building total yearly energy use should lie within the interval of about 160-190 kWh/(m^2·year) and that the average use should be around 177 kWh/(m^2·year). After installing a heat recovery system, the building total energy use should lie between 115-135 kWh/(m^2·year), which is a decrease of around 24-35 % in total energy savings.

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Lund, Sweden
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1 Introduction

This chapter presents background information, which shortly describes the need for this report and a detailed literature review is presented as well, which gives a hint about what has been done in the subject as well as future prospects. In addition, general objectives are presented as well, which lists specific set of questions that serve as basis for this project, and which will be answered throughout the report.

1.1 Background

The building stock in the European Union (EU) is responsible for approximately 40 % of the total energy use as well as 36 % of carbon dioxide (CO_2) emissions. The European Commission (EC) has been looking into the possibilities of lowering this energy use and has come up with different sets of laws that all the countries of the union must follow. According to their calculations, the energy use can be lowered by 5 to 6 % and the CO_2 emissions by 5 % by renovating the existing buildings. Furthermore, all types of new buildings must be built as nearly zero energy buildings (NZEBs) from 31 December 2018 (applies to public buildings) and 31 December 2020 (applies to all the other types of buildings) (Commission, 2016).

On the Swedish national level, all the newly produced residential buildings in 2014 comprised of under one percent of the total building stock; a trend that slightly increased in 2015, but does not change considerably over the years (Fastighetsägarna, 2016) & (SCB, 2016). Therefore, in order to mitigate the Sweden building stock's negative impact regarding the energy use, the focus must be directed towards the existing buildings.

Between years 1965-1974, just over one million new dwellings were built in Sweden in the so-called "Million Program". This program was a part of a revised social reform program proposed by the government at the time. The goal was to give a home to every citizen of Sweden at a reasonable price. Today, many of these buildings are in needs of technical renovations as well as improved energy efficiency in order to keep them operational (Boverket, 2014). This situation gives excellent opportunity to install and study different technical solutions for lowering the energy use and pave the way for new energy renovation strategies that could be implemented in the future, not only to the "Million Program"-buildings, but also to all other types of existing buildings.

1.2 Literature review

As already mentioned the biggest energy, and subsequently environmental and economical, savings can be made by renovating the existing buildings, since they comprise of major part of the total building stock. The problem in today Swedish society is that the economical incitements for energy renovations are low. Moreover, the understanding about the actual savings among the construction actors is not very well known, lack of technical solutions is limited and follow-up of both the individual projects as well as the development in general is poor (Byggindustrier, et al., 2011). Therefore, Byggindustrier et al., (2011) has developed 15 specific suggestions to what the construction actors can do in order to boost the energy renovations of the existing buildings. Byman & Jernelius, (2013) tackles the same problem, but from the perspective of energy renovating the “Million Program”-buildings. Byman & Jernelius, (2013) also focuses on the governmental instruments, meaning that the economical incitements in today society is inadequate and that the actors need help from the government. Sandoff, (2015) also examines the business conditions of energy renovating existing buildings from the “Million Program”, and states that the biggest problem today is the economical incitement. This concludes indeed that the existing building stock needs to be energy renovated in order to lower the energy use, and that the biggest problem today is the economical incitements.

The process of energy renovating a building always starts with some kind of investigation that shows if it is economically viable to do the renovations. One crucial step in this process is to find out the actual yearly energy use of the building as it is in the present. This can be done accurately by measuring the building total energy use, but this is very time consuming and thereby expensive. Another way is to simulate the building energy use via engineering and statistical methods among others. These methods have different level of accuracy, where the engineering methods such as computer simulations are more accurate compared to the statistical methods, which are empirical in nature (Hai-xiang & Magoulès, 2012). Reddy, (2006) states that the computer simulation tools is a relatively reliable way of accurately predicting a building energy use, even though there are shortcomings due to the uncertain nature of the input parameters.

There are also new ways that are being developed in order to get even more accurate energy usage predictions. One new way of doing this is using artificial intelligence, and more specifically, using the artificial neural networks (ANNs). ANN is constructed to work in a way similar to that of a human brain. The advantage is that the models can be built more complex and that the simulations can be performed considering many different variables at once (U. Teoman & Betul Bektas, 2008). However, this area of energy use prediction is relatively new and still in the developing phase. In addition, the availability of the method may be a problem.

Therefore, for now, engineering and statistical methods could be used with relatively good accuracy.

One of the crucial issues in a project where energy simulations are an important aspect is to predict the specific input values for a building, which is modelled in the energy program. The prediction of input values need to be defined in a way that are more adapted to realistic scenarios. One approach to improve the definition for the input values is to perform measurements to the typical buildings of the society, where the result of the different parameters can be used as reference for input values. In present, the input values are defined by worst-case scenarios or by building codes etc., which does not give an equitable representation of a realistic usage of buildings in the society (Malie, et al., 2007).

Nikolaou, et al., (2015) states that the model-based calculations have numerous benefits, where the model can be modified with various input values to offer different requested outputs. Model-based calculation have some drawbacks though; the building needs to be modelled by a skilled user. For energy simulations, numerous input parameters are needed in order to get accurate results. In addition, this kind of method for energy simulations need significant amount of time, which in turn is economically expensive.

Energy savings regarding the ventilation system of a building with exhaust air only system could range from 50 – 80 % if heat recovery is installed. The range depends on the efficiency of the heat exchanger together with the building airtightness (Ventilation, 2016). It is crucial for older buildings that the airtightness is improved when installing heat recovery on the ventilation system. This is because leakages through the building envelope could disrupt the airflows in the rooms as well as the heat loss will reduce the energy savings from the heat exchanger (Miljö, 2013).
The question, which is important for most building owners, is if the heat recovery system is a cost-effective solution. A study performed by Taylor, et al., (2015) shows that during the ventilation system lifetime, which was estimated to be around 20 years, the heat recovery system would indeed be cost-effective. Therefore, the conclusion can be drawn that installing a heat recovery could be good way to save energy in a building.

Traditionally, when conducting building simulations, it requires a definition of a set of input parameters that are processed through more or less complex mathematical models in order to generate a final, deterministic result. As mentioned, the input parameters in question may be obtained through national regulations, different guidelines or standards etc. The definition of what values the parameters should adopt may vary depending on the source. Therefore, some kind of qualified decision has to be made along the way when it comes to picking out the values that will be processed.

However, the aforementioned methodology does not include the stochastic nature of the input parameters, which means that the parameters are in fact uncertain and unpredictable in real life, and thus the obtained simulation results might be far from giving the correct picture of the actual performance of the building. So in order to evaluate the uncertainties in the simulation results due to the uncertainties in the definition of the input parameters, different practices such as the sensitivity and uncertainty analysis or stochastic methods such as Monte Carlo simulations could be employed (Van Gelder, et al., 2013); (Almeida & Ramos, 2014); (Janssen, 2012).

Sensitivity analysis and uncertainty analysis are two related practices that are usually run together when it comes to determine how the uncertain input parameters inserted into a computational model affect the result outcome from that same model. The difference between the practices is that they process either the input parameters themselves (uncertainty analysis), or the result outcome based on those input parameters (sensitivity analysis) (Helton, et al., 2011); (Wikipedia, 2016).

Sensitivity analysis is the study of how the individual, uncertain input parameters affect the outcome of the results. When performing building simulations, some kind of evaluation in the confidence of the model and its results is recommended. The sensitivity analysis provides this evaluation by showing in a quantitative way which (if any) of the individual input parameters is the biggest contributor to the uncertainty in the results. In other words, which of the parameters affect the results the most in a way that the results deviate from giving the correct picture of the reality (Wikipedia, 2016); (Nguyen & Reiter, 2015).

Uncertainty analysis is the study of how the individual input parameters may differ in reality compared to the deterministic nature in which they are processed in a computational model. This difference in the values of the input parameters leads to direct effects on the output results. If the results are unrealistic, huge economic losses may occur (Wikipedia, 2016); (Helton, et al., 2011).

One example of how an input parameter may differ in reality compared to the assumptions is the U-value of a wall; there is an easy way to calculate the U-value for one particular wall, but that U-value may worsen over the years due to old age. Another example could be the ventilation flows, which were never controlled from the design stage by measuring them, and may be in fact better or worse in reality.

Measuring all of the different input parameters would be time-consuming and thereby economically expensive. Therefore, in order to consider all of the different variations that the input parameters may adopt in their values, different techniques are available. One of these techniques is the Monte Carlo simulations and is used in this thesis.

Monte Carlo simulations are based on a sequence of random numbers derived from the initial input variables, for which probabilistic distributions are known or can be estimated. Then, a set of these distributed values is randomly generated and the chosen values are used to produce the result in a simulation tool for that particular combination. The accuracy of the Monte Carlo simulations depends on the number of simulations performed, where the higher amount of simulations gives more accurate results (Almeida & Ramos, 2014); (Van Gelder, et al., 2013).

When mentioning the building use in this report, it is always referred to the specific energy use, if not otherwise stated. Specific energy use of a building is the total energy that the building uses for its ventilation system, facility electricity and space heating. All other types of energy usages such as the energy needed for heating the domestic hot water, or the tenant electricity, is not included. The specific energy use is divided by A_{temp}, which is the heated area of the interior of the building, and is expressed in $kWh/(m^2 \cdot year)$ (Anon., 2011).

As already mentioned, when trying to predict the energy use of an existing building throughout a year, there are many input parameters used in a simulation tool that are either hard to obtain or assume. The reason for predicting the energy usage is mainly in order to see if that particular building is using more energy than needed in terms of leakages through a faulty or outdated building envelope. If yes, then some renovations should be made. However, to see if these renovations are economically viable, the correct energy usage of the building needs to be predicted as accurately as possible.

When trying to simulate a building energy use that represents the reality, many different input parameters need to be obtained. These parameters could for instance be the U-values of the envelope materials, doors, windows etc. or drawings of the building needed to make a model. Firstly, it can be quite hard to get these values from the building manager since the building is a few decades old and the drawings may be in bad shape. In addition, any other technical information may have been lost over the years. Secondly, even if the information is available, it can be hard to assume the correct values of e.g. the U-values of the envelope, since the quality of the material changes for the worse over the years and subsequently so does the U-value itself.

Because of the aforementioned difficulties, this report will try to zero in and process the uncertain input parameters. This will be done by modelling a building from the “Million Program” situated in Linköping, Sweden. After an initial collection of the input parameters and technical information needed to make as representative model of the reality as possible in a simulation tool, the uncertain input parameters will be pointed out and processed.

1.3 Aim and objectives

The aim of this project is to study how the variation of the input parameters used in an energy simulation tool influence the outcome of the results from that same tool. The desired result is a prediction of an existing building yearly energy use. Preferably, one single value should be obtained, which would give the exact information about the energy use. However, since both engineering and statistical methods are used, and since they are of uncertain nature, an interval will be obtained instead, within which it is considered as most probable that the building energy usage should fall within. In order to achieve the goal of trying to predict the yearly energy use of the building, a few main questions are answered throughout this report:

- How hard is it to obtain the building information?
- What input parameters should be considered when simulating the yearly energy use?
- Which values should be used for each the considered parameters?
- How sensitive are the individual parameters?
- How certain are the simulated energy results?
- What energy savings can be made when installing a heat recovery system?

2 Methods and material

In this chapter, the methodology of this project as well as information about the studied building will be provided. In short, this project is about trying to find a method for predicting an existing building yearly energy use as accurately as possible, with the help from an energy simulation tool and a statistical method. Conventionally instead of using the statistical methods, real-life measurements of the building are performed (e.g. U-values, ventilation flows etc.) in order to obtain the necessary information that is further used in the simulation tool as input parameters. Even though this methodology is most hands-on and can be made as accurately as wanted, the time and economical costs of it are not very defendable. By using a statistical method in which different input parameters used for the simulation tool are varied and processed, the accuracy of the results can be obtained within fraction of the time it takes using the conventional method. This time saving will make up for the potential loss of the accuracy in the results, which is fine because the need for accuracy at this point in the planning phase can be sacrificed if it means that the time for completing the entire phase is significantly decreased. In addition, gaining more accuracy does not provide a bigger pay-off for the purpose. In the following subchapters, information about which input parameters were processed in this project, the simulation tool, and the building information needed for making a working model in the simulation tool will be provided.

