Application of an energy sensitivity analysis when refurbishing buildings in Sweden

Denise Hermansson & Gabriela Miti Tsuge Costa

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Examiner: Henrik Davidsson (Department of Architecture and the Built Environment)

Supervisor: Åke Blomsterberg (Department of Architecture and the Built Environment),
Niko Gentile (Department of Architecture and the Built Environment)

Keywords: Sensitivity analysis, Energy performance, Million program project, Refurbishment, IDA ICE

Thesis: EEBD - # / YY

Abstract

The European commission have set targets regarding the reduction of emission of greenhouse gases, the improvement of the energy efficiency and the use of renewable resources of energy respectively by 20 % by the year of 2020. Swedish targets are even more ambitious compared to the European Commission that aims to reduce the greenhouse gas emissions by 40 %, improve the energy efficiency by 20 % and make 50 % of the energy be produced from renewable resources. The building sector is one of the major responsible for energy consumption, therefore renovating the existing non-efficient building have a big role to achieve this target. During the 1960’s, the Swedish government initiated a program to build a million dwellings to supply the demand of the rapidly growing population. Today, the majority of these buildings need renovation.

The aim is to perform and present a method for assessing the sensitivity of different refurbishing measures in an actual building case in terms of total energy use that could then be applied to equivalent buildings. The goal is to distinguish the most influencing refurbishing parameters and performing a life cycle cost to determine whether they are reasonable to implement or not.

This study is based on a real building located in Lund at Linero. The building is nearly 50 years old and was built by Lund Kommuns Fastigheter AB, LKF during the Million programme project. LKF and Cityfied provided the required data to validate a simulated model built in the software IDA ICE. The sensitivity analysis was performed by using a screening-based method where extreme values for refurbishing parameters were studied in order to determine their importance i.e. sensitivity index, from an energy aspect. Three renovation packages were created to assess the energy use, percentage of people dissatisfied and cost efficiency.

By using this method, the most influencing parameters on the energy use could be identified. Renovation package #1 was able to reduce the energy use by 45 % but was not the most cost beneficial. Renovation package #3 which included parameters that had a lower influence on the energy use, showed to be the most cost efficient out of the three packages.

The SI method does not include all the important factors that should be considered when performing a renovation. The energy demand is highly impacted by the dependency of the set ranges. The wider it is, the higher the SI becomes and the narrower it is, the lower it gets. As the cost is not included in the method, it sets no boundaries whether how wide the range can be. This will mislead the investor to make decisions based on inadequate information and is therefore not recommended.

Preface

We would like to express our gratitude to our supervisors Åke Blomsterberg and Niko Gentile at the Energy and Building design department at LTH for the guidance, support and engagement through the learning process of this master thesis.

Thanks to Jesper Svärd from LKF and Jeanette Green from IVL for providing the required data, and for letting us perform our study on one of LKF's buildings.

Many thanks to Petter Wallentén for the support with IDA ICE and answering all of our questions, and to Henrik Davidsson for examining our thesis and giving us valuable feedback and encouragement in the final stages of our work.

At last, we would like to thank our family and friends for all the support and encouragement during this period. And thank each other for the friendship, the hard work and the laughter during this time.

Denise Hermansson & Gabriela Miti Tsuge Costa
2019-03-05

Table of content

1 Introduction

According to the European Commission, EUC (2018a), buildings represent 40 % of the total energy consumption and 36 % of the total CO_2 emissions in the European Union, EU. Around 75 % of the buildings in EU are energy inefficient (EUC, 2016) and about 35 % of them are over 50 years old (EUC, 2018a).

1.1 European and Swedish energy and climate goals

The EUC has set energy and climates targets for the years of 2020, 2030 and 2050. For 2020, all EU countries should reduce in 20 % the emission of greenhouse gases (GHG) in comparison with 1990 levels, have 20 % of the energy use coming from renewable resources and improve in 20 % the energy efficiency (EUC, 2018b). This legislation covers the sectors of housing, agriculture, waste and transport excluding aviation. For 2030, the targets are at least 40 % reduction of the GHG emissions, at least 27 % of use of renewable resources and at least 27 % energy efficiency improvements (EUC, 2018c). Regarding the reduction of energy consumption of buildings, the EU has two main legislation: the Energy Performance of Buildings Directive and the Energy Efficiency Directive (EUC, 2018a). For the targets to 2050, the EUC want to achieve a low-carbon economy and it gives some suggestion of how to achieve a climate-friendly and less energy-consuming economy in a cost-efficient way (EUC, 2018d). All the main sectors (agriculture, power generator, construction, industry, transport, etc.) are included and expected to reduce the GHG emissions and achieve the total emissions of 80 % lower than the levels of 1990. The reduction should be through domestic reductions without relying on international credit, and this could be achieved with investments and development of new clean technologies. Regarding the building sector, the EUC affirm that the emissions could be almost close to zero, with the reduction of 90 % by 2050. It is possible to improve the energy demand of the buildings with the use of passive housing technology in new buildings and refurbishing old buildings. Also, by replacing fossil fuel in heating, cooling and other activities with renewable energy sources (EUC, 2018d).

The Swedish climate goals are even more ambitious than the EU’s, by 2045 Sweden aims to have a net-zero emission of greenhouse gases, GHG and have at least 85 % lower emissions of other gases than measured in 1990 (Government Offices of Sweden (GOS) 2017). For 2020, the Swedish climate and energy targets are to reduce in 40 % the emissions of GHG compared with the measured levels from 1990, to be 20 % more energy efficient compared with 2008, and at least 50 % of the energy being provided by renewable resources (GOS 2015).

Sweden´s building stock represents about 30 % of the country´s total energy use which means that the biggest potential of saving energy is in the existing built buildings (Energimyndigheten 2017). According to a study performed in 2002 by the BOOM-group at KTH, 85 % of the apartments built during the Million Program Project are still up for renovation (Boverket 2010). A later study in 2008 showed that 78 % are still in need of renovation and 40 % had to be modernised within the next few years. These buildings have a higher energy use than newer buildings. Renovating these buildings is an excellent opportunity to implement energy saving measures.

1.2 Million Program Project

The years between 1961 and 1975 are considered to be the high peak of building in Swedish history as 1.4 million dwellings were built during this period (Johansson 2012). In 1965, the Swedish government made the decision to initiate the Million Program Project, which meant that a million dwellings were to be built during the following 10-year period to deal with the rapidly growing population and relocation to the cities. The Million Program buildings are well planned and effectively fulfils their purpose, although the majority are currently at a stage where renovations are required after 40 years – 50 years of use (Boverket 2014). Out of the remaining approximate 830 000 apartment dwellings from this era, more than 600 000 are facing extensive cost renovations within the nearest future (Johansson 2012). This majorly includes new installations for ventilation, electricity, windows, balconies and exterior façade layers (Boverket 2014). This is required due to high-energy demands, faulty indoor environments and in some cases decontamination of hazardous substances (VVS Företagen 2009).

The building technique during this time differs from what has previously been traditionally used with load bearing exterior façade and interior heart walls (Johansson 2012). Instead, the bookcase structure was adapted where the exterior and partition walls were the load bearing structure. The buildings are mainly considered as low height buildings with half of its stock with three to four levels. A third has brick as a covering façade material and 15 % respectively is covered in either plaster, prefabricated concrete elements or multiple materials in combination. Other typical features are the wide and more useful balconies and the wall to wall windows.

In 1960´s the heating system was changed from wood and coal burning to oil or electricity driven and was considered to be everlasting and cheap. The oil crisis in 1973 meant that almost every newly built single-family house had to be heated with electricity and the nuclear power had to expand to cover the lost energy provided by oil. A lot of attention was brought to save energy among the population. The development of district heating was very slow in its early years in the 1940´s (Energiföretagen 2017a). It was not until the oil crisis it had its real breakthrough. At this time the newly built dwellings from the Million Program Project could directly be connected to the district heating.

As the heating prices during the time of development in the high peak years were low, not a lot of effort was put into insulating the buildings (Johansson 2012). This means that there is a large potential for energy savings if well-planned measures are applied. Optimally the energy use can be diminished to less than half, although few buildings are in such a bad state where such an extensive renovation is worth it.

1.3 Linero residential district

Lund is one of the oldest cities in Scandinavia with one among the hundred highest ranked universities in the world (Lunds kommun 2017). About 119 000 inhabitants live in Lund’s municipality, whereof circa 40 000 are full time study students attending Lund University. During 1969 – 1972, the residential areas Havamal and Eddan was built in the Linero district situated in eastern part of Lund (LKF [No date]), see Figure 1. In these two areas, 28 three-story buildings with a total of 681 apartments were built by Lunds Kommuns Fastighets AB, LKF. Linero has a population of about 6 000 people, a good infrastructure with supermarket, health care centre, sports hall etc., and good transport connections with central Lund (Cityfied 2014).

Figure 1: Linero residential district in eastern part of Lund (Google maps).

The architect responsible for the design was Sten Samuelson (LKF [No date]). All the buildings have the same characteristics and orientation with concrete façades with metallic details, entrances facing north, balconies facing south and no windows facing either east or west, see Figure 2 and Figure 3. In general, the buildings have identical layout, the only difference would be the number of staircases and entrances which would affect the total area.

Figure 2: One of the entrances facing north (photo taken by the authors).

Figure 3: The south facing façade (photo taken by the authors).

The buildings are today nearly 50 years old and are in need of renovations where a few of the planned measure by LKF is to renovate and change the bathrooms, sewage and water systems, electricity system, ventilation, among other things (LKF [No date]).