2.1 The input parameters

The input parameters are presented in this section, which are used for running the necessary computer simulations needed for this project. When dealing with simulation tools, many different input parameters need to be known in order to get as accurate simulation results as possible. The simulation tool that was used in this project considers many different input parameters, which could be used for the simulations. Due to time limitations, not all of the possible input parameters were obtained and used. Instead, thirteen (13) input parameters were chosen and processed, because they were considered as most important, as well as they could be relatively easily obtained within the given time window. The thirteen processed parameters are as follows:

- U-values
    - Roof
    - Walls
    - Foundation
    - Windows
    - Doors
- Occupants
- Infiltration

- Thermal Bridges
- Indoor Temperature
- Ventilation
- Electricity
    - Tenant
    - Facility
- Domestic Hot Water (DHW).

2.2 Finding the values for the input parameters

How was a value of a certain input parameter found? For example, let us consider the U-value for roof. There was a search for references online as well as physical books for what type of roof should the building from that period have. Together with blueprints of the actual building and information about the roof composition from the book, the decision was made that this certain roof U-value should be 0.20 W/(m^2·K). Because there is no way to know the actual U-value without performing (expensive) real-life measurements, the possibility must be considered that this value may not be correct in reality. Therefore, some kind of strategy is needed to process this uncertainty. To do this, the value of 0.20 W/(m^2·K) is considered to be the mean value of what should be the probability for that specific roof. The mean value is also known as the median or the 50th percentile. This uncertain value is further varied into four more steps, two on each side, which all represent a possibility that this value could adopt in reality. These other steps were values for the 10th, 30th, 70th and 90th percentiles.

This methodology was applied to all of the input parameters. Often, the values for the 10th, 50th and 90th percentiles could be easily obtained from the sources, and in these cases, the values for the 30th and 70th percentiles were calculated through normal distribution. Other times, all of the different values could easily be obtained from the sources. There was even times when there was no way of determining the values for a certain parameter and in these cases, the values were educationally guessed. The subchapters below presents all the input parameters processed in this project, as well as their values used for simulations. In addition, the detailed explanation to how each of the values of the input parameters were obtained is provided. Finding a scientific source that validates the usage of a specific value for a specific input parameter was one of the key moments of this project.

2.2.1 U-values

Roof
A report from Swedish National Housing Board (Boverket) held a big scientific project called BETSI (finished in 2010) in which they revised the Swedish building stock. In the BETSI report, it can be found what average U-value for roofs was used

for apartment buildings built between 1961-1975 (Boverket, 2010). This value is 0.20 W/(m^2·K) and is considered as the mean value or in other words, the value falling under the 50th percentile. From the same figure in the BETSI report, the values representing the 10th and 90th percentiles were obtained, which are 0.17 W/(m^2·K) and 0.23 W/(m^2·K), respectively. The values falling under the 30th and 70th percentiles were both calculated through normal distribution according to Formulas 2-1 and 2-2, respectively. Table 2.1 shows the overview of all the values.

$$P_{30} = P_{50} - (P_{50} - P_{10}) \cdot 0{,}41 \tag{2-1}$$

$$P_{70} = P_{50} + (P_{90} - P_{50}) \cdot 0{,}41 \tag{2-2}$$

P_{XX} is the value falling under the given percentile, and 0.41 is a standard coefficient.

Table 2.1 *The values for the parameter U-value, Roof used for simulations.*

Percentile	U-value/ (W/(m^2·K))
90	0.23
70	0.21
50	0.20
30	0.19
10	0.17

Wall

When obtaining the U-values for the walls, the same procedure was used as above. The source was also the same (Boverket, 2010). The only thing that is different is of course the U-values themselves that fall under the different percentiles. Table 2.2 shows the overview of the U-values used for the simulations.

Table 2.2 *The values for the parameter U-value, Wall used for simulations.*

Percentile	U-value/ (W/(m^2·K))
90	0.49
70	0.44
50	0.41
30	0.38
10	0.34

Foundation

When obtaining the U-values for the foundation, the same procedure was used as above. The things that are different is the source (Boverket, 2010), and of course the U-values themselves that fall under the different percentiles. Table 2.3 shows the overview of the U-values used for the parameter U-value, Foundation.

Table 2.3 *The values for the parameter U-value, Foundation used for simulations.*

Percentile	U-value/ ($W/(m^2 \cdot K)$)
90	0.29
70	0.28
50	0.27
30	0.26
10	0.25

Window

When obtaining the U-values for the windows, the same procedure was used as above. The source was also the same as for the parameter *U-value, roof* (Boverket, 2010). The only thing that is different is of course the U-values themselves that fall under the different percentiles. Table 2.4 shows the overview of the U-values used for parameter U-value, window.

Table 2.4 *The values for the parameter U-value, Window used for simulations.*

Percentile	U-value/ ($W/(m^2 \cdot K)$)
90	3.10
70	2.98
50	2.90
30	2.82
10	2.70

Door

Another report from Swedish National Housing Board on the BETSI project shows that the board used 1.7 $W/(m^2 \cdot K)$ for all the external doors when doing their calculations (Boverket, 2010). This U-value was considered as the 50th percentile in this project. The 10th and 90th percentiles were decided through educated guess and 30th and 70th percentiles were calculated through normal distribution as Formulas 2-1 and 2-2 show. Table 2.5 shows the overview of the U-values used for parameter U-value, door.

Table 2.5 *The values for the parameter U-value, door used for simulations.*

Percentile	U-value/ ($W/(m^2 \cdot K)$)
90	3.50
70	2.44
50	1.70
30	1.41
10	1.00

2.2.2 Domestic hot water (DHW)

When obtaining the values for this parameter, a report from a project named THUVA II was used. In this report, there was a graph where all of the values needed for this project were obtained (Bagge, et al., 2015). However, the values in the THUVA II report are given in m^3/m^2. This needed to be changed to $kWh/(m^2\cdot year)$ in order to be able to use the information in the simulation tool. Due to research, this is easily done by multiplying the values that are read out from the graph by a factor of 55 (according to the supervisor of this project). Table 2.6 shows the values used in this project.

Table 2.6 *The values for the parameter Domestic Hot Water used for simulations.*

Percentile	**Domestic Hot Water/ (kWh/(m^2·year))**
90	41.25
70	26.40
50	19.25
30	13.75
10	8.25

2.2.3 Infiltration

In a report from SP Technical Research Institute of Sweden, all the values needed for this input parameter could easily be obtained by reading them out from a graph. In this graph, the values were already normally distributed and presented as such (Wahlgren, 2010). Table 2.7 presents the different values used for simulations.

Table 2.7 *The values for the parameter Infiltration used for simulations.*

Percentile	**Infiltration/ (l/(s·m^2))**
90	1.25
70	0.73
50	0.62
30	0.40
10	0.30

2.2.4 Thermal bridges

The values falling under the 10th, 30th, 50th, 70th and 90th percentiles for this parameter were all assumed. When it comes to deciding thermal bridges for a building, there is not one definitive answer. Instead, a master thesis from Department of Building and Environmental Technology, Lund University was found and in that report, the authors calculated their thermal bridges to be between 17 – 36 % of the total transmission loss factor (UA) depending on the type of building

(Danebjer & Ekström, 2012). However, the 17-36 % values are valid for low-energy buildings. To compensate for the fact that the building used for simulations in this project is not a low-energy building, the values 17-36 % were lowered by a factor 7 to an assumed span of 10-29 %. In this assumed span, the values falling under the 10th and the 90th percentiles were set to 10 % and 29 %, respectively, i.e. 10 % and 29 % of total transmission loss factor (UA). The 50th percentile was assumed to be in the middle of the span, i.e. approximately 20 % of total UA. 30th and 70th percentiles were assumed to fall under the normal distribution and calculated using Formulas 2-1 and 2-2. UA was also calculated for the building used in this thesis, and the complete calculations are showed in the section below. Table 2.8 shows the final values that fall under the different percentiles for thermal bridges used for the simulations.

Table 2.8 *The values for the parameter Thermal Bridges used for simulations.*

Percentile	**Thermal bridges/ ($W/(K·m^2_{envelope})$)**
90	0.069
70	0.066
50	0.064
30	0.062
10	0.059

Thermal bridges calculation

This section presents the thermal bridges calculation made for the case study building. The calculations were done manually using Microsoft Excel and the simulation tool.

The calculation started by obtaining the U-values and areas for the entire building envelope; the walls, the roof and the foundation. The U-values used are the values that fall under the 50th percentile, and the total areas are obtained from the simulation tool. When this was done, the UA-values were calculated simply by multiplying the U-values and areas together. Table 2.9 shows all of the above.

Table 2.9 *The U-values, areas and UA-values for the entire building envelope.*

Component	**Median U-value/ ($W/(m^2·K)$)**	**Area/ m^2**	**UA-value/ (W/K)**
Wall	0.41	536	220
Roof	0.20	420	84
Foundation	0.27	420	113
Total	-	**1376**	**417**

In order to get the total UA-value for the building, the UA-values for the doors and windows are also needed. Note that the areas of the windows and doors is included in the total area presented in Table 2.9, but that they need to be used separately in order to get the total UA-values for the doors and windows that are needed for the final thermal bridges calculation. Table 2.10 shows the calculations made in order to get the UA-values for the windows and doors.

Table 2.10 *The U-values, areas and UA-values for all the windows and doors.*

Openings	**Median U-value/ (W/(m^2·K))**	**Area/ m^2**	**UA-value/ (W/K)**
Windows	2.20	129	283
Doors	1.70	23	39
Total	-	-	**322**

Total thermal bridges for the entire building is obtained by dividing the total UA-values by the total areas. However, since the thermal bridge is not equal to the total area of the entire building, but only a small part, an assumption was made that the thermal bridge is 10 % of the total value obtained from the calculations. Table 2.11 shows the final calculated thermal bridges for the entire building, including the assumption of 10 %. Note that the thermal bridges can be calculated in different ways and thereby have different units depending on the purpose. The unit for the thermal bridges for this particular simulation tool has to be in W/(K·m^2_{envelope}).

Table 2.11 *Total thermal bridges calculation for the entire building.*

Unit	**Value**
UA-value/ (W/K)	739
Area/ m^2	1376
Thermal bridge/ (W/(K·m^2_{envelope}))	**0.054**

Finally, in order to get the different values falling under the five different percentiles, the value of the total calculated thermal bridge (i.e. 0.054 W/(K·m^2_{envelope})) from Table 2.11 was increased by the assumed span of 10 % to 29 %, as described in chapter 2.2.4 above. Note that the end-result is the same if you increase the UA-value *or* the thermal bridge value. Table 2.8 above shows the final values used for simulations.

2.2.5 Indoor temperature

BETSI report used in e.g. chapter 2.2.1 could also be used for deciding what indoor temperatures to use for simulations in this project. There is a graph, from which the indoor temperatures could easily be read out. Table 2.12 shows the values used for simulations.

Table 2.12 *The values for the parameter Indoor temperature used for simulations.*

Percentile	**Indoor temperature/ °C**
90	23.7
70	22.7
50	21.9
30	21.4
10	20.2

2.2.6 Air flows

The report from Swedish National Housing Board used in e.g. chapter 2.2.1 was also used when obtaining the input values for this parameter. The board has decided through national rules and regulations that the airflow into a building should at least be 0.35 $l/(s \cdot m^2)$ (Boverket, 2010). In addition, BETSI report states that the mean value for air flows are a bit higher for the apartment buildings from the period around 1970's. Therefore, the values for this parameter were assumed for the 10th, 50th and 90th percentiles. The values for the 30th and the 70th percentiles were calculated through normal distribution according to equations 2-1 and 2-2. Table 2.13 shows what values were used in the simulations for this parameter.

Table 2.13 *The values for the parameter Air Flows used for simulations.*

Percentile	**Air flows/ ($l/(s \cdot m^2)$)**
90	0.67
70	0.58
50	0.53
30	0.47
10	0.39

2.2.7 Electricity

Tenant electricity

The report from project THUVA II used in chapter 2.2.2 was also used when deciding what values this input parameter will adopt. There is a graph in that report from which the values needed for this thesis could easily be read out (Bagge, et al., 2015). However, these values need to be transformed from *kWh/*(m^2*·year)* to *W/zone* in order to be able to use them in the simulation tool. More information about how this transformation was done is provided at the end of this subchapter. Table 2.14 shows all the values used for the simulations in IDA ICE.

Table 2.14 *The values for the parameter Tenant Electricity used for simulations.*

Percentile	Tenant electricity/ (kWh/(m^2·year))
90	46
70	34
50	26
30	21
10	16

Facility electricity

A report from a project that tried to map the electricity use of apartment buildings in Sweden was used when deciding the value falling under the 50th percentile for this input parameter. In that report, it can be found that the average electricity use for apartment buildings in Sweden is 22 kWh/(m^2·year) (Bröms & Wahlström, 2008). This value is thus considered to fall under the 50th percentile and needs to be converted to W/zone before using it in the simulation tool. More information about this conversion is provided at the end of this subchapter. The values for the 10th and 90th percentiles were assumed by educated guess and the values for the 30th and 70th percentiles were calculated through normal distribution using the equations 2-1 and 2-2. Table 2.15 shows the values falling under the different percentiles used in this project.

Table 2.15 *The values for the parameter Facility Electricity used for simulations.*

Percentile	Facility electricity/ (kWh/(m^2·year))
90	55
70	30
50	22
30	15
10	5

Unit transformation

As already mentioned, the values from Table 2.14 and Table 2.15 need to be transformed into different units in order to be used in the simulation tool. This transformation is done from *kWh/(m^2·year)* to *W/zone* and is presented in Table 2.16. Equations 2-3 and 2-4 were used for this transformation:

$$EL_{tenant} = \frac{Y \cdot 1000/8760 \cdot 736.53}{16} \qquad (2\text{-}3)$$

$$EL_{facility} = \frac{Z \cdot 1000/8760 \cdot 840.2}{4} \tag{2-4}$$

Y & Z represents the value falling under a certain percentile. Number 736.53 is building total area in m^2 of only the apartments, and 840.2 is the total are of the building in m^2, both obtained from the simulation tool. The number 8760 is the total number of hours per year. The numbers 16 and 4 are the total amount of zones used in the simulation model for tenant and facility electricity, respectively.

Adding this information into the simulation tool was a bit tricky and needed to be simplified, since the working model is simplified itself. This was solved by only adding one light source and one equipment point per zone, which also meant per apartment, and dividing the total power per zone as shown in Table 2.16 between these two. An assumption was made for how much of the total power per zone should be assigned to the light source and equipment point, respectively. This was done by assuming a ratio between lights and equipment to be 30/70 for tenant electricity and 10/90 for facility electricity. This is also presented in Table 2.16.

Table 2.16 *Values (rounded) for tenant and facility electricity used in the simulation tool.*

Percentile	**Tenant electricity/ (W/zone)**			**Facility electricity/ (W/zone)**		
90	242	Light	73	1319	Light	132
		Equipment	169		Equipment	1187
70	179	Light	54	719	Light	72
		Equipment	125		Equipment	647
50	137	Light	41	528	Light	53
		Equipment	96		Equipment	475
30	110	Light	33	359	Light	36
		Equipment	77		Equipment	324
10	84	Light	25	120	Light	12
		Equipment	59		Equipment	108

2.2.8 Occupants

The same report from project THUVA II used in chapter 2.2.2 was used when deciding the input values for this parameter. In that report, there can be found that the mean presence in buildings is set to 0.0166 people per m^2 (Bagge, et al., 2015). The reason for this odd number is that it accounts for the schematics of the presence, since the occupants are not present all the time inside of a building. However, the number 0.0166 needs to be adapted for the simulation tool in a way that it shows the presence as amount of occupants per apartment (pcs/apartment). This was done by multiplying 0.0166 by the total area of the eight apartments of the building, which gives a value of 12.2259. This number is then divided by the amount of apartments, i.e. eight, which gives the result of approximately 1.53 pcs/apartment. The number 1.53 was considered as the value falling under the 50th percentile. The values for the 10th and the 90th percentiles were educationally assumed, and the values for the 30th and the 70th percentiles were calculated through normal distribution according to Equations 2-1 and 2-2. Table 2.17 shows all values falling under the five different percentiles, which were used for the simulations in this project.

Table 2.17 *The values for the parameter Occupants used for simulations.*

Percentile	**Occupants/ (pcs/apartment)**
90	2.78
70	2.04
50	1.53
30	1.25
10	0.84

2.3 Processing the input parameters

Because there are thirteen parameters and five different values per parameter, and because the simulation tool can only considerer one value per parameter at a time, some kind of strategy was needed in order to consider all of the parameters for the result output. A statistical method called Monte Carlo simulations was implemented. It is possible to make a detailed analysis of the input parameters, but in order to do that, 13^5 different simulations would have to be performed. This is of course not possible in reality. Instead, 100 different simulations were performed. The values of the input parameters used in the simulation tool were picked by randomly selecting thirteen of the values, one of each for every simulation. The random number generator function in Excel was used. After performing the 100 simulations, the results (building yearly energy use) were gathered and arranged from highest to lowest. Since unknown set of data tends to follow normal distribution according to statistical theory, an interval around the 50th percentile was obtained within which the probability is the highest that the building yearly energy use should lie. More information about this is provided in chapter 3.

2.4 Input parameters - Overview

In Figure 2.1, all the parameters are presented together with their specific values for the different percentiles used in the simulation tool. This presentation is for overview purpose. The value falling under the 10th percentile is always to the left or upper. The value falling under the 90th percentile is to the right or lower. The three other values in between are the values representing the 30th, 50th and 70th percentiles, in order from left to right or up to down, respectively.

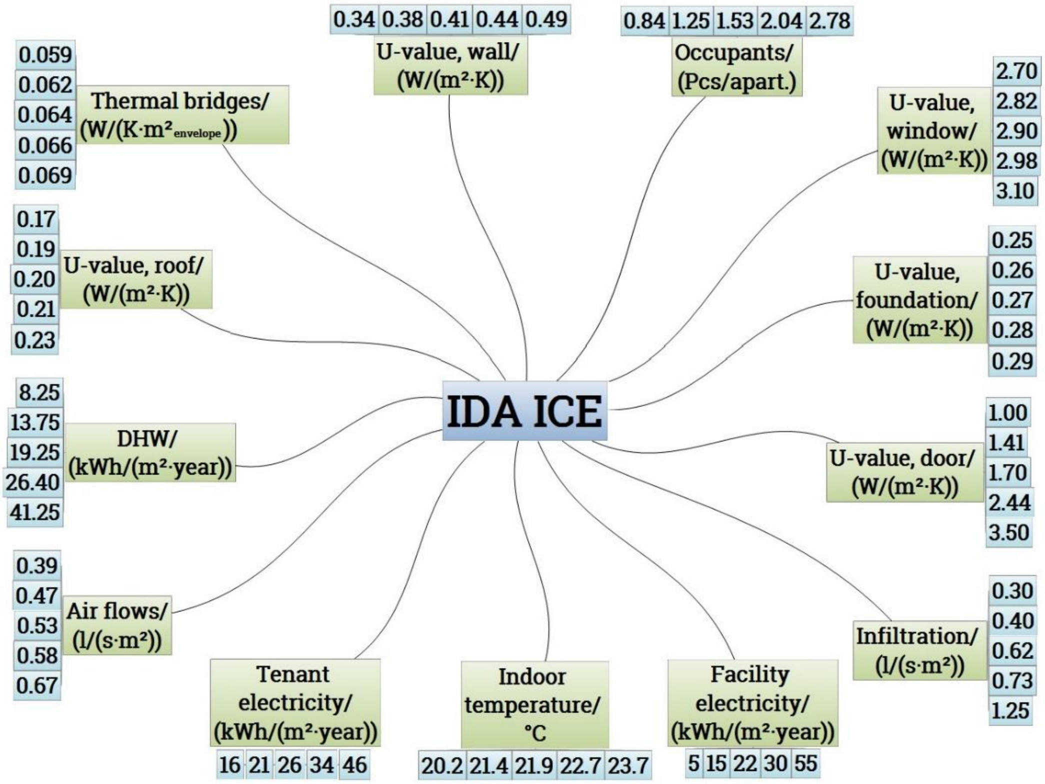

Figure 2.1 *Overview of all the 13 parameters, and their values, used for simulations. Values for 10th percentiles (up/left); values for 90th percentiles (down/right). Values for 30th, 50th and 70th percentiles, respectively (in between).*

2.5 The simulation tool – IDA ICE

When running the necessary simulations needed for this project, the simulation tool IDA ICE was used exclusively. IDA ICE or IDA Indoor Climate and Energy is a building simulation tool that accurately models the building geometry and its systems such as ventilation, heating, cooling, wind/electrical plants etc. as well as its controllers. The tool simulates in a whole-year and dynamic multi-zone manner that reflects the thermal indoor climate of one or more zones as well as the yearly energy use of the entire building. The tool is developed by a Swedish privately held company called EQUA, which was founded in Stockholm, year 1995, but is today available in many countries and in many languages all over the world (EQUA, 2016). For this project, version 4.7 of the tool was used.

2.5.1 General prerequisites

Some general settings in IDA ICE were changed from default to specific. These changes are presented in Table 2.18. Note that the rest of the settings are left on default. Default values for transformation from energy to heat in IDA ICE regarding light and equipment were set to 60 %, which means 40 % of the energy transforms to heat. Par example, the specific energy use for tenant electricity between the low and median values varies by 10 kWh/(m^2·year) and 40 % of this energy is 4 kWh/(m^2·year), which means the specific energy has also decreased by that much.

Table 2.18 *General prerequisites for input values used in IDA ICE.*

Factor	**Input value**
Location data	Linköping/Malmslätt (ASHRAE 2013)
Climate file	Linköping/Malmslätt
Wind profile	Suburban (ASHRAE 1993)
Zone model fidelity	Energy model
Integrated window shading	Blinds between panes (BRIS)
Generator efficiencies heating - COP	District -1
Generator efficiencies cooling - COP	District -1
Generator efficiencies DHW - COP	District -1
Orientation of the building	33°
Type of ventilation system	CAV
Schedule for internal gains	Always on
Pressure rise for air supply (Fan)	600 Pa
Pressure rise for air exhaust (Fan)	400 Pa
Simulation type	Periodic, with time-split parallelization

2.5.2 Choosing the level of detail in the simulation model

The duration of a single simulation depends mostly on two things; one is the computer processing power and the second is how much information the simulated model contains. Comparison between different simulation models, where all the models have the same specific settings in IDA ICE is needed to determine the duration. The method used in this comparison were performed by setting all the 13 parameters to the values that represent the 50th percentile for each specific parameter. All other settings were set to default and the model was simulated as an energy model and not as a climate model. The reason for doing this is to find out if a simpler model may be used for numerous simulations performed in this project later on, in order to save time, but not at the expense of the accuracy of the model.

The four models, which were compared, are presented in Figure 2.2, where the number (1) illustrates the detailed model, the number (2) illustrates the apartment division, the number (3) illustrates the apartment + north and south division and the number (4) illustrates the floor division.

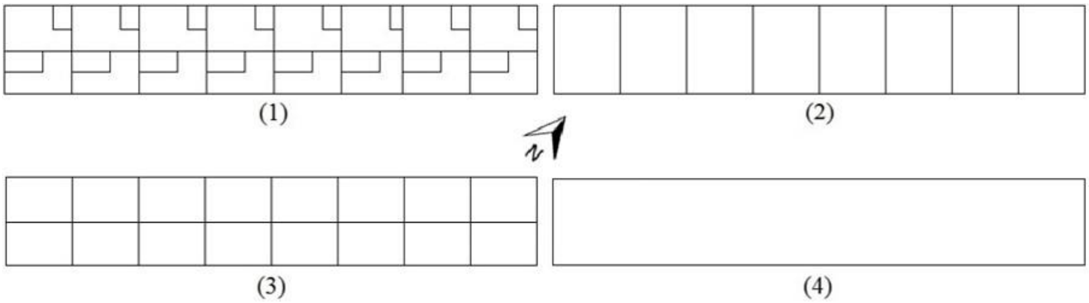

Figure 2.2 *Comparison between different simulation models in IDA ICE.*

The floor layout for the detailed model was modelled as accurately as possible compared to the drawings with all the separate rooms in each apartments. The apartment division is modelled with one zone for each apartment, which means that all the separate rooms are joined together with no internal walls beside the loadbearing walls between each apartment. The floor layout for the apartment + north and south division is similar to the previous model. The added change is north and south division, which means that each apartment is separated by an internal wall, in order to compensate for the fact that the solar gains are higher on the south side of the building. The floor layout for the floor division is modelled with no internal walls on the entire floor area.