The Linero district is a part of a large-scale demonstration performed by Cityfied which aims to develop a strategy to for developing smart cities that could be adapted to European cities (Cityfied 2013). It focuses on reducing the energy demand and GHG emissions and increasing the use of renewable energy resources.

A sensitivity analysis is a valuable and widely used tool to explore a building's performance and characteristics from different aspects (Tian 2013). It can distinguish key factors that will influence the most and help develop an alternative and more energy efficient design approach (Heiselberg et al. 2013).

1.4 Aim and goal

The aim is to perform and present a method for assessing the sensitivity of different refurbishing measures in an actual building case in terms of energy use that could be applied to equivalent buildings.

The goal is to diminish the energy use by distinguishing the influencing key refurbishing parameters through assessing their sensitivity. Lastly, a life cycle cost will be done to determine whether they are reasonable to implement or not.

1.5 Limitations

- Although, some balconies are in reality glazed, the balconies in the Base case are all simulated as non-glazed. The balconies were simulated as shading objects and not as a separate zone due to complications in software. As the balcony doors are almost only made up of glass they are simulated as windows.
- Havamal and Eddan are currently undergoing renovations set to be finished spring 2018, but the suggested renovations measures in this study are not based on LKF's

measures. The buildings prior being renovated are solely used as a realistic reference for this sensitivity and cost analysis.

- Only one multifamily building in Eddan was simulated.
- The possible moisture impact of the suggested improvements was not assessed.
- Price growth rates for district heating and electricity is assumed based on future prognosis and past behaviour.
- As no study for the behaviour of the occupants regarding internal heating such as occupancy, equipment and lighting had to be assumed based on statistics and requirements.
- Since the acquired energy use data from LKF represents the total energy used by all buildings in Eddan, the assumption was made that each building used equally amounts of energy per m².
- No complete study of the thermal comfort was performed; the PPD was used as an indicator.

2 Base case description

Havamal and Eddan are separated by Vikingavägen, see Figure 4. The chosen building to be simulated and used as a base case is highlighted, see Figure 4.

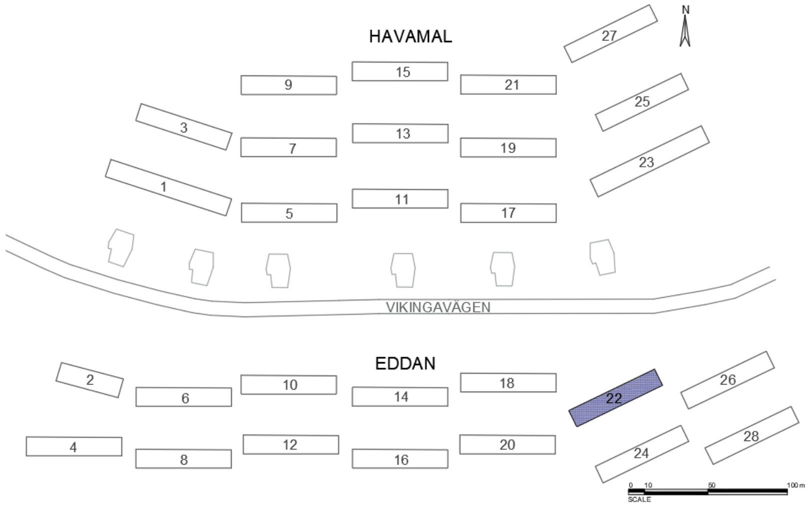


Figure 4: Havamal and Eddan with the studied building highlighted.

2.1 Plan layout

The building has three floors where each floor has eight apartments varying in size from 20 m² – 86 m² and a basement. The apartments are located around three staircases, there is no elevator in the building. The total building area is approximately 2 365 m². See Figure 5 for the floor plan for the 1st floor and see Appendix 1 for a closer view of all floors.

Figure 5: Layout of 1st floor.

2.2 Building construction and thermal characteristics

LKF and Cityfied provided the technical description of the building, and the materials and the constructions' U-values are presented in Table 1.

Table 1: Construction details before renovation.

Exterior wall facade		
Orientation	Construction - from outside to inside	U-value / (W/(m² · K))
North (LKF)	80 mm Concrete Airgap Wind barrier 95 mm Insulation and wooden studs PE-foil 13 mm Wooden particle board 13 mm Gypsum board	0.5
South (LKF)	Painted eternit board 95 mm Insulation and wooden studs PE-foil 13 mm Wood particle board 13 mm Gypsum board	0.5
East/West (LKF)	80 mm Concrete 100 mm EPS 100 mm Concrete	0.35
Basement (Cityfied)	Plaster 70 mm Wool insulation 230 mm Impermeable concrete 300 mm Drainage aggregate	0.5
Load bearing interior walls		
Location	Construction	U-value / (W/(m² · K))
Floor 1-3 (Cityfied)	150 mm/ 180 mm Concrete	3.54/3.79
Basement (Cityfied)	150 mm Concrete	3.79
Foundation		
Location	Construction – from inside to outside	U-value / (W/(m² · K))
Bottom slab (Cityfied)	40 mm Concrete topping 100 mm Structural concrete 200 mm Drainage aggregate	0.4
Floor		
Location	Construction – from lower to upper side	U-value / (W/(m² · K))
Above basement (Cityfied)	210 mm Structural concrete 70 mm Wood wool slab	0.79
Floor 1-3 (Cityfied)	210 mm Structural concrete	3.4

Roof		
Location	Construction – from inside to outside	U-value / $(\mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K}))$
Roof (LKF & Cityfied)	100 mm + 20 mm Insulation board 250 mm Concrete slab	0.3
Windows		
Location	Construction	U-value / $(\mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K}))$
North façade (LKF)	Floor 1 – 3; 1 + 1 glass window	1.7
South façade (LKF)	Floor 1 – 2; 1+ 1 glass window	2.7
	Floor 3; 2 glass window	2.2

2.3 Thermal bridges

The Cityfied report provided the total losses from the thermal bridges in the building, see Table 2.

Table 2: Thermal bridges (Citified).

Thermal bridge	**Comment**	**Heat loss / (W/K)**
Sill under infill walls towards south	Dim. 95 mm · 95 mm, length 60 m on 3 floors	20
Window perimeter	280 m in total using estimated value 0.055 W/(m · K)	15
Ground floor slab	Edge insulated with 30 mm EPS	12
First floor slab	Edge insulated with 40 mm mineral wool	7
Second floor slab	Edge insulated with 40 mm mineral wool	7
Attic floor slab	Edge insulated with 40 mm mineral wool	7
Outer corners	Estimated value	3
Concrete heel for façade towards north	Estimated data: 2 heels per element, 17 heels per floor, dimension 5 cm · 20 cm per heel	4
Total		**75**

2.4 Ventilation

The building has an exhaust air ventilation system with no heat recovery, and a pressure regulated fan installed in 2006 (Cityfied 2014). Due to lack of cleaning and maintenance, an average airflow per apartment was measured to 7.4 l/s in the bathrooms and 9.2 l/s in the kitchens. And the airflow in the basement was measured to 64 l/s. The average airflow is 0.31 l/(s · m²), which is lower than the requirement of 0.35 l/(s · m²) set by Boverket (2017a).

2.5 Energy use

Because of how the measuring meter for used heating, including heating for domestic hot water, DHW, and electricity is located and installed, the given data by LKF is representing all 14 buildings in Eddan and a measured average for year 2013 – 2017. As the buildings have different size, the data was recalculated into per m² to be easier comparable. Figure 6 presents the monthly mean values for space heating and DHW where the measured data from LKF is the left bar and the simulated data from Cityfied is the right bar. No exact data for DHW heating was provided but was assumed by LKF to be around 30 % out of the total cold-water consumption and was then calculated to 30 kWh/ (m² · A_{temp} · year). Cityfied assumed that the heating provided during July and August was for heating DHW and was then assumed constant throughout the year.

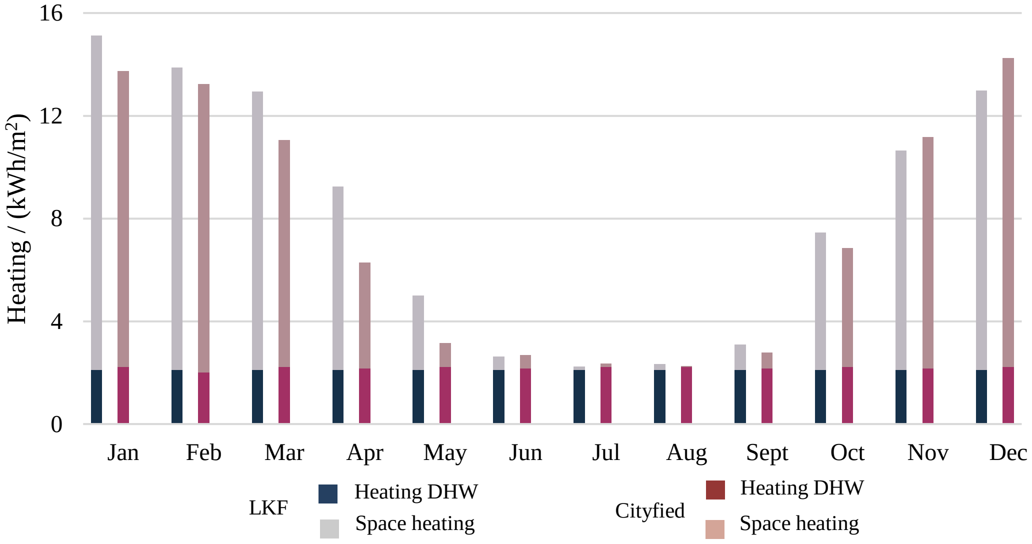


Figure 6: Heating use.

Statistics published by the Swedish Energy Agency in 2017 based on energy data collected during 2016 from all over Sweden, showed that an average multifamily building connected to district heating, used in average about 138 kWh/(m² · year) for space heating and DHW (Energimyndigheten 2017). Those buildings that were built before 1960 had an average usage of 147 kWh/(m² · year) and those built after 1980 used less than the average measured during the year 2016. Buildings built in 2010 or later used significantly less at about 90 kWh/(m² · year). See Table 3 for a comparison with the data from LKF and Cityfied with the average use stated by the Swedish Energy Agency.

Table 3: Average energy use for heating.

Source	Average energy use for heating / (kWh/ (m² · year))
Swedish Energy Agency	138
LKF	97
Cityfied	90

2.5.1 Electricity use

The provided data from LKF for electricity use considered only the electricity used in the common spaces as entrance, stairwells, outdoors, basement etc, and Cityfied considers the whole building including apartments, see Figure 7.

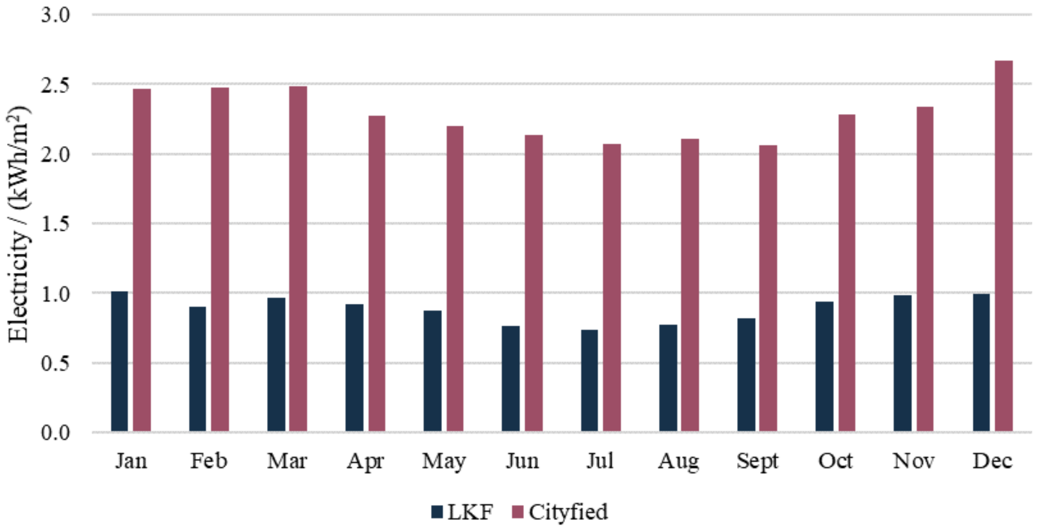


Figure 7: Electricity use.

3 Sensitivity analysis

“Sensitivity analysis studies the relationships between information flowing in and out of the model” (Saltelli, Chan & Scott 2000, p. 4).

Sometimes performing physical studies on a system can be too time-consuming, inefficient and even impossible to do (Saltelli, Chan & Scott 2000). Instead, research is performed on mathematical or computational models which mimic or approximate the studied system.

A sensitivity analysis, SA can have different meanings depending on if it is an engineer, chemist, economist etc. who implements the analysis. Although, every study aims to determine parameters’ correlation to each other, exclude unimportant parameters from the subsequent study, distinguish if a maximum variation occurs in a certain range of inputs and describe how the parameters interact. All this to finally have solution that answers to the project´s aim.

There are different methods to be applied when performing a SA, all with their own strengths and weaknesses. The aim and circumstances of the study will decide which of the methods is the best suited for the cause. An analysis can either give qualitative or quantitative results meaning either telling how much more important one factor is than another or rank the factors in order of importance.

The screening-based method is considered by Heiselberg et al. (2013) and Satelli, Chan & Scott (2000), as one of the main categories: local, global and screening-based method. But Tian (2013) consider it as a method within a global SA. This is because a screening-based method could both be considered as a local and global SA (Satelli, Chan & Scott 2000). The screening method is defined by its use, while a local and a global method are defined by how they treat factors.

The purpose of a screening method is to distinguish the key parameters that affect the output the most from a large number of input parameters (Satelli, Chan & Scott 2000). A typical screening is made my implementing the one-at-a-time, OAT-method. One parameter at a time is tested where extreme values are chosen around a standard value to determine the sensitivity of the model because of the varying values. The parameter is reset to its initial value before the next parameter is tested.

4 Methodology

The adopted software and methods are described and explained as to why they are suitable for the project´s cause.

4.1 IDA Indoor Climate and Energy

IDA Indoor Climate and Energy, IDA ICE is a software developed by EQUA Simulation AB which can perform accurate studies of the indoor climate in specific thermal zones to simulate the total energy consumption of a whole building (EQUA Simulation AB 1995-present). It is possible of simulating anything from very simple to complex cases, taking specific surroundings and environmental properties into consideration such as shading, weather, ground type etc.

Because it is a very flexible software is can be used for HVAC sizing, thermal comfort, control optimization, system analysis, daylight assessment, comparison with certification systems as LEED and BREEAM and many more. The software is widely used by various companies in Scandinavia because of this reason and is constantly adapting to new requirements and regulations.

In their latest update 4.8, a beta-function of a sensitivity analysis was released. Previously, a separate calculation software has usually been used to perform the sensitivity analysis with the output from IDA ICE, but now EQUA is aiming to incorporate that function directly into the program making it one of few software with this possibility.

4.2 Using a screening-based method

The method used for this study is a screening-based standard OAT-method where a range of extreme maximum and minimum values are being assessed for parameters with a certain occurrence regardless of circumstances. The first step is to decide what output is to be focused on when performing the SA which is in many cases the building performance (kWh/ ($m^2 \cdot$ year)) and/or the indoor environment from different aspects (Heiselberg et al. 2013).

The following step describes the process of deciding what parameters to include in the sensitivity analysis by determining its sensitivity index, SI. This is done by implementing the OAT-method where each parameter is evaluated individually. Its SI is then calculated by using Equation 1, where two extreme values on either side of the standard value are used to decide the studied parameter´s importance to the SA. The SI is expressed in percentage (%).

$$\mathrm{SI} = \frac{E_{max} - E_{min}}{E_{Standard}} \cdot 100\ \% \tag{1}$$

Where E_{max} and E_{min} represent the maximum and minimum generated total energy use.

The ranges were set considering what could be found in the market, limitations due to the existing building structure to avoid influencing the layout and design of the building.

The parameters that did not reach the aimed SI percentage could then be excluded from the following steps in the method, as they did not affect the output enough to be considered.

4.3 Life cycle cost

The cost assessment was done by including the effect of inflation, meaning real interest and growth rates, to estimate the true earning power (Park 2012). The cost is regulated by a compound growth that increase or decrease the cash flows by a constant percentage over time.

All the future costs were recalculated into a present worth factor, P by using Equation 2 to bring all future costs into a present value to tell the investor how much they need to invest and show the plausible payback time compared to if no modification was applied. Depending on if the real interest and growth rate were equal or unequal either Equation 2a or 2b was used.

$$P = \begin{cases} A_1 \left(\dfrac{1 - (1+g)^N (1+i)^{-N}}{i - g} \right) & \text{(2a)} \\ A_1 \left(\dfrac{N}{1+i} \right) \text{ (if } i = g\text{)} & \text{(2b)} \end{cases}$$

Where i and g represents respectively the interest and growth rate, N the evaluation time in years and A_1 being the cost after one year.

A_1 can be calculated by using following Equation 3.

$$A_1 = A_0 \cdot (1 + i) \qquad (3)$$

Where A_0 is the initial investment the investor needs to invest.

The cost assessment was done by using the flexible and versatile calculation software Excel (Microsoft Corporation 2018).

5 Implementation

Following assumptions and decisions were made during the project to obtain the desired outputs.

5.1 Simulating the Base case

The building internal partitions were simplified, and each apartment was considered as one zone. The apartments were divided into types depending on the number of rooms (bedrooms and living room, excl. kitchen, bathroom, corridors and closet). There are five different types of apartments, see Figure 8, 9, 10 and 11. The stairwells and basement were also considered as their own zone types.

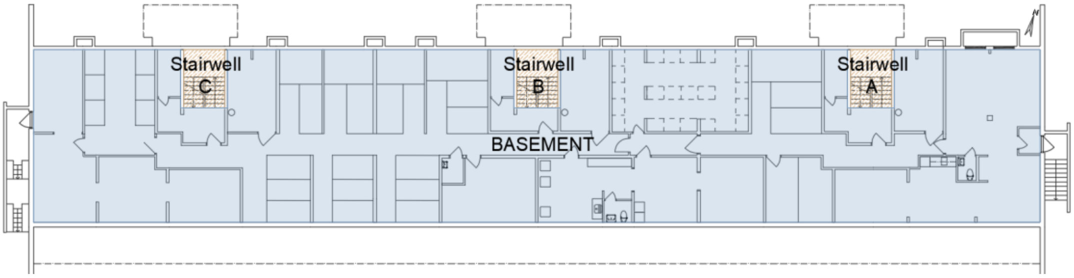


Figure 8: Zone division – basement.