Table 2.19 show that the detailed simulation of the building had both the highest energy use and duration per simulation. The “Apartment + north/south division”-model is one of the more accurate models together with “Floor division”-model from an energy use perspective. The two models energy use are 16 kWh/(m^2·year) less, compared with the “Detailed”-model. From a duration perspective, the fastest model is “Apartment division”. The model, which was chosen from both an energy use and duration perspective, was “Apartment + north/south division”. The reason for this choice is that the results of the energy use differs the least compared to the detailed model, which is considered as more important than the duration per simulation.

Table 2.19 *Choice in type of model used for sensitivity analysis simulations (green).*

Model	**Energy use/ (kWh/(m^2·year))**	**Time per simulation/ sec**
Floor division (1 zone = 1 whole floor)	167	260
Apartment + north/south division (1 zone for north side of one apartment, 1 zone for south)	**167**	**170**
Apartment division (1 zone = 1 whole apartment)	160	157
Detailed (1 zone = 1 room)	183	7300

2.6 Heat recovery

When all of the 100 simulations were finished, additional simulations were performed with added heat recovery onto the ventilation system. The simulations with heat recovery were performed on the 10th, 25th, 50th, 75th and 90th simulation file, after the files were arranged from highest to lowest, in order to represent the different percentiles for the heat recovery parameter.

In IDA ICE, the heat recovery was added by accessing the heat exchanger through the air-handling unit (AHU), which is listed under HVAC system tab. The heat exchanger efficiency was varied in three steps 75 %, 80 % and 85 % on each of the files representing the five percentiles (10th, 25th, 50th, 75th and 90th). Additional setting that was made in IDA ICE considering the heat exchanger is that the minimum allowed leaving temperature was set to 1°C. This is in order to prevent frost damages in the ventilation system.

2.7 Building information

In this chapter, all relevant information about the building will be provided, such as geometrical information, technical information, building envelope materials etc. This information is used for building a working model in IDA ICE needed for running all of the necessary simulations needed in this project.

The studied building used in this project was already a subject of a big research study, which was partially run by Lund University. The purpose of the study was to see how big the savings could be if heat recovery is installed to the current exhaust air only ventilation system. This gave access to much of the information about the building, which was already prepared. We had access to a contact person who is an operating technician of the building in Linköping where the building is situated, who could help us with gathering all the needed information. In addition, a study visit to the site was done for one day, where additional technical information on the building could be obtained.

2.7.1 Geometrical information

The building, built in 1969, is a typical two-floor building from the “Million Program”, without a basement and with a cold attic. It has never been renovated between the years 1969 - 2016.

Figures 2.3 and 2.4 show the original drawings of the building, which could be obtained from the building technician. As can be seen in the figures, the quality of the drawings varies a lot. Figure 2.3 showing the façades and gables of the building is of relatively good quality, whilst Figure 2.4 showing the floor plans of the building is in considerably worse condition. As mentioned, the bad quality of drawings is a common problem for buildings that are a few decades old. This problem may lead to that assumptions have to be made when modelling a building in a simulation tool. In this example, there was a scale present on all the drawings so the made assumptions were kept at a minimum. Figure 2.5 shows the floor plans of the whole building in a more detailed manner.

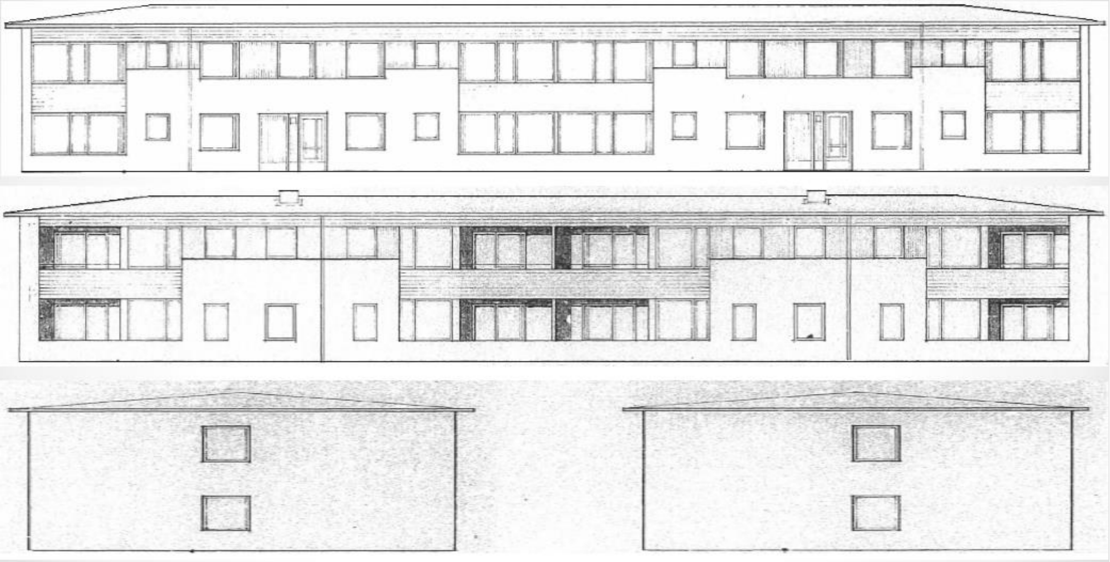

__Figure 2.3__ The façades and gables of the building. Northwest façade (upper), southeast façade (middle), southwest gable (lower left) and northeast gable (lower right).

__Figure 2.4__ Floor plans, original drawings. Ground floor (upper) and first floor (lower). There are in total six two-bedroom apartments (red) and two three-bedroom apartments (green).

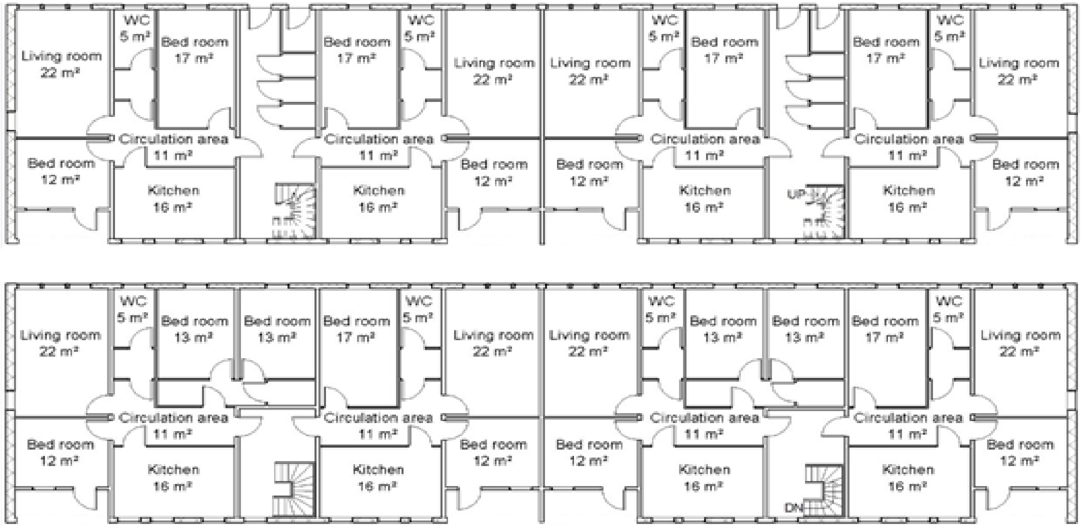

Figure 2.5 *Floor plans (detailed). Ground floor (upper) and first floor (lower).*

2.7.2 Radiators

Table 2.20 presents the power from each radiator, which were obtained from drawings. Each radiator specific power was attached to a specific window type. These radiators are placed underneath all windows in IDA ICE with their specific powers added. The length of the radiators are the same as the length of the windows.

Table 2.20 *Placement of radiators under the different window types according to Figures 2.14 and 2.15 in chapter 2.8.5.*

Window type	**Radiator power/ W**
F31	375
F32	485
F21	510
F143	825
F63	1015
F62	1135
XP1	1400
F73, F40, F143 (Living room)	1620
F143 (First floor)	915
F62 (First floor)	1100

2.8 Building technology

In this chapter, the building technology of the studied building will be presented in order to give a more detailed information regarding the construction. The materials and layers in the construction of the building is presented to show how the model is built in IDA ICE, where only the thickness of the insulation is modified to meet the desired U-values presented in chapter 2.2.1. The materials and their properties were collected from drawings, site visiting and different sources from internet. In addition, a physical book called “Så Byggdes Husen” was used (Björk, et al., 2013). The book describes the materials of typical buildings built throughout the years in Sweden. The building has three different external wall types, which are the gable walls, the balcony walls, and the external walls with brick and wooden panel as the external layer.

Using IDA ICE, the building was modelled with the help of the information obtained from the drawings. Some simplifications were made on the construction when modelling the building in IDA ICE. This was done to eliminate the errors from the program on the junctions of each corner or with the different wall types.
The external wall on the building was constructed as a brick wall with wooden panels close to the windows.

2.8.1 Roof

The roof structure of the building was constructed as a cold attic with the inclination of 1:20, which means that the insulation is placed on the concrete slab. Figure 2.6 shows a schematic picture of the roof construction.

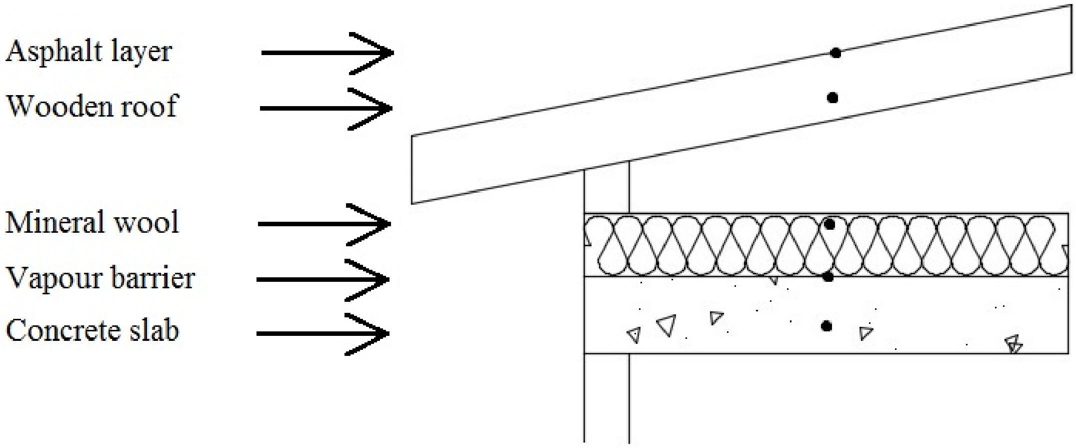

Figure 2.6 *Layers of the roof construction.*

Table 2.21 presents the different thicknesses of the materials in the roof. The total thickness of the roof slab is 290 mm.

Table 2.21 *Materials of the roof construction with their thicknesses.*

Material	Thickness/ mm
Asphalt layer (outside)	-
Wooden roof	-
Insulation	130
Vapour barrier	-
Concrete slab (inside)	160

2.8.2 External walls

The external walls are constructed as a brick wall where areas close to the windows and balconies have wooden panel as the external layer instead of brick. The building has three different types of walls; the description of the walls is in following order: gable walls, balcony walls, external walls with brick and wooden panel around some windows and doors as the external layer. Figure 2.7 shows a schematic picture of the gable wall construction.

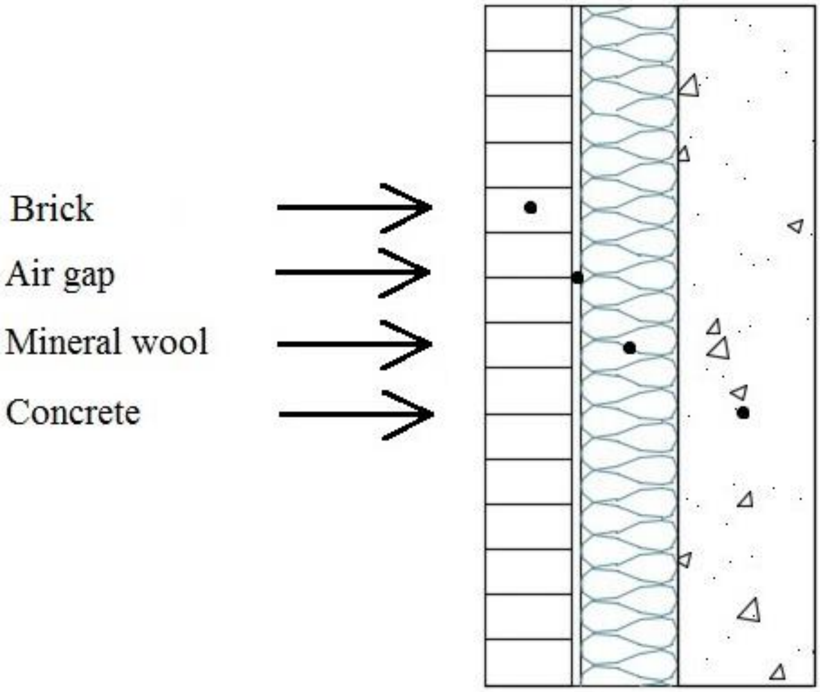

Figure 2.7 *Layers in the gable wall construction.*

Table 2.22 presents the different thicknesses of the materials in the gable walls. The total thickness for the gable wall is 360 mm.