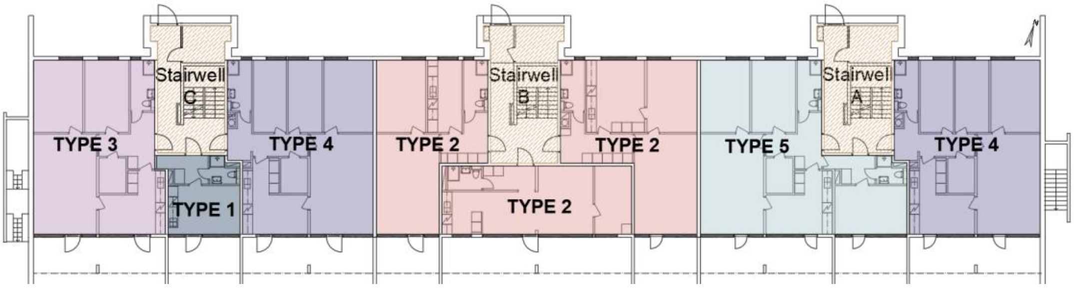


Figure 9: Zone division – 1st floor.

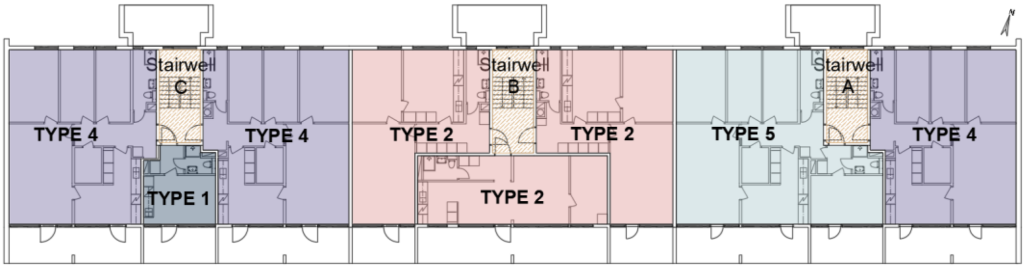


Figure 10: Zone division – 2nd floor.

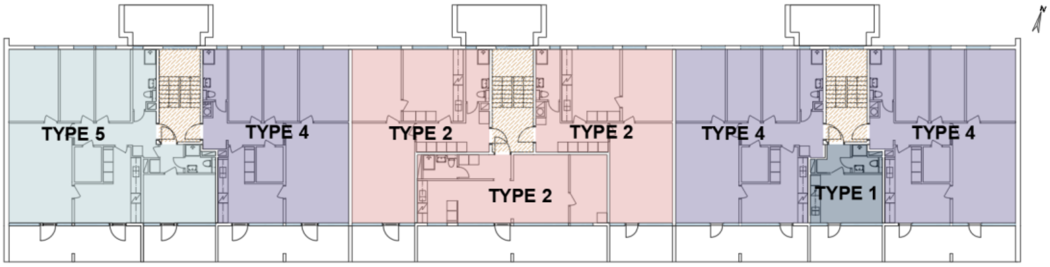


Figure 11: Zone division – 3rd floor.

5.1.1 Internal heat gains

5.1.1.1 Occupancy

No data for occupancy, occupancy schedule and appliances were provided. Therefore, Sveby's recommendations were used (Sveby 2012). See Table 4 for the applied internal heat gains caused by occupants depending on apartment size and the assumed occupancy schedule.

Table 4: Occupancy in different apartment's size and occupancy schedule (Sveby).

Apartment size	1 room	2 rooms	3 rooms	4 rooms	5 rooms
Occupancy / person	1.42	1.63	2.18	2.79	3.51
Schedule	14 hours per day average				

5.1.1.2 Equipment

Standard values for apartment appliances are presented in Table 5. Depending on the apartment size, number of bathrooms with washing machine and dryer etc. the total heat gains depending on equipment varies. The appliances were assumed to be turned on 24 hours a day.

Table 5: Heat gain from type of equipment (Sveby).

Equipment	**Apartments / (kWh/year)**
Fridge and freezer	720
Cooking	390
Laundry and drying	210
Stereo	60
TV	150
DVD	60
Computer	270
Others	390
Total	**2 250**

5.1.1.3 Lighting

The current lighting status in the building was not provided and was estimated to the following, see Table 6 (Dubois et al 2016). Two different light bulbs were assumed to be installed in the building; one for the commonly used areas as entrances, staircases and basement and one for the apartments.

Table 6: Lamp properties.

Location	**W**	**lm/W**	**Schedule**	
Common areas	72	100	**Stairwell**	12 hours per day
			Basement	12 hours per day (half on)
Apartments	15	80	8 hours per day	

See Appendix 2 for each zone’s estimated heat gains from occupancy, equipment and lighting.

5.1.2 Windows and openings

The windows were simulated by using the simplified window type in IDA ICE. The balcony doors are of the same type and are simulated as a window as they are practically only glass. See Table 7 and Figure 12.

Table 7: U-values of the installed window types.

Window type	U-value / $(W/(m^2 \cdot K))$
1	1.7
2	2.7
3	2.2

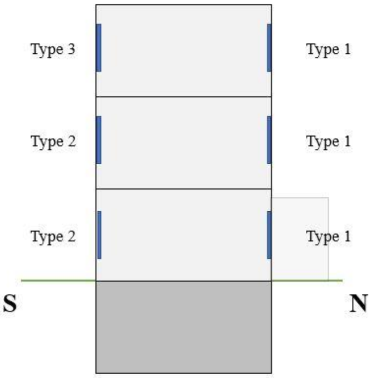


Figure 12: Schematic view of placement of window types.

5.1.3 Heating the DHW

As IDA ICE require a set value for the heating of DHW, an average value based on the data from LKF and Cityfied was used and set to 28.19 kWh/m² and year.

5.1.4 Surrounding shading

The adjacent multifamily buildings were modelled to consider their shading onto the studied object, see Figure 13. Their building heights varied between 8 m – 10 meters due to some being built at different ground heights.

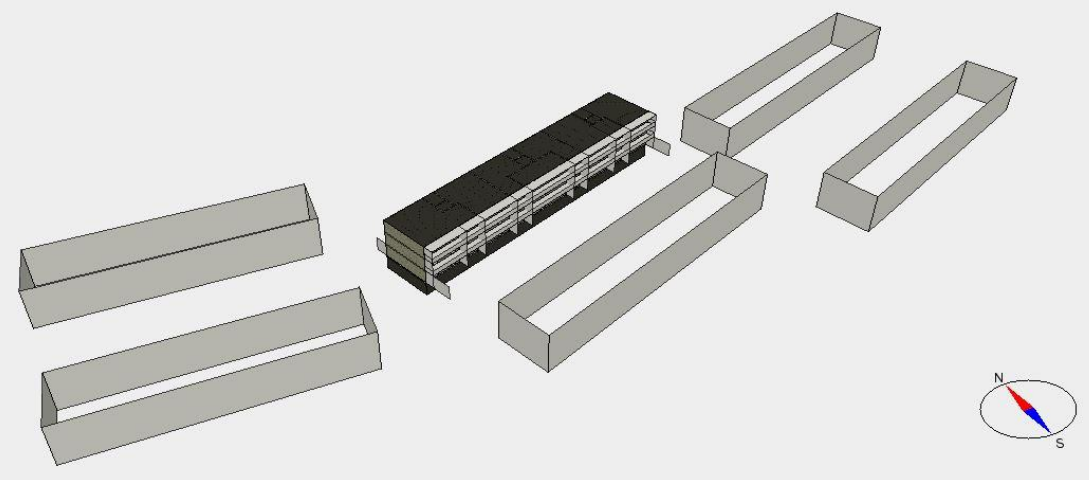


Figure 13: Studied building with adjacent shading objects.

5.1.5 Ventilation

As some apartments have an extra bathroom, the airflow for bathrooms was doubled. The operating schedule for the fans were set to be always on. See Appendix 3 for each apartment's estimated airflow.

5.2 Sensitivity index

The studied parameters where chosen because of their influence on the energy use (Westerbjörk 2017). It states that the biggest opportunity in saving energy is by applying measures to the ventilation and the building envelope.

Every value for each parameter was simulated and set to give the total energy use per year as an output, e.g. the total heating and electricity use, see Figure 14 for an illustrative graph where A represent a parameter. Each parameter´s scenario was simulated one by one in IDA ICE to then decide the SI. The studied parameter was changed back to its Base case value before proceeding with the next parameter.

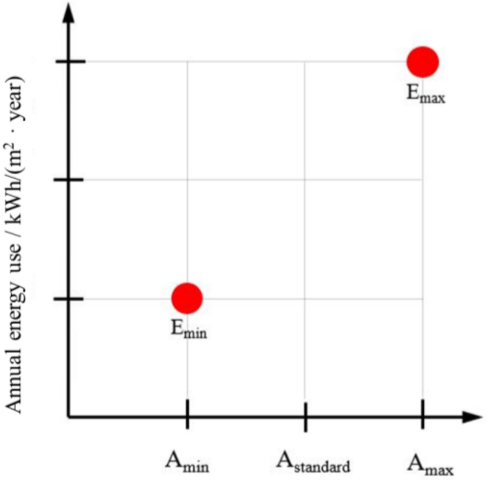


Figure 14: Illustrative graph of generated energy use due to range of extreme values of a parameter A.

The SI is based on evaluating the total energy used per year that each parameter with its extreme values could generate.

The parameters that exceeded the SI-limit of 10 % were closer studied in order to determine where within their intervals they begin to be considered as having a significant impact on the energy use in order to be included in the study’s following steps.

5.2.1 Intervals for the sensitivity analysis

The used maximum and minimum values for each studied parameter is presented in Table 8.

Table 8: The chosen intervals for each parameter.

Parameter	Min. value	Max. value
Insulation thickness in north façade / m	0.30 (ISOVER Saint-Gobain, 2018a)	0.05 (Björk, Kallstenius & Reppen, 2013)
Insulation thickness in south façade / m	0.30	0.05

<table>
<tr><td colspan="2"></td><td colspan="3">(ISOVER Saint-Gobain, 2018a)</td><td colspan="2">(Björk, Kallstenius & Reppen, 2013)</td></tr>
<tr><td colspan="2">Insulation thickness in roof / m</td><td colspan="3">0.5
(ISOVER Saint-Gobain, 2018b)</td><td colspan="2">0.15
(Björk, Kallstenius & Reppen, 2013)</td></tr>
<tr><td colspan="2">Insulation material / (W/(m^2 · K))</td><td colspan="3">0.036
(ISOVER Saint-Gobain, 2018c)</td><td colspan="2">0.041
(Finja 2018)</td></tr>
<tr><td colspan="2">Window U-value – North / (W/(m^2 · K))</td><td colspan="3">0.8
(Passive House Institute, 2015)</td><td colspan="2">2.9
(Avasso, 2003)</td></tr>
<tr><td colspan="2">Window U-value – South / (W/(m^2 · K))</td><td colspan="3">0.8
(Passive House Institute, 2015)</td><td colspan="2">2.9
(Avasso, 2003)</td></tr>
<tr><td colspan="2">Setpoint temperature in apartments / °C</td><td colspan="3">18
(Boverket 2017)</td><td colspan="2">26
(Boverket 2017)</td></tr>
<tr><td rowspan="3">Lighting – Common areas</td><td>W</td><td colspan="2">23</td><td rowspan="2">· 2</td><td colspan="2">72</td></tr>
<tr><td rowspan="2">lm/w</td><td colspan="2">117</td><td colspan="2">100</td></tr>
<tr><td colspan="3">(Philips Lighting, 2018a)</td><td colspan="2">(Same properties as in the Base case)</td></tr>
<tr><td rowspan="4">Lighting – Common areas + Apartments</td><td></td><td colspan="2">Common areas</td><td>Apartments</td><td>Common areas</td><td>Apartments</td></tr>
<tr><td>W</td><td>23</td><td rowspan="2">· 2</td><td>8</td><td>72</td><td>15</td></tr>
<tr><td rowspan="2">lm/w</td><td>117</td><td>131</td><td>100</td><td>80</td></tr>
<tr><td colspan="2">(Philips Lighting, 2018a)</td><td>(Philips Lighting, 2018b)</td><td colspan="2">(Same properties as in the Base case)</td></tr>
<tr><td colspan="2">Specific fan power, SFP /</td><td colspan="3">0.60
(Warfvinge & Dahlblom 2015)</td><td colspan="2">2.00
(Warfvinge & Dahlblom 2015)</td></tr>
<tr><td colspan="2">Exhaust air heat pump and balanced</td><td colspan="3">COP = 3.5</td><td colspan="2">Without</td></tr>
</table>

ventilation with heat recovery - FTX	η = 85 % (Wahlström 2014)	

5.3 Life cycle cost

The inflation (Svenska Riksbanken 2018) and interest (Statistiska centralbyrån 2018) rate were set respectively at 0.8 % and 1.8 %, which are average values based on rates collected during 2007 – 2017.

Individual prices for building components were picked from Sektionsfakta NYB (Wikells 2010) and VVS (Wikells 2015). The district heating price was set at 72.50 öre/kWh according to the present-day price (Kraftringen 2018a). An average electricity price based on prices measured during 2015 – 2017 was set at 1.96 SEK/kWh (Eurostat 2018).

Growth rates for prices of district heating and electricity were tried in different scenarios; 2 %, 3 %, 4 % and 5 %.

The used lifespan for each parameter is based upon documented studies and experience of building components (VVS Företagen 2009) and the general life span of a multifamily building (Sartori & Hestnes 2007). The evaluation time is set to 50 years.

5.4 Percentage of People dissatisfied

The PPD is an index which provides a quantitative prediction of the percentage of thermally dissatisfied people and its acceptable level is < 10 % (ASHRAE STANDARD 2010). This was used to give an indication to how the thermal comfort was affected by each scenario.

5.5 Renovation packages

The parameters that exceeded the 10 % SI limit were assembled into Renovation package #1 to find a solution with the lowest energy demand.

Renovation package #2 was established due to the eventuality of too high PPD levels when simulating the first package. It included the same parameters as in package #1 but with some alterations to the parameters to possibly lower the PPD level.

A third renovation package was constructed to consider the parameters that did not exceed the 10 % SI-limit but showed to be much more cost efficient. For the parameters to be included in this package, the parameters had to have a payback time within every studied growth rate.

6 Results and Analysis

The outputs from the study are presented and analysed.

6.1 Validation of the Base case

The result for heating the Base case is presented in Figure 15. In overall, the Base case simulation requires more heating than the obtained data from LKF and Cityfied.

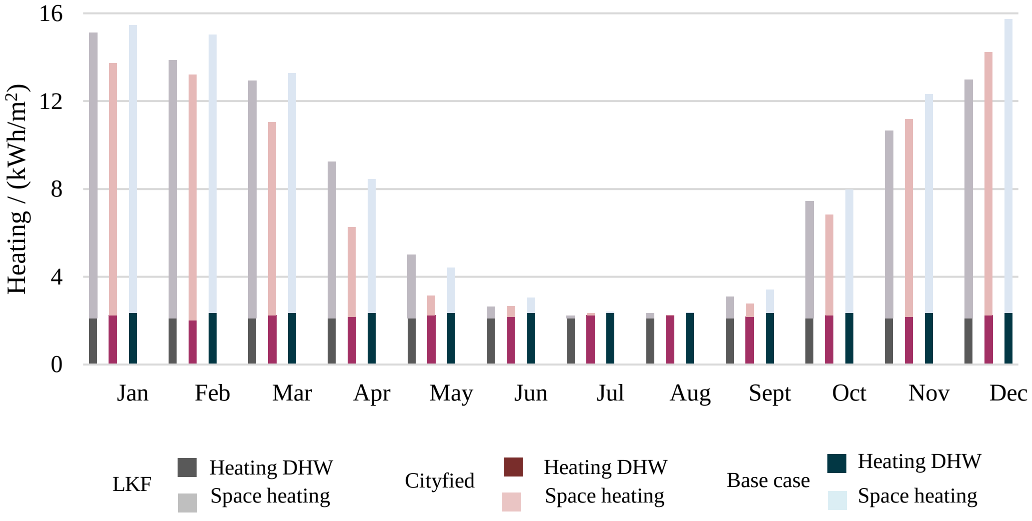


Figure 15: Comparison of monthly heating use between LKF, Cityfied and Base case.

Looking closer at the space heating in Figure 16, the Base case follows the same trend with a higher required heating during the winter months and lower during the summer months. But is still overall higher than the others.

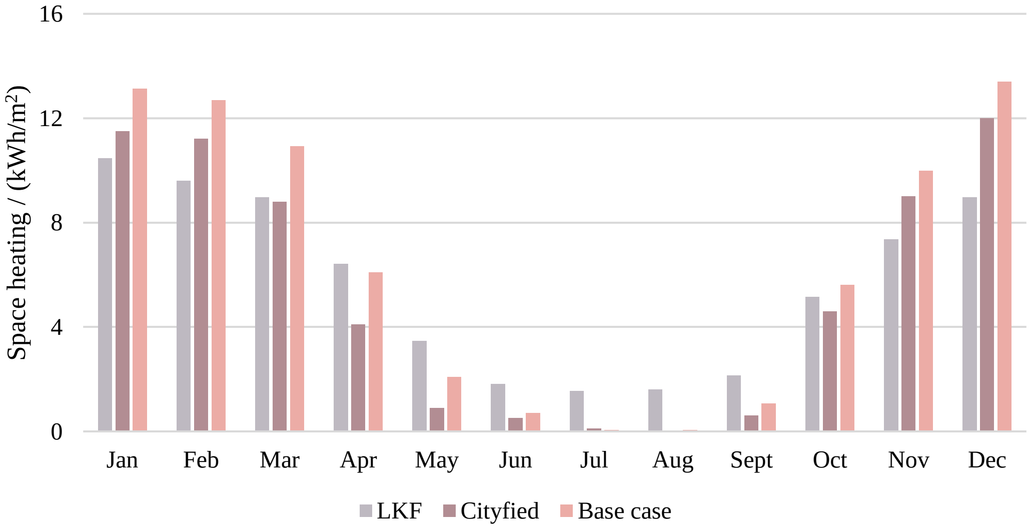


Figure 16: Comparison of monthly space heating use between LKF, Cityfied and Base case.

As the Base case´s heating for DHW is based on the data from LKF and Cityfied, it is somewhat higher than the data from Cityfied due to LKF´s varying data but is constant throughout the year, see Figure 17.