Table 2.22 *Materials of the gable wall construction with their thicknesses.*

Material	Thickness/ mm
Brick (outside)	100
Air gap	10
Mineral wool	100
Concrete (inside)	150

Figure 2.8 shows a schematic picture of the balcony walls construction obtained from drawings.

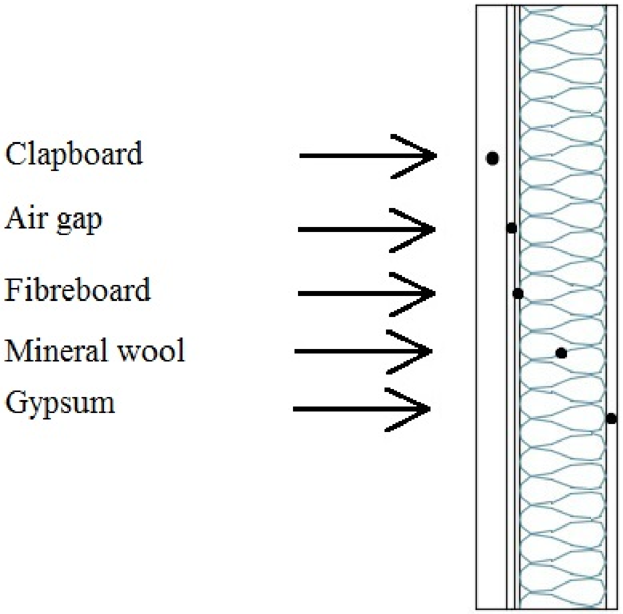

Figure 2.8 *Layers in the balcony wall construction.*

Table 2.23 presents the different thicknesses of the materials in the balcony walls. The total thickness of the balcony wall is 160 mm.

Table 2.23 *Materials of the balcony wall construction with their thicknesses.*

Material	Thickness/ mm
Clapboard (outside)	37
Air gap	10
Fibreboard hard	3
Mineral wool	100
Gypsum (inside)	13

Figure 2.9 shows a schematic picture of the external wall construction obtained from the drawings.

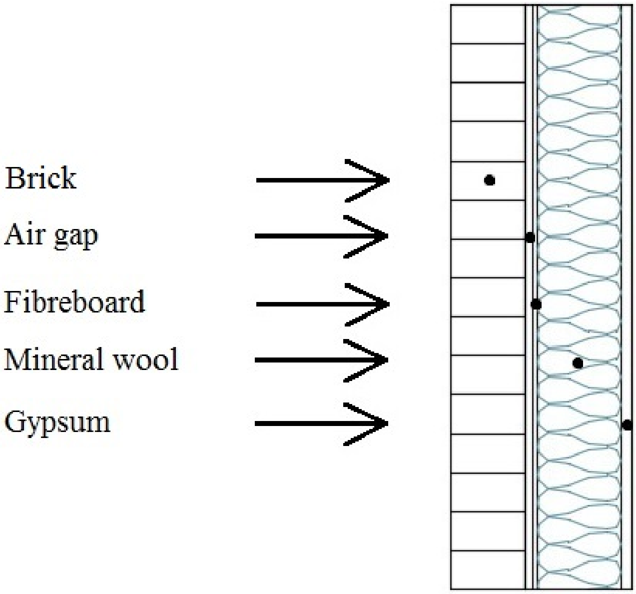

Figure 2.9 *Layers in the external wall construction.*

Table 2.24 presents the different thicknesses of the materials in the external wall. The total thickness of the external wall is 226 mm.

Table 2.24 *Materials of the external wall construction with their thicknesses.*

Material	**Thickness/ mm**
Brick (outside)	100
Air gap	10
Fibreboard hard	3
Mineral wool	100
Gypsum (inside)	13

2.8.3 Internal walls

Internal walls between each apartment are load bearing concrete walls with a thickness of 150 mm. Figure 2.10 shows a schematic picture of the internal loadbearing wall construction.

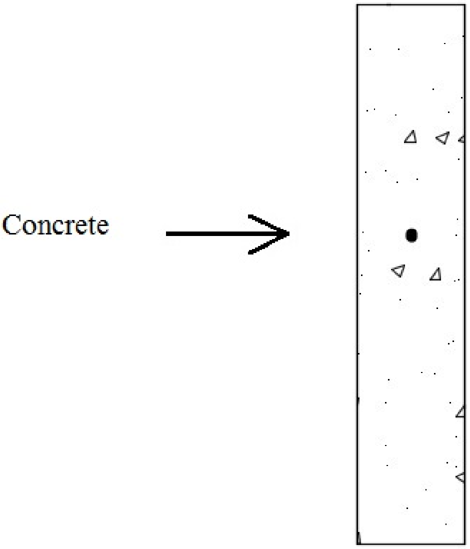

Figure 2.10 *Layers in the internal loadbearing wall construction.*

Table 2.25 presents the thickness of the material in the internal loadbearing wall.

Table 2.25 *Materials of the internal wall construction with their thicknesses.*

Material	**Thickness/ mm**
Concrete wall	150

Internal walls within the apartments are wood structured walls. Figure 2.11 shows a schematic picture of the internal wall construction obtained from drawings.

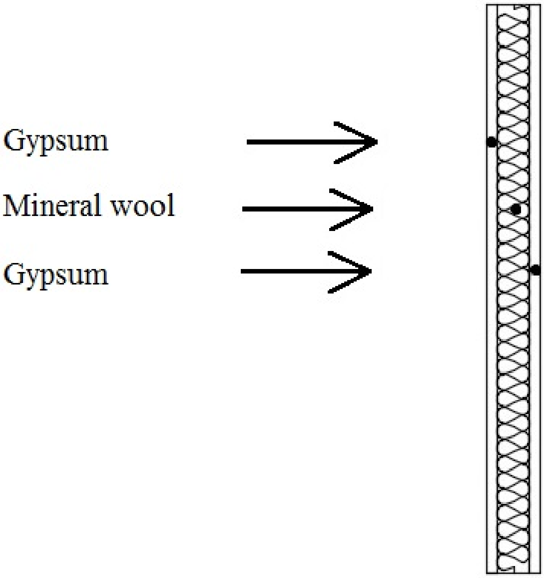

Figure 2.11 *Layers in the internal wall construction.*

Table 2.26 presents the different thicknesses of the materials in the internal wall. The total thickness of the internal wall is 70 mm.

Table 2.26 *Materials of the internal wood constructed wall with their thicknesses.*

Material	Thickness/ mm
Gypsum	13
Mineral wool	44
Gypsum	13

2.8.4 External and internal slab

The external and internal slabs are constructed with concrete layer where the internal layer is floor coating. Figure 2.12 shows a schematic picture of the external slab construction.

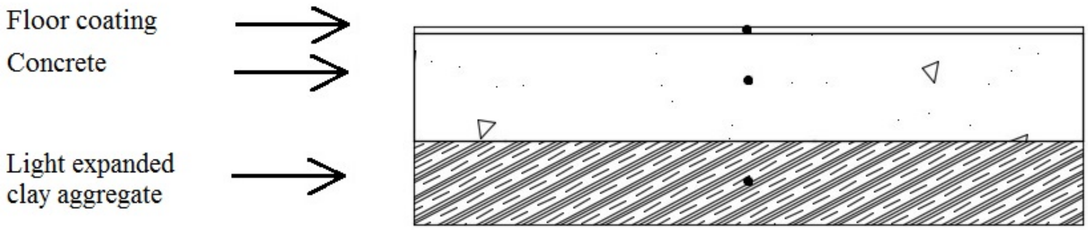

Figure 2.12 *Layers in the external slab construction.*

Table 2.27 presents the different thicknesses of the materials in the external slab. The total thickness of the external slab is 295 mm.

Table 2.27 *Materials of the external slab construction with their thicknesses.*

Material	Thickness/ mm
Floor coating (top layer)	10
Concrete	160
Light expanded clay aggregate (bottom layer)	125

Figure 2.13 shows a schematic picture of the internal slab construction used between floors.

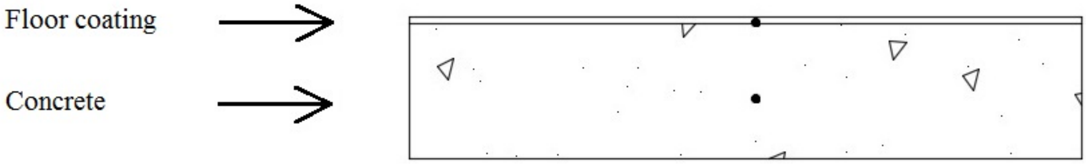

Figure 2.13 Layers in the internal slab construction.

Table 2.28 presents the different thicknesses of the materials in the internal slab. The total thickness of the internal slab is 210 mm.

Table 2.28 *Materials of the internal slab construction with their thicknesses.*

Material	Thickness/ mm
Floor coating (top layer)	10
Concrete (bottom layer)	200

2.8.5 Windows

The windows are constructed with a wooden frame with two-pane glass. The windows have never been replaced under the lifetime of the building. The sill height for the windows varies from 800 mm to 1200 mm depending on the type of the window as Table 2.29 shows. Total number of windows on the building is 90.

Table 2.29 *All the windows, external doors and balcony doors on the buildings envelope with their size and quantities.*

Literature	Width/ mm	Height/ mm	Sill height/ mm	Amount/ pcs
F 21	885	985	1200	8
F 31	885	1385	800	4
F 32	1185	1385	800	6
F 40	585	1585	800 (640 Living room)	16
F 62	1185	1385	800	8
F 63	1485	1385	800	10
F 73	1485	1585	640	8
F 143	1485	1385	800 (640 Living room)	16
FD 1	885	2185	-	8
XF 1	1185	1185	1200	6
XP1	890	2065	-	4

Figure 2.14 and 2.15 show the placement of all the windows, external doors and balcony doors around the building envelope. These figures are presented to link the

specific window literature to a specific placement in the building together with the specific radiator type (according to Table 2.20) underneath it. The floor plans are taken from IDA ICE. Note that only the left floor plans are displayed and the right part is an identical mirrored image. This choice in display is due to clarity reasons.