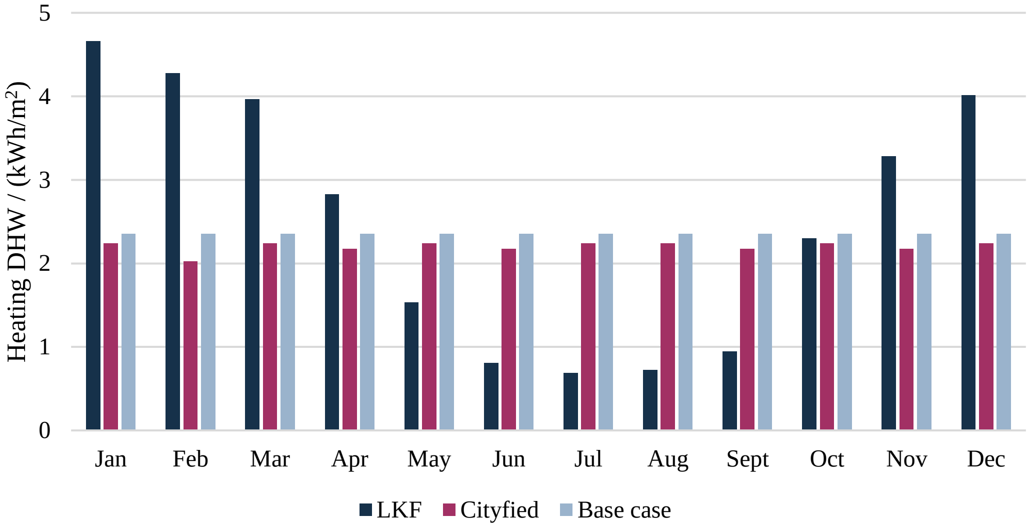


Figure 17: Comparison of monthly DHW heating use between LKF, Cityfied and Base case.

The electrical use results were divided in two to compare the results got from Cityfied and LKF with the base case model. The electricity use considering both household and facility is 47 % higher than the data from Cityfied, see Figure 18.

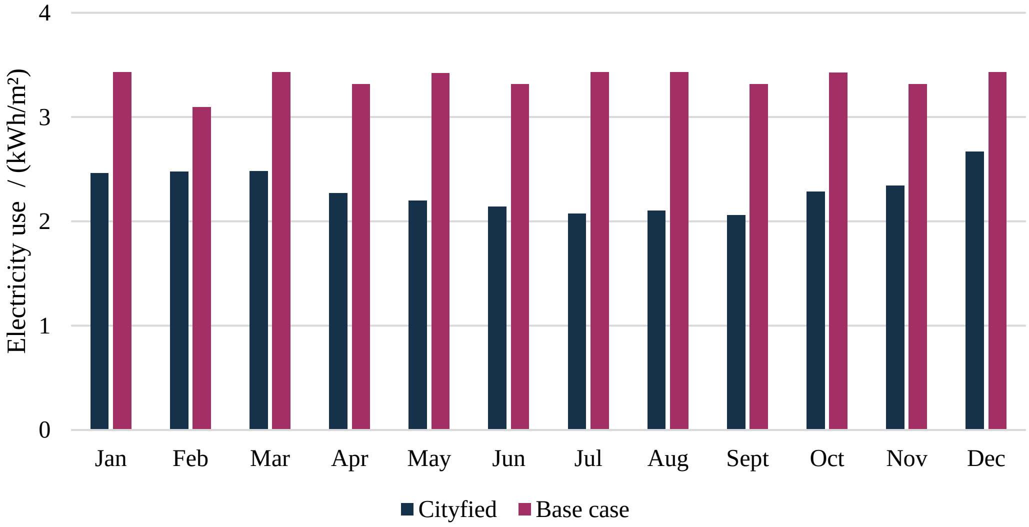


Figure 18: Comparison of monthly electricity use between Cityfied and Base case.

The electricity use for only the facility is 4 % less than the data from LKF, see Figure 19.

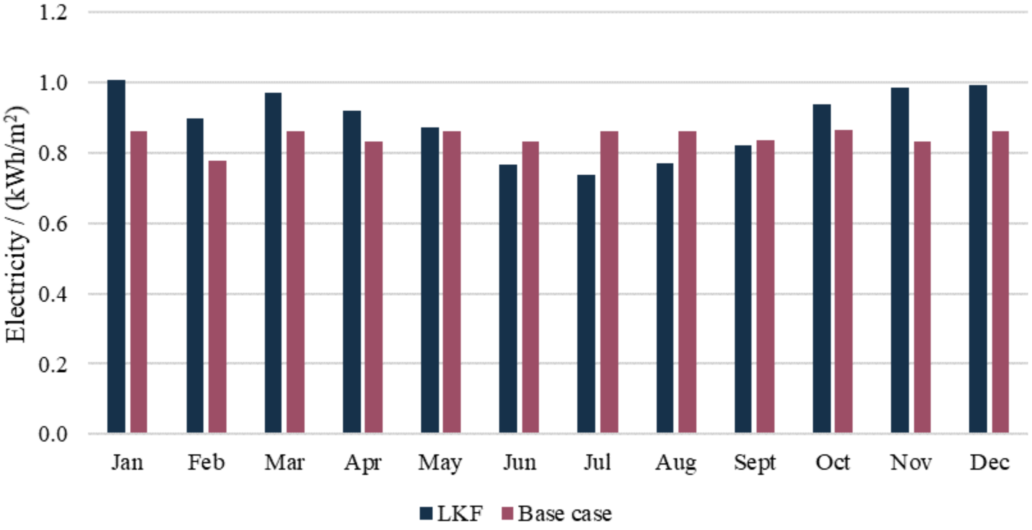


Figure 19: Comparison of monthly electricity use between LKF and Base case.

The overall total energy use for the Base case is differing only ± 6 % from LKF and Cityfied, see Table 9. Although, the energy distribution between space heating, heating DHW and electricity is varying more from what LKF and Cityfied have stated.

The PPD for the Base case was simulated to 68 %.

Table 9: Base case deviation compared to LKF and Cityfied.

Energy categories	Base case deviation compared to:	
	LKF	Cityfied
Space heating	-15 %	58 %
Heating DHW	53 %	7 %
Electricity	- 4 %	- 63 %
Total energy use	6 %	- 6 %

Compared to the average annual heating use of a multifamily house in Sweden, provided by the Swedish Energy Agency, the data from LKF and Cityfied are respectively 29 % and 35 % less, see Figure 20. The Base case have a higher heating use and is 25 % less than the average annual heating use.

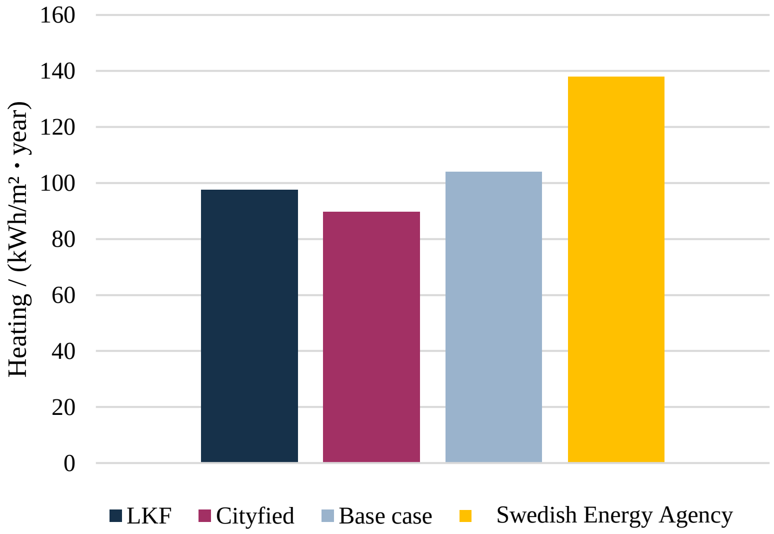


Figure 20: Yearly energy use for LKF, Cityfied and Base case compared to the annual average heating use stated by Swedish Energy Agency

6.2 Sensitivity index

The SI for every parameter was calculated after obtaining the total energy demand for each extreme and standard value, see Table 10.

Table 10: SI for each parameter.

Insulation thickness in north façade	**(Unit)**	**Total energy use / (kWh/(m² · year))**	**Sensitivity index**
Max. value	0.05 m	149.9	7.2 %
Min. value	0.30 m	139.5	
Insulation thickness in south façade	**(Unit)**	**Total energy use / (kWh/(m² · year))**	**Sensitivity index**
Max. value	0.05 m	146.2	3.0 %
Min. value	0.3 m	141.8	
Insulation thickness in roof	**(Unit)**	**Total energy use / (kWh/(m² · year))**	**Sensitivity index**
Max. value	0.15 m	141.6	2.2 %
Min. value	0.5 m	138.1	
Windows - North	**(Unit)**	**Total energy use / (kWh/(m² · year))**	**Sensitivity index**
Max. value	2.9 W/(m² · K)	148.3	4.5 %
Min. value	0.8 W/(m² · K)	141.6	
Windows - South	**(Unit)**	**Total energy use / (kWh/(m² · year))**	**Sensitivity index**
Max. value	2.9 W/(m² · K)	148.1	14.3 %
Min. value	0.8 W/(m² · K)	126.9	
Setpoint temp. in apartments	**(Unit)**	**Total energy use / (kWh/(m² · year))**	**Sensitivity index**

Max. value		26 °C	189.6	44.7 %
Min. value		18 °C	125.1	
Lighting – Common areas		**(Unit)**	**Total energy use / (kWh/(m^2 · year))**	**Sensitivity index**
Max. value		72 W	144.2	1.2 %
Min. value		23 W	142.5	
Lighting – Common areas + Apartments		**(Unit)**	**Total energy use / (kWh/(m^2 · year))**	**Sensitivity index**
Max. value	Common areas	72 W	144.2	1.4 %
	Apartments	15 W		
Min. value	Common areas	23 W	142.3	
	Apartments	8 W		
Insulation type		**(Unit)**	**Total energy use / (kWh/(m^2 · year))**	**Sensitivity index**
Max. value		0.04 W/(m · K)	142.1	1.0 %
Min. value		0.036 W/(m · K)	140.7	
Specific fan power, SFP		**(Unit)**	**Total energy use / (kWh/(m^2 · year))**	**Sensitivity index**
Max. value		2.00	145.6	1.7 %
Min. value		0.60	143.1	
Exhaust Air Heat pump and Balanced Ventilation with Heat recovery - FTX		**(Unit)**	**Total energy use / (kWh/(m^2 · year))**	**Sensitivity index**
Min. value		COP = 3.5 η = 85 %	123.7	14.3 %
Max. value		Without	144.2	

The parameters are ranked from highest to lowest SI, see Table 11. The critical value of SI 10 % is marked, telling which parameters were further used for Renovation package #1.