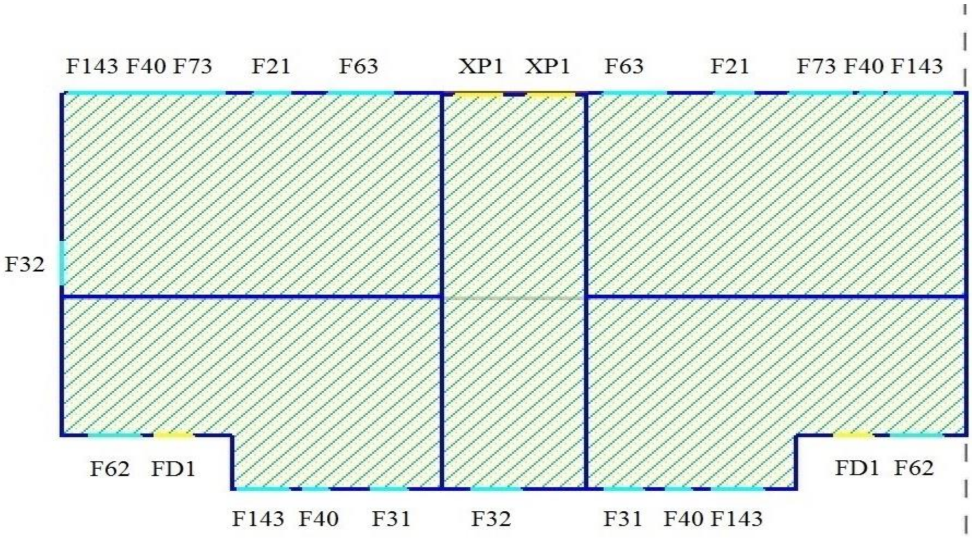

Figure 2.14 *Placement of every windows, external doors and balcony doors on the ground floor according to Table 2.29. Only half of the floor is displayed; second half is a mirrored image to the right and is identical.*

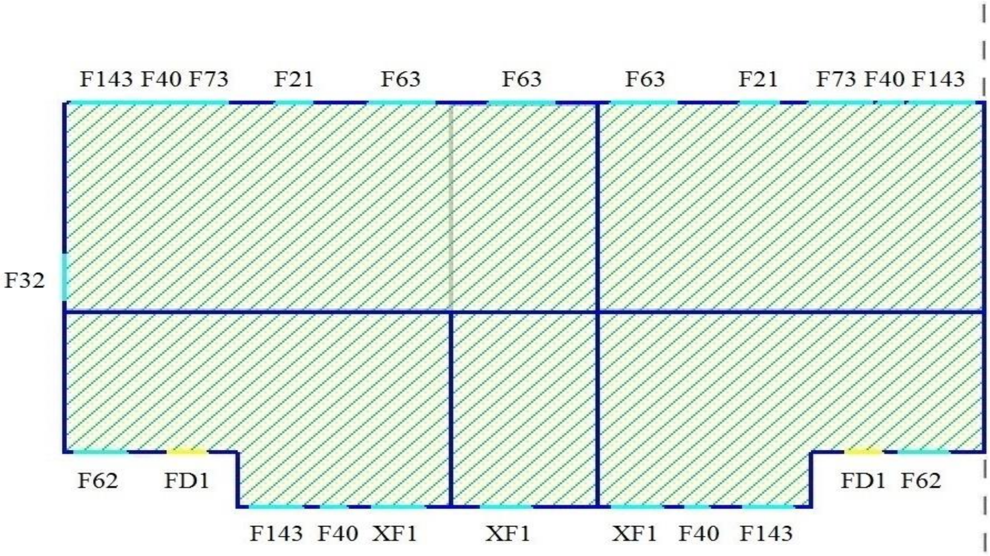

Figure 2.15 *Placement of each windows, external doors and balcony doors on the first floor according to Table 2.29. Only half of the floor is displayed; second half is a mirrored image to the right and is identical.*

2.8.6 Doors

The construction of the apartment doors was simplified since the need for details was considered as unnecessary in this project. The default materials in IDA ICE were used when making a door and only the thickness was varied in order to obtain the desired U-values as presented in Table 2.5 in chapter 2.2.1.

3 Results

This chapter presents the average energy use and the distribution of simulated energy use, which describes the distribution of the 100 simulations and what the average energy use is. In addition, the impact on the energy use by individual parameters are presented as well. Selected individual parameters are chosen for the reason that they can easily be controlled with real-life measurements. Moreover, heat recovery is presented as well, which compares the specific energy use of a ventilation system with and without heat recovery.

3.1 Average and distribution of simulated energy use

Figure 3.1 shows the average specific energy use as a function of the number of simulations. The values of the input parameters in the simulations are all randomly selected. The average specific energy use, as calculated in Excel, for all of the 100 simulations is 177 kWh/(m^2·year), which means that in theory, the building yearly energy use should be this particular value. However, there is no way to be certain that this obtained value is the right one due to the many uncertainties. Therefore, an interval within which the real value should lie within is sought.

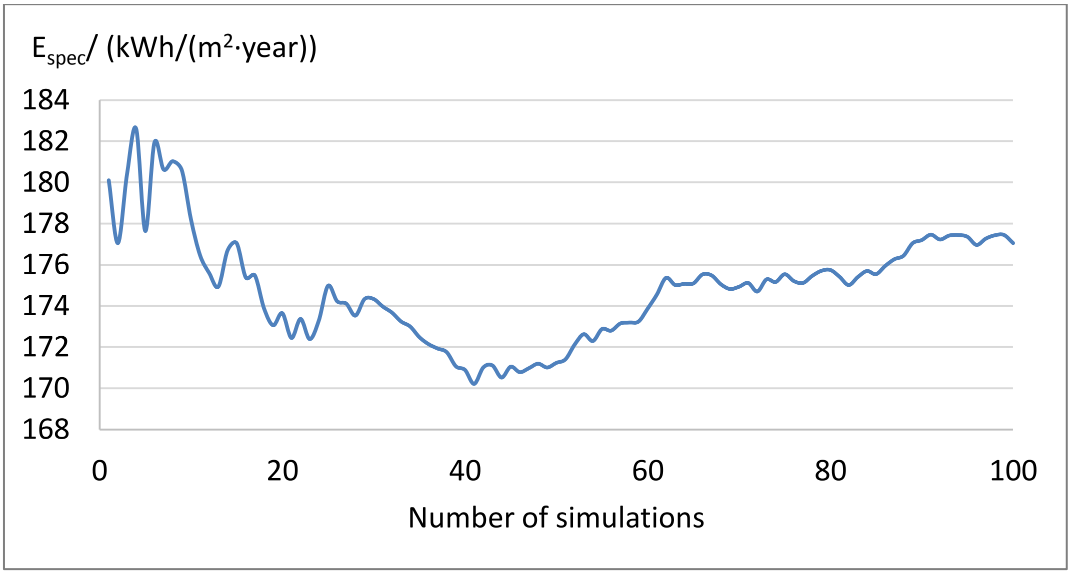

Figure 3.1 *Average value for the specific energy use after a certain number of simulations.*

Looking at Figure 3.1, the graph show that after a few simulations, the results showing the specific energy use can alter significantly from one simulation to another. With higher number of random simulations, the line showing the specific energy use shows a sign of levelling out around one value (mean) in the middle of the graph. This means that the building yearly energy use should be close to this mean value, i.e. approximately 177 kWh/(m^2·year).

Two extreme scenarios with high and low specific energy uses were also simulated in order to see within which span the building yearly energy use should lie within. The result for the extreme scenario with low specific energy use is 99 kWh/(m^2· year). This scenario was simulated with low U-values (i.e. the values falling under the 10th percentiles) on the building envelope and with low input values for the technical parameters. The parameters occupancy and tenant electricity were set to high input values (i.e. the 90th percentiles), because these parameters heat up the building for free.

The result for the extreme scenario with high specific energy use is 261 kWh/(m^2· year). This scenario was simulated with high U-values (i.e. the values falling under the 90th percentiles) on the building envelope and with high input values for the technical parameters. The parameters occupancy and tenant electricity were set to low input values (i.e. 10th percentiles). Thus, the interval within which the real building yearly energy use should fall under is between 99-261 kWh/(m^2·year).

The graph in Figure 3.2 show the distribution of the specific energy use for the 100 randomly selected simulations arranged from lowest to highest values in order to obtain the percentiles of the simulations themselves. Furthermore, the graph shows that the interval within which the specific energy use should lie within is 138– 230 kWh/(m^2·year) (min-max). According to statistical theory, it is most probable that the real value should lie within an interval between the 25th and 75th percentile, which as the graph shows is approximately 159 – 194 kWh/(m^2·year).

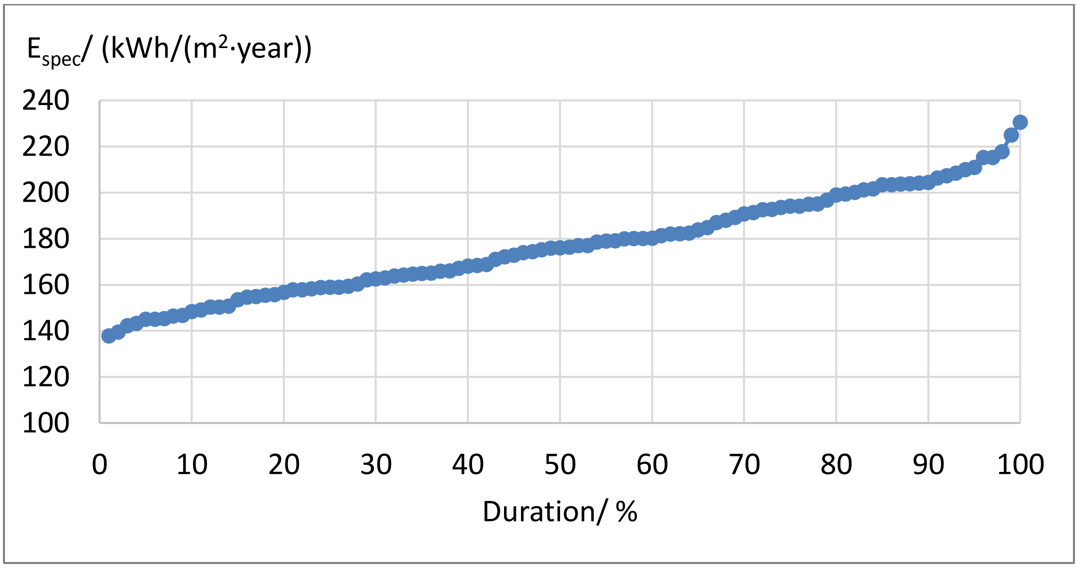

Figure 3.2 *Distribution of specific energy use for the 100 performed simulations.*

3.2 Individual parameters

In this chapter, some individual parameters are presented and processed in order to see their individual impact on the results. These particular parameters were chosen because they were considered as having the biggest impact on the results. In addition, they could easily be measured in real-life. The presented parameters are indoor temperature, ventilation flows, tenant electricity, facility electricity, domestic how water and heat recovery.

3.2.1 Indoor temperature

The graph in Figure 3.3 shows as expected that the specific energy use increase when the building is heated up to higher indoor temperatures. The line representing the mean value shows this trend. All the lines except the one showing the 90-percentile decrease at 21.9 °C, which could be because those specific simulations have some extreme values in their settings, due to random selection of the values of the input parameters, which decrease the overall energy use in the building. Par example, if the building indoor temperature is measured to 21 °C, then by looking at the graph it can be observed that the mean energy use of the building should be around 170 kWh/m^2·year (or in theory, within the interval of 150 – 195 kWh/(m^2·year)), if only this particular parameter is considered.

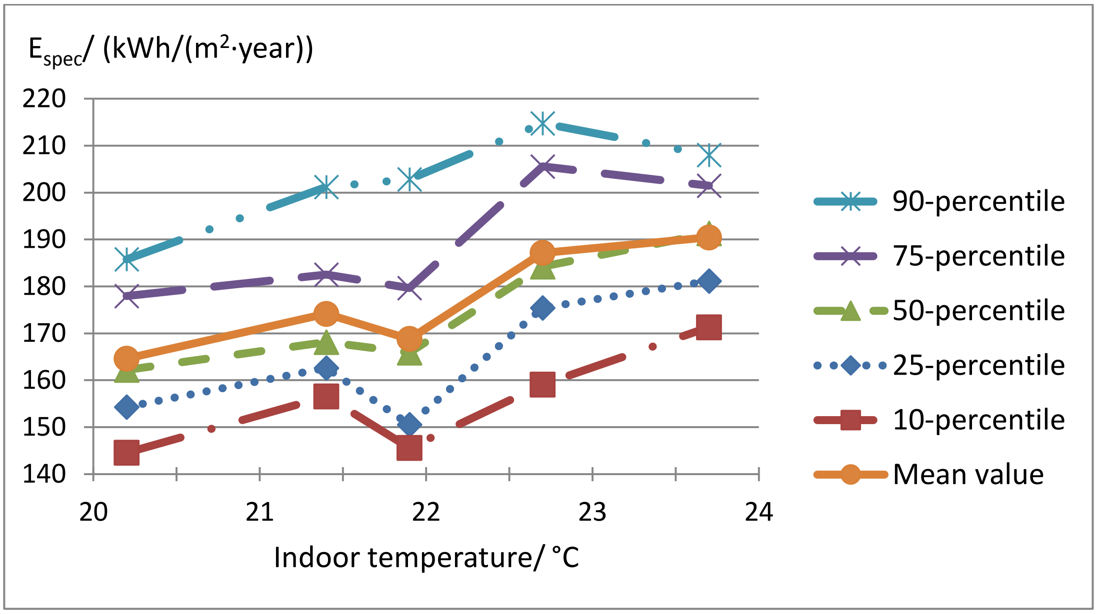

***Figure 3.3** Specific energy use as a function of indoor temperature.*

If the interval within which the specific energy use should lie is represented by 50 % of the simulations according to statistical theory (i.e. 25th to 75th percentile), then the interval for the specific energy use decreases to between 160 – 180 kWh/(m^2·year). By observing the different percentiles in Figure 3.3, it shows that the parameter indoor temperature is uncertain. This is because the percentiles increase or decrease more than the mean value does from one temperature point to another.

3.2.2 Air flows

The graph in Figure 3.4 show that the line representing the mean value for the specific energy use is increasing with higher airflows. If the airflows are measured and the result is for example 0.67 l/(s·m^2), then by observing the graph it can be seen that the building energy use should lie between 177 – 219 kWh/(m^2·year). If the result is represented by 50 % of the simulations closest to the median (i.e. 25th to 75th percentile), then the interval for the specific energy use decreases to 187 – 209 kWh/(m^2·year).

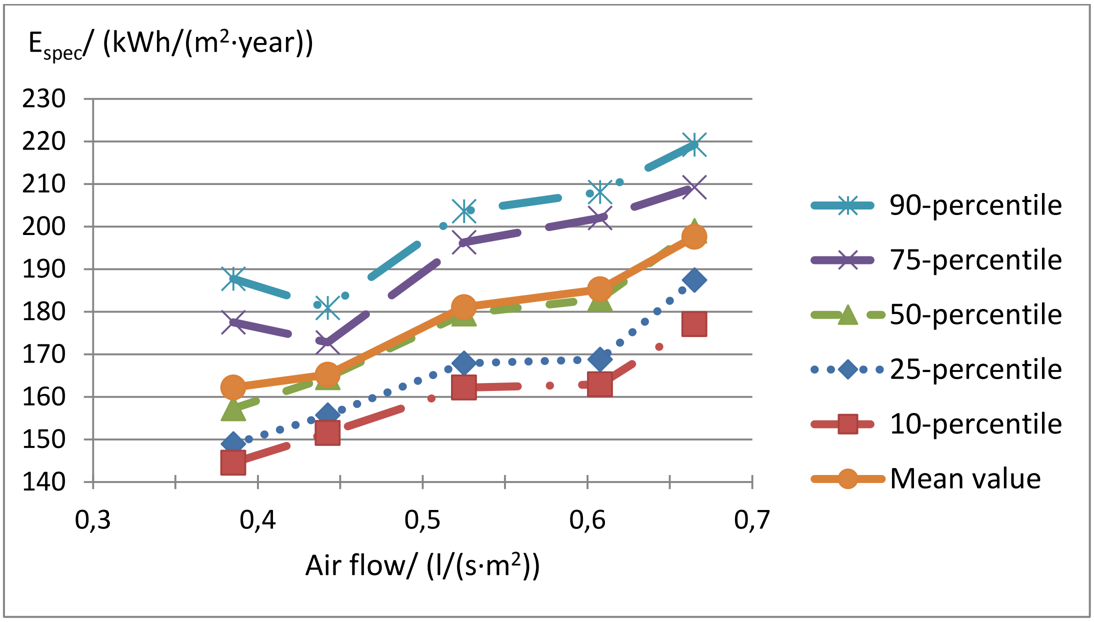

Figure 3.4 Specific energy use as a function of ventilation flows.

The different lines, for example the lines showing 75-percentile and 90-percentile on the graph in Figure 3.4, show that some of the extreme values with airflow 0.44 l/(s·m^2) have lowered the specific energy use. The mean value line for the specific energy use is still increasing with higher airflows. This indicates that the anomalies for the 75-percentile and 90-percentile lines occurring at the point of 0.44 l/(s·m^2) does not affect the mean specific energy use significantly.

3.2.3 Tenant electricity

The graph in Figure 3.5 show that the line representing the mean value for the specific energy use is decreasing when the tenants are using more electricity. The behaviour of the tenants would affect the building specific energy use, if the tenants in the building were for example using 34 kWh/(m^2·year). Then, by observing the graph, the building energy use should probably lie between 156 – 200 kWh/(m^2·year). If the result is represented from 50 % of the simulations (i.e. from 25th to 75th percentile), then the interval for the specific energy use have decreased to 163 – 197 kWh/(m^2·year).

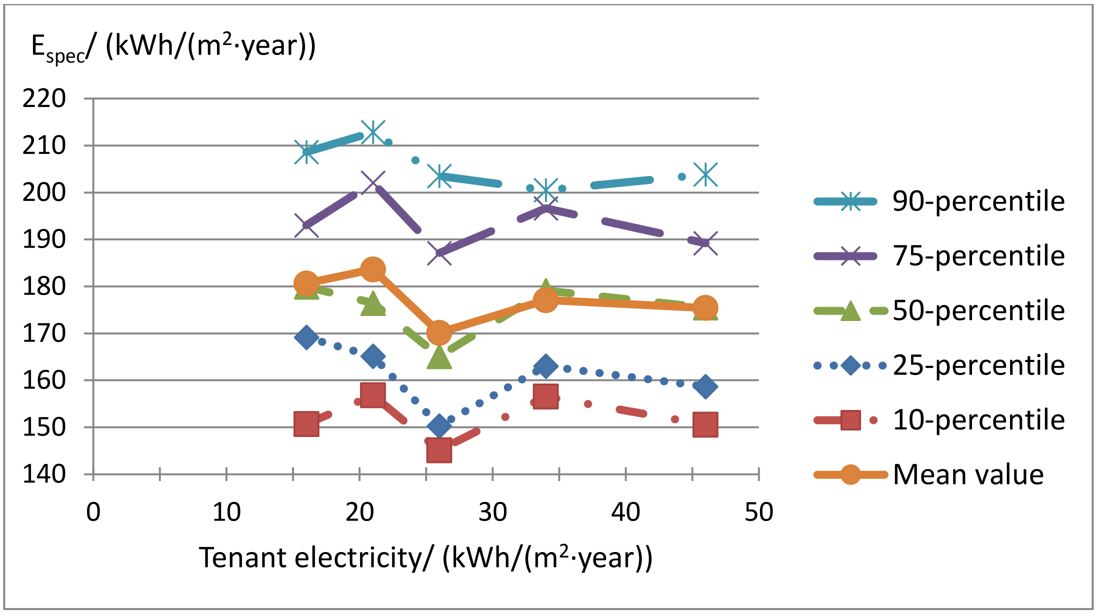

Figure 3.5 *Specific energy use as a function of tenant electricity.*

The different percentiles, on the graph in Figure 3.5 show that some of the extreme values with tenant electricity have increased the specific energy use. This can be observed on the point where the tenant electricity use is 21 kWh/(m^2·year). The mean value line representing the specific energy use is still decreasing slightly when the values goes from lower to higher tenant electricity, so those anomalies have not affected the specific energy use significantly.

By observing Figure 3.5, it is not clear if the specific energy use is decreasing sufficiently, so additional analyses were performed in order to see if the specific energy is decreasing enough. Table 3.1 show that when the tenants are using more electricity in the building, the specific energy is indeed decreasing, indicating that the graph in Figure 3.5 is reliable.

Table 3.1 *Additional analysis on tenant electricity in IDA ICE.*

Percentile	**Tenant electricity/ (kWh/(m^2·year))**	**E_{spec}/ (kWh/(m^2·year))**
90	46	166
50	26	174
10	16	178

3.2.4 Facility electricity

The graph in Figure 3.6 show that the line representing the mean value for the specific energy use is increasing when the building is using more electricity, which is in accordance to the theory. Depending on how much electricity the building is using, it would affect the specific energy use slightly. If the electricity for the facility in the building is for example 30 kWh/(m^2·year), then by observing the graph, the building specific energy use should most likely be around 145 – 203 kWh/(m^2·year). If we look at 50 percent of the simulations (i.e. 25th to 75th percentile), then the interval for the specific energy use have decreased to about 159–195 kWh/(m^2·year).

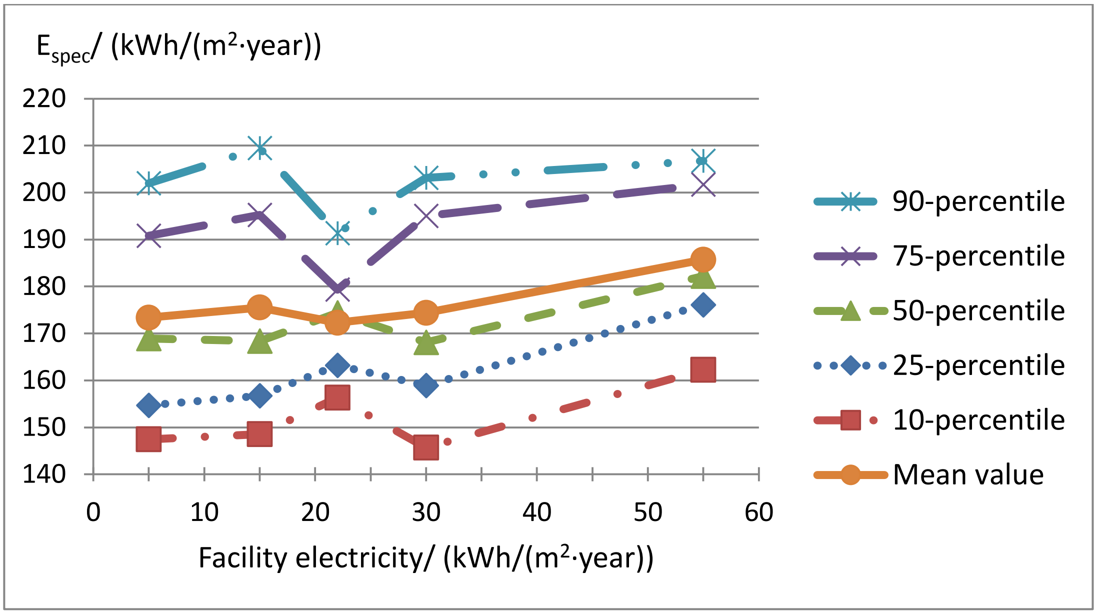

Figure 3.6 *Specific energy use as a function of facility electricity.*

The different percentiles in Figure 3.6 show that some extreme values have both decreased and increased the specific energy use. This can be observed on the point where the electricity for the facility are 22 kWh/(m^2·year) and 30 kWh/(m^2·year). The mean value is still increasing slightly with higher electricity use, so those anomalies do not affect the mean specific energy use significantly.

3.2.5 Domestic hot water

The graph in Figure 3.7 show that the line representing the mean value for the specific energy use is increasing when the building is using more DHW. If the owner of the building is measuring how much hot water the building is using and the result is for example 26 kWh/(m^2·year), then by observing the graph it can be seen that the building specific energy use should lie within the interval of about 157 – 201 kWh/(m^2·year). If we look at 50 % of the simulations instead (i.e. 25th to 75th percentile), then the interval for the specific energy use have decreased to around 165 – 194 kWh/(m^2·year).

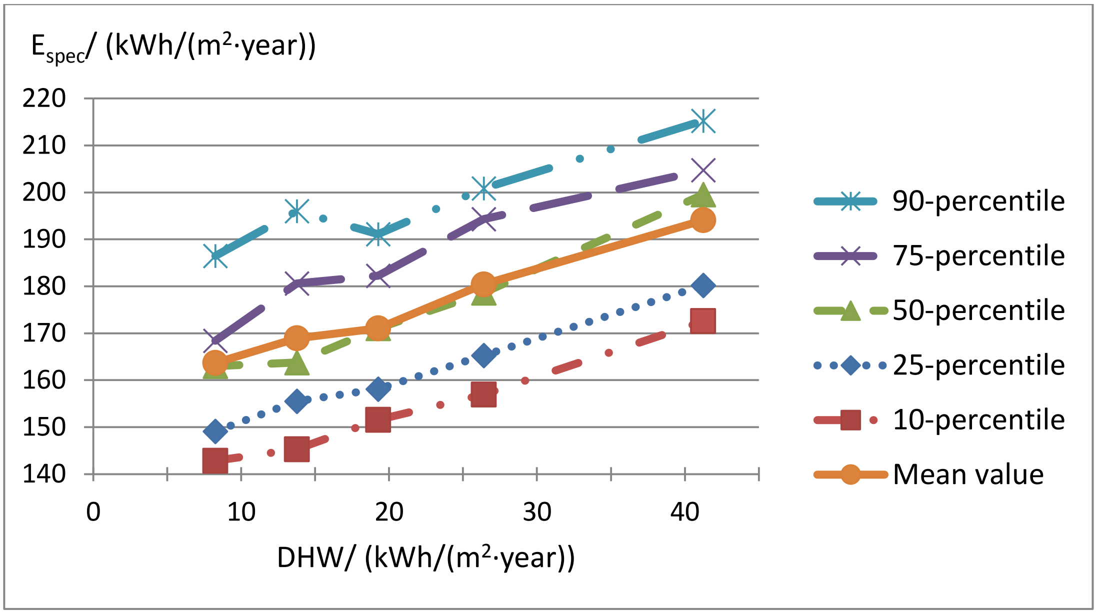

Figure 3.7 *Specific energy use as a function of domestic hot water.*

The graph in Figure 3.7 show that some of the lines representing different percentiles, for example 75-percentile and 90-percentile, have lower specific energy use while the domestic hot water is increased. This could be because some of the simulations where the domestic hot water is set to approximately19 kWh/(m^2·year) have been simulated with more extreme values on the other parameters due to random selection.