Table 11: Parameters are ranked according to their SI and if they exceed the 10 % SI level.

Rank	Parameter	SI / %
1.	Setpoint temperature in apartments	44.7 %
2.	Windows - South	14.3 %
3.	Exhaust Air Heat pump and Balanced Ventilation with Heat recovery - FTX	14.3 %
Sensitivity Index of 10 %		
4.	Insulation thickness in north façade	7.2 %
5.	Windows - North	4.5 %
6.	Insulation thickness in south façade	3.0 %
7.	Insulation thickness in roof	2.2 %
8.	Specific fan power, SFP	1.7 %
9.	Lighting – Common areas + Apartments	1.4 %
10.	Lighting – Common areas	1.2 %
11.	Insulation type	1.0 %

6.2.1 The setpoint temperature in apartments

Each degree within the interval for setpoint temperature and their generated SI is presented in Table 12.

Table 12: Parameter study for setpoint temperature.

Setpoint temp. in apartments	(Unit)	Total energy use / (kWh/(m² · year))	Sensitivity index
Max. value	21 °C	144.2	13.2 %
Min. value	18 °C	125.1	
Max. value	21 °C	144.2	11.0 %
Min. value	19 °C	128.3	
Max. value	21 °C	144.2	6.1 %
Min. value	20 °C	135.4	
Max. value	21 °C	144.2	0 %
Min. value	21 °C	144.2	
Max. value	21 °C	144.2	-5.1 %
Min. value	22 °C	151.6	
Max. value	21 °C	144.2	-11.4 %
Min. value	23 °C	160.6	
Max. value	21 °C	144.2	-17.9 %
Min. value	24 °C	170.0	
Max. value	21 °C	144.2	-24.7 %
Min. value	25 °C	179.8	
Max. value	21 °C	144.2	-31.5 %
Min. value	26 °C	189.6	

When the setpoint temperature is increased from 19 °C to 20 °C, the SI exceeded the 10 % SI-limit. Note that when there is a negative SI there is an increase in energy use.

6.2.2 Windows - South

The results of the parametric study of the window U-value in the south façade is presented in Table 13.

Table 13: Parametric study for window U-value in South facade.

Windows - South	(Unit)	Total energy use / (kWh/(m² · year))	Sensitivity index
Max. value	2.9 W/(m² · K)	148.1	14.3 %
Min. value	0.8 W/(m² · K)	126.9	
Max. value	2.9 W/(m² · K)	148.1	13.9 %
Min. value	1.0 W/(m² · K)	127.6	
Max. value	2.9 W/(m² · K)	148.1	9.9 %
Min. value	1.5 W/(m² · K)	133.5	
Max. value	2.9 W/(m² · K)	148.1	5.8 %
Min. value	2.0 W/(m² · K)	126.9	
Max. value	2.9 W/(m² · K)	148.1	0 %
Min. value	2.9 W/(m² · K)	148.1	

The SI exceeded 10 % somewhere between the U-values of 1.0 W/(m² · K) and 1.5 W/(m² · K).

6.2.3 FTX

Three FTX-systems and their generated SI is presented in Table 14 and are being compared to if no system was installed.

Table 14: Parametric study for FTX-system.

Exhaust Air Heat pump and Balanced Ventilation with Heat recovery - FTX	(Unit)	Total energy use / (kWh/(m² · year))	Sensitivity index
Max. value	Without	144.2	0 %
Min. value	Without	144.2	
Max. value	Without	144.2	13.5 %
Min. value	COP = 2.5 η = 70 %	124.8	
Max. value	Without	144.2	13.6 %
Min. value	COP = 3.0 η = 80 %	124.6	
Max. value	Without	144.2	14.3 %
Min. value	COP = 3.5 η = 85 %	123.7	

The SI-limit is exceeded when the FTX-system with the least performing characteristics is applied.

6.3 PPD-level of Renovation package #1 and #2

The simulated PPD levels for the three parameters that exceeded the 10 % SI-limit is presented in Table 15. Lowering the setpoint temperature had the biggest impact on the PPD and increased it by 13 % compared to the Base case. Installing an FTX-system did not affect the PPD and changing the windows in the south façade would lower the PPD by 4 %.

Table 15: The simulated PPD level for the three parameters that performed best energy wise.

Parameter	PPD / %
Windows in south facade	64
FTX-system	68
Setpoint temperature	81
Base case	68

The PPD level of Renovation package #1 which is a combination of these three parameters are presented in Table 16. Compared to the Base case, the PPD level was 17 % higher. This led to the construction of Renovation Package #2 where the setpoint temperature was reset to 21°C which was used in the Base case, in order to minimalize the effect on the thermal comfort. Now the PPD level decreased to 47 %, being 21 % lower than the Base case.

Table 16: The simulated PPD-level for Renovation package #1 and #2.

Renovation package	PPD / %
Renovation package #1	85
Renovation package #2	45
Base case	68

6.4 Life cycle cost

6.4.1 Payback time for individual parameter

All the parameters' payback time was calculated and compared to the evaluation time of 50 years, see Table 17. Installing new windows in south or north did not prove to be cost efficient as it did not give a payback time within the 50-years. Increasing the insulation thickness in the facades in north, south or in the roof could optimally give a payback time at around 5 years. Changing the lighting properties in the common areas and apartments or only in the common areas would pay off after 2 years regardless of what growth rate. Similarly, a constant payback time regardless of what growth rate could be observed for installing an FTX-system and lowering the setpoint temperature. Install a different kind of insulation type showed to not be cost efficient if the growth rate was set to 2 % but would in the remaining give a payback time.

Table 17: Payback time for each individual parameter.

Growth rate /	Setpoint temperature 18°C	Windows in south façade	FTX-system	Insulation thickness in north façade	Windows in north façade	Insulation thickness in south façade	Insulation thickness in the roof	Lighting in common areas and apartments	Lighting in common areas	Insulation type
2 %	1	-	4	22	-	30	25	2	2	-
3 %	1	-	4	9	-	8	10	2	2	13
4 %	1	-	4	7	-	6	8	2	2	12
5 %	1	-	4	6	-	5	7	2	2	8

The parameters that were assembled into Renovation package #3 were the FTX-system, insulation thickness in the roof and façade to the north and south and lighting in both apartments and common areas. Note that the setpoint temperature was kept at 21°C.

6.4.2 Payback time for the renovation packages

Two payback times could be observed for renovation package #1 and #2 which is due to the reinvestment in new building components that is paid off before the next required investment, see Table 18. To graphically clarify the occurrence of two payback times, see Appendix 4.

Only Renovation package #3 was able to yield a payback in all studied growth rates and within a time period of 10 – 12 years. Package #1 did not manage to have a payback when the growth rate was set to 2 % and had the shortest payback time of 22 years. The second package performed the worst out of the three having the shortest payback time of 29 years and no observed payback time for when the growth rate was set to 2 % or 3 %.

Table 18: Payback time for the renovation packages.

Growth rate /	Renovation package #1	Renovation package #2	Renovation package #3
2 %	-	-	12
3 %	26 / 45	-	11
4 %	24 / 38	47	10
5 %	22 / 34	29 / 41	10

6.5 PPD-level of Renovation package #3

The PPD-level of Renovation package #3 was simulated to 51 %, see Table 19.

Table 19: Each renovation package's PPD-level compared to the Base Case.

Renovation package	PPD / %
Renovation package #1	85
Renovation package #2	45
Renovation package #3	51
Base case	68

6.6 Savings in energy and cost

Each renovation package's energy use compared to the Base case is presented in Figure 21. Renovation package #1 was able to diminish the energy use the most by 44 %.

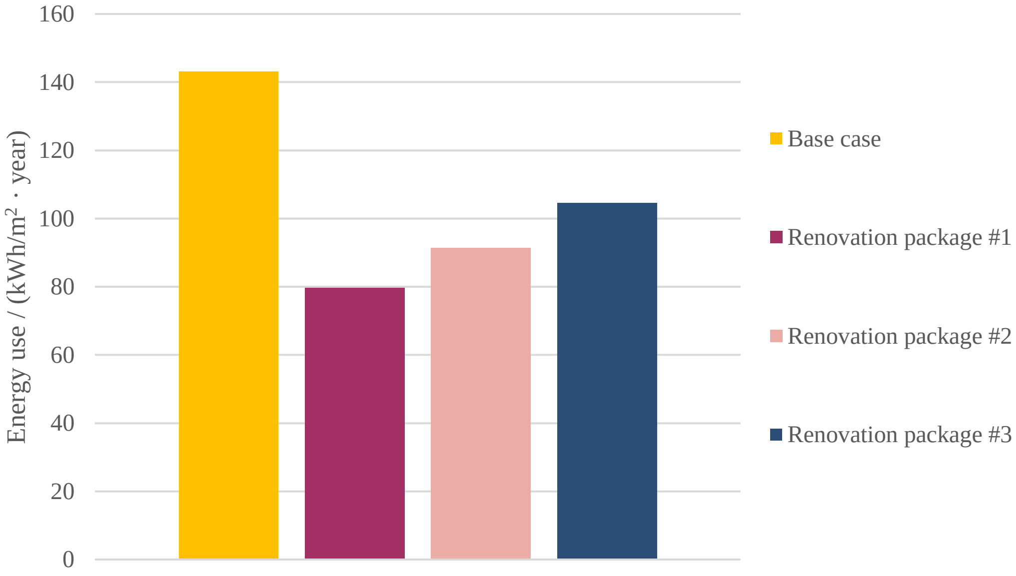


Figure 21: The yearly energy use.