By observing the mean value in Figure 3.3, 3.4 and 3.7 a pattern can be observed. In these three cases the pattern for indoor temperature, ventilation flow and DHW occurs with the mean value starting roughly from 165 kWh/(m^2·year) and ending at 192 kWh/(m^2·year). This pattern can also be observed for the 10-percentile and 90-percentile lines in all of the three figures.

3.3 Ventilation with heat recovery

Table 3.2 shows the specific energy use of the building with the heat recovery added to the existing exhaust-only ventilation system. The heat recovery was simulated with an efficiency of 75 %, 80 % and 85 %. From the 100 simulations, different percentiles were selected for simulations with heat recovery. The percentiles selected were the files for the 10th, 25th, 50th, 75th and 90th percentile, and the extreme scenarios with maximum and minimum energy use. The specific energy use for each percentile was collected from Figure 3.2. The specific energy use varies between 100 – 260 kWh/(m^2·year) with exhaust air only as the selected ventilation system.

Table 3.2 *Specific energy use with heat recovery added on the exhaust air only ventilation.*

Percentile	**Specific energy use/ (kWh/(m^2·year))**			
	Exhaust air only	**Ventilation with heat recovery**		
		Heat recovery efficiency		
		75 %	**80 %**	**85 %**
min	100	70	68	66
10	148	110	108	106
25	159	118	116	115
50	176	129	127	125
75	194	135	131	128
90	204	149	146	145
max	260	202	199	197

By observing Table 3.2, it can be seen that the results differ when adding heat recovery. When the simulations are finished, the span for the energy use will probably vary between the 25th to 75th percentiles, which represents 50 % of the simulations around the median. With only exhaust air system, the building energy use should lie between 159 – 194 kWh/(m^2·year), and when adding the heat recovery on the ventilation system, the building energy use should instead vary between 115 – 135 kWh/(m^2·year). Thus, the energy savings utilised by adding heat recovery to the ventilation system compared to exhaust-only air system are between 44 – 59 kWh/(m^2·year).

To summarize, with heat recovery added on the ventilation system, the savings for the specific energy use are indeed achieved. With exhaust air only, the specific energy use of the building should lie within the interval of 159 – 194 kWh/(m^2·year). With added heat recovery on the ventilation system, the interval decreases to 115 – 135 kWh/(m^2·year). This gives the energy savings of 44 – 59 kWh/(m^2·year). Note that the presented values are most probable according the statistical theory, and that in real-life, the real values of the building energy use may very well lie somewhere between the extreme scenarios shown in Table 3.2

4 Discussion

This project was about trying to predict an existing building yearly energy use as accurately as possible, which is needed to know in order to decide whether it is viable to perform any energy renovations. To achieve the goal of predicting the yearly energy use, engineering and statistical methods were used, in the form of computer simulations through IDA ICE and Monte Carlo simulations, respectively. Many values along the way needed to be assumed (and they are mentioned throughout the report), which leads to greater inaccuracy in the end-result.

For starters, it is often hard to obtain accurate information of old buildings. Both drawings and other technical information may be in bad shape or unavailable. This was the case in this project. The drawings were often in bad shape or not detailed enough to make a completely accurate model in the simulation tool. Because of this, some of the values and other details needed to be assumed or simplified. These simplifications could maybe lead to the results not representing the reality as accurately as possible. Nevertheless, the available geometrical information was considered as adequate enough for the purpose. However, since the building was already a part of a big research project, other information such radiator power was available. This additional information only made it simpler to build a simulation model that was considered as representative of the reality as possible, which only facilitates the purpose of this project.

When building a model in the simulation tool, the information about the exact composition of the building components such as walls was required. As mentioned, the drawings were not detailed enough to provide this information. Instead, information about the composition of the components was found in a physical book that describes in detail how the buildings of that period were built in Sweden. Even though the information found in the book is considered as relatively accurate, there is no way to know that it completely corresponds to the actual building in question, without doing extensive field studies. Therefore, the U-values of the building envelope may differ significantly from the reality. In addition, all the information needed for the simulation tool about the windows and doors was assumed. This could also lead to unrepresentative results of the reality and it is not possible to know without performing extensive measurements.

One of the bigger parts of this project was to decide which input parameters to use and which values they should adopt. The latter is considered as the crucial part in accurately predicting a building yearly energy use; yet it is completely assumed. Although, the assumptions were made on the scientific basis, due to the time limitations and limited access to this type of information, only one or two sources per input parameters were used. When redoing the same type of project as this one, more time should be spent on finding the scientific sources in order to ensure the accurate representation of the reality. In fact, this part alone could be made into a whole, separate project.

When a representative value for one input parameter was found, there was no way of knowing if this value is accurate for this specific building. One example is the U-values for the wall; even if the exact composition of the wall is known, the age of the materials makes it hard to know the exact U-value in present. Therefore, a variation of the values was made in order to try to compensate for this uncertainty. The variation was made in five steps, where some of the found values was considered as the mean (or the 50th percentile), others as the 10th and 90th percentile, and the rest of the values were considered as normally distributed. The normal distribution of the values is purely an assumption, and this can lead to further inaccuracies. In some cases however, information about how the values of a certain input parameter should be spread was directly available from the source, which contributes to fewer uncertainties.

The simulation model in IDA ICE needed to be simplified due to time limitations, and limited computer power. As described in chapter 2.5.2, the amount of time per one simulation in the detailed model is significantly higher than for the chosen one. The fact that 128 simulations were performed in total makes it a necessity to choose the model that takes less time to simulate. This will of course give more unrepresentative results of the reality, and this fact needs to be considered. Furthermore, many of the settings in IDA ICE were left at their default values due to time limitations, which can also contribute to further uncertainties.

IDA ICE cannot run all of the processed input parameters simultaneously, but needs to run one set of values at a time, hence the random selection. This fact needs to be considered, since the reality is more dynamic than this. In addition, the way of input of certain values may be questionable. Par example, the tenant electricity was not known, but rather assumed. In addition, when inputting the assumed values for the tenant electricity, there was no way of knowing the number of equipment and light bulbs in each apartment. Therefore, if accurate results are required and there is more time, this information should be collected in detail. This goes for all of the other input parameters, really.

As mentioned, when doing the Monte Carlo simulations in this project, the number of runs were set to 100 due to time limitations. However, different sources recommend this number to be at least 500, and rather upwards of several thousands.

Even though the number of simulations were considered as adequate for the purpose of this project, if the time is not an issue more simulations should be performed, in order to be on the safe side.

Generally, when trying to predict the real energy use of a building per year, the methodology used in this project may be useful. The most important question that need to be answered is which level of accuracy is required to a certain type of project. If the accuracy level is high, then it subsequently leads to the fact that more time is needed in the design stage. As discussed above, there were many simplifications and assumptions made in this project. Many of these can be solved by accurately measuring the values of the input parameters. In addition, this whole project was made based on only one building, which makes it impossible to draw the conclusion that this methodology is representable in general. However, if the high level of accuracy for the energy use of a building is not needed, then the methodology used in this project can be very helpful.

5 Conclusion

The goal of this project was to try to predict a building total energy usage over the year. For this, simulations were performed in computer tool IDA ICE and statistical methods such as sensitivity analysis and Monte Carlo simulations were used. A single exact value of the building energy use could not be found, but rather an interval within which the real-life value should be, was sought.

Yearly energy use of the building was predicted to lie within the interval of about 100-260 kWh/(m^2·year). This interval could be further shortened to 160-191 kWh/(m^2·year) if the assumption is made that the collected data tends to be normally distributed around the median, i.e. between 25th and 75th percentiles. Furthermore, the average energy use of the building was predicted to be around 177 kWh/(m^2·year) after doing the 100 simulations.

Installing heat recovery on the current ventilation system was also considered in order to see what the energy savings might be. If assuming that the unknown data is normally distributed, the interval within which the building total yearly energy use should lie is about 115-135 kWh/(m^2·year). This corresponds to energy savings of about 42-62 kWh/(m^2·year), or 24-35 %.

The methodology presented in this project could be used for all types of existing buildings when trying to predict the yearly energy use. However, the accuracy that can be achieved to this date is limited. This is due to many uncertainties that arise when dealing with the input parameters. This could be solved if more research is done on this part in order to obtain a type of framework or database on the variation of input parameters for different types of buildings, which could be used for faster and more accurate collection of initial data.

Summary

In order to decide if any energy renovations should be implemented onto an existing building, present information about the building actual yearly energy use is required. This information could par example be obtained by extensive measurements on the building envelope (e.g. the U-values etc.), and on the building technical systems (e.g. ventilation flows etc.). After performing the measurements, the acquired information would need to be compiled and manually calculated and/or computationally simulated in order to get the final answer to how much energy a building actually use per year.

Even if this methodology would be most hands-on and could be made as accurately as desired, the economical and time costs of it would not be very well defendable. At this phase of a project of energy renovating a building, the information about the building energy use is preferably obtained as quickly as possible and with minimal initial costs. Therefore, the purpose of this thesis is to try to solve this problem by providing a relatively fast answer on how to obtain the actual building yearly energy use, and thereby minimizing the initial costs. The thesis is composed of five chapters and uses computational and statistical methods to deal with the problem. Another key moment of this thesis was to find out what input parameters to use and which values they should adopt.

Chapter 1 of this report is an introductory chapter, and is divided into three different parts. First part gives a general overview of why energy renovations are needed and should be made standard. Second part shows an extensive literature review done by the authors, which further strengthens the awareness of the importance of energy renovations onto existing buildings. Third part presents the aims and objectives of this thesis and provides a set of specific questions, which are answered throughout this report.

Chapter 2 is divided into four main parts (and many subparts), and it presents the complete methodology of this project. Part One deals with the input parameters which were needed for this report. Complete presentation of which input parameters were used and what values they adopted is presented here. Part Two presents the simulation tool as well as its general prerequisites. Part Three explains the methodology of what additional energy saving could be made if a heat recovery system was installed on an present exhaust air only ventilation. Part Four provides information about the case study building. Geometrical information, relevant technical information, and building technology is presented here.

The results chapter of this thesis is presented in Chapter 3. It is divided into three parts. Part One shows the results of the performed simulations, where an interval is obtained within which the building yearly energy use is most probable to fall. Part Two presents a sensitivity analysis of five different input parameters, which are thought to have the biggest impact on the results individually. Part Three shows the results of how much additional energy savings could be made by installing a heat recovery system onto a present exhaust air only ventilation system.

Chapter 4 is the discussion chapter, which discusses the thesis in general and highlights different encountered problems with the methodology, which need extra attention in order to be able to get the correct end-result. Generally, this chapter mentions that geometrical information about old buildings is often limited and assumptions need to be made when building a model in a simulation tool. Moreover, finding the values for different input parameters is tedious and more time is needed in order to maximize the accuracy of the end-result. Finally, this chapter argues that the results may be somewhat inaccurate because of the simplifications made to the simulation model due to time limitations.

The conclusions are drawn in Chapter Five. Most importantly, the yearly energy use of the building was predicted to fall within the interval of 100 – 260 kWh/(m^2·year), and this interval could be even more shortened to between 160 – 191 kWh/(m^2·year), after the statistical methods were implemented. Furthermore, when installing the heat recovery system onto the ventilation, the interval within which the building yearly energy use should fall within should be about 115 – 135 kWh/(m^2·year). This corresponds to additional energy savings of about 24 – 35 %.

On the endnote, the authors argue that the methodology used in this thesis can be implemented to all other types of buildings, but that the accuracy to this date is limited, mainly because of the uncertain input parameters. This problem could be solved by doing more research on different types of buildings, creating a type of framework and/or database regarding the variation of the input parameters.

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