The biggest possible and average cost savings for each package is presented in Table 20. Optimally, the biggest cost and average cost savings would be if renovation package #3 would be implemented.

Table 20: The packages' biggest possible and average cost savings.

Renovation package	Biggest possible cost saving (MSEK)	Average cost savings (MSEK)
#1	5.0	1.99
#2	2.6	0.20
#3	7.4	4.86

6.7 Compilation of renovation packages' results

Each renovation package's biggest and average cost savings, diminished energy and PPD-levels compared to the Base Case are presented in Table 21. Renovation package #1 had good results in both cost savings and in energy use but had a higher PPD-level than Base case. Renovation package #2 was able to lower the energy use by the same percentage as #1 and decrease the PPD-level below the Base case's level but did not save as much as package #1. The third package had the highest cost savings, the second best result for PPD and although performing the worst when diminishing the energy still managed to diminish it by 30 %.

Table 21: Compilation of the renovation packages' results.

Renovation package	The biggest possible cost savings (MSEK)	Average cost savings	Diminished energy	PPD-level compared to Base Case 68 %
#1	5.0	1.99 MSEK	44 %	85 %
#2	2.6	0.20 MSEK	36 %	45 %
#3	7.4	4.85 MSEK	27 %	51 %

7 Discussion

As the used data for the Base case's energy use was assumed to be equally divided between the 14 buildings in the area, the reliability of the simulated energy use can therefore not be considered very high. If the data was measured solemnly for this studied building the reliability would be immensely higher and easier to validate. In order to validate this assumption, the simulated energy use was compared to collected statistics by a reliable source to be within reasonable ranges for general energy consumptions for multifamily buildings in Sweden.

The screening-based method is a wide spread method used when performing various SAs. Likewise, IDA ICE is a very well-known software for energy simulations in the construction trade. Although, the acquired knowledge of their functions and limitations were restricted which could have affected the reliability and validity of the simulations negatively.

The made assumptions for the chosen intervals when performing the SA, were motivated by how buildings from the same time were built and what materials and constructions are used in modern time. This yielded a result representing a SA of refurbishing measures for a general building stock built during 1960's – 1970's which used the studied multifamily building as a reference point. The validity of the results could be higher if the focus of the study only was specific for this multifamily building but would still be questionable whether it was credible as specific data was still missing and had to be assumed.

The energy demand is highly impacted by the dependency of the set ranges. The wider it is, the higher the SI becomes and the narrower it is, the lower it gets. As the cost is not included in the method, it sets no boundaries whether how wide the range can be. For example, nothing prevents the range to include unreasonable insulation thicknesses as the cost is not considered. If it were, it would find a solution where the highest energy saving could be achieved when taking into account what the project can afford.

The decision to study the impact of the setpoint temperature on the energy demand showed to be very complex as it affects so many other aspects of the building performance. For instance, it affects the thermal comfort in ways that was not fully assessed in the method that was used in this study. The PPD-level only gives an indication of the behaviour of the thermal comfort but is far from portraying the whole picture.

The SI sets the level of importance to which parameter can be considered to be most important and further be used in the SA. The critical level has to be decided based upon what goals are aimed to be achieved. As this project does not have a certain goal regarding economy and energy other than diminish it as much as possible that the current construction allows, the critical SI was assumed to 10 %. This decision lacks support and can therefore be questioned if the limit should be lower.

In order to simulate the Base case, assumptions regarding internal heat gains, lighting, ventilation etc. had to be made as this information was not provided. The assumptions relied on collected statistics and requirements that had to be met, meaning that the likeliness of this scenario representing the actual conditions of the building debatable. But as the simulated

Base case was considered to be fairly close of representing a building built in the same decade it was considered as a validated case that was further used in the study.

The used formulas for the LCC are recognized methods for calculating the cost efficiency of scenarios where an investment has to be made. The lifespans used for the building components and buildings seemed at times very short, as for example windows had an estimated lifespan of 30 years but would most probably be used for a longer period of time in reality. Similarly, for the building’s lifespan which is estimated to be around 50 years. If this was the case the LCC calculation would give a very different result as a reinvestment in windows and ventilation systems could be postponed with several years. A similar observation could be made regarding the lifespan if buildings which was estimated to be 50 years but would possibly be used for longer time. Combined with postponed investments for renovation measures and longer actual lifespans, the prices for materials, hiring manpower etc. could also change even if being based on well-known and reliable statistics, give a much different result.

The SI method solemnly focuses on the influence on the energy use of the building; it does not consider the cost or the thermal comfort. In reality, these factors are equally important to incorporate into the method to obtain a useful result. Therefore, this method is not recommended as it does not include enough information for the investor to make a well-founded decision.

8 Conclusion

By using this method, the most influencing parameters on the energy use could be identified. Renovation package #1 was able to reduce the energy use by 45 % but was not the most cost beneficial. Renovation package #3 which included parameters that had a lower influence on the energy use, showed to be the most cost efficient out of the three packages.

The SI method does not include all the important factors that should be considered when performing a renovation. The energy demand is highly impacted by the dependency of the set ranges. The wider it is, the higher the SI becomes and the narrower it is, the lower it gets. As the cost is not included in the method, it sets no boundaries whether how wide the range can be. This will mislead the investor to make decisions based on inadequate information and is therefore not recommended.

9 References

Avasso, Diana. 2003. Effektiva fönster – en bra investering. August 19th. http://www.viivilla.se/gor-det-sjalv/fonster--dorrar-1/effektiva-fonster-en-bra-investering1/ [2018-10-23]

ASHRAE STANDARD (2010). Thermal environment conditions for human occupancy. http://arco-hvac.ir/wp-content/uploads/2015/11/ASHRAE-55-2010.pdf [2018-05-19]

Bixia (2017). *Ingen risk för skyhöga elpriser*. https://www.bixia.se/om-bixia/press/nyheter/2017/ingen-risk-for-skyhoga-elpriser [2018-05-17]

Björk, C., Kallstenius, P. & Reppen, L. (2013). *Så byggdes husen 1880–2000*. Mölnlycke: Elanders Sverige

Boverket (2017a). *Luft och ventilation i bostäder*. https://www.boverket.se/sv/byggande/halsa-och-inomhusmiljo/ventilation/luft-och-ventilation-i-bostader/ [2018-05-17]

Boverket (2017b). *Termisk komfort*. https://www.boverket.se/sv/PBL-kunskapsbanken/regler-om-byggande/boverkets-byggregler/termiskt-klimat/?fbclid=IwAR1XFNTZ6WciI8pEfL6naxrhQipAOJ7bcM6lM83J08bSkPjLMIzAdUrxMAY [2018-11-21]

Boverket (2010). *Teknisk status i den svenska bebbygelsen – resultat på projektet BETSI*. https://www.boverket.se/globalassets/publikationer/dokument/2011/betst-teknisk-status.pdf [2018-04-26]

Boverket (2014). *Under miljonprogrammet byggdes en miljon bostäder*. http://www.boverket.se/sv/samhallsplanering/stadsutveckling/miljonprogrammet/ [2018-02-22]

Cityfied (2013). *Cityfied Project overview*. http://www.cityfied.eu/The-CITyFied-Project/About.kl [2018-05-18]

Cityfied (2014*). Preliminary technical definition of the Swedish demo site.* http://www.cityfied.eu/ [2018-04-27] Note: Have to sign up to access the pdf.

Dubois, M.C., Boer, J.D., Deneyer, A., Fuhrmann, P., Geisler-Moroder, D., Hoier, A., Jakobiak, R., Knoop, M., Koga, Y., Osterhaus, W., Paule, B., Perola, P., Stoffer, S. & Tetri, E. (2016). *Building Stock Distribution and Electricity Use for Lighting*. http://task50.iea-shc.org/Data/Sites/1/publications/Technical_Report_T50_D1_final.pdf [2018-05-09]

Encyclopaedia Britannica (2018). *Probability density function.* https://www.britannica.com/science/density-function [2018-05-10]

Energiföretagen (2017a). *Fjärrvärme – A real success story.* https://www.energiforetagen.se/globalassets/energiforetagen/om-oss/fjarrvarmens-historia/fjarrvarme_story.pdf [2018-04-26]

Energiföretagen (2017b). *Låga prisökningar för fjärrvärme 2017*. https://www.energiforetagen.se/pressrum/nyheter/2017/oktober/laga-prisokningar-pa-fjarrvarme-2017/ [2018-05-17]

Energimyndigheten (2017). *Energistatistik för flerbostadshus 2016*. Bromma: Arkitektkopia AB

Energimyndigheten (2014). *Frånluftsvärmepumpar*. http://www.energimyndigheten.se/tester/tester-a-o/franluftsvarmepumpar/ [2018-10-29]

European Commission (2016). *Clean energy for all Europeans*. Brussels: European Commission. http://eur-lex.europa.eu/resource.html?uri=cellar:fa6ea15b-b7b0-11e6-9e3c-01aa75ed71a1.0001.02/DOC_1&format=PDF

European Commission (2018a). *Buildings*. https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings [2018-02-22]

European Commission (2018b). *2020 climate & energy package.* https://ec.europa.eu/clima/policies/strategies/2020_pt [2018-02-22]

European Commission (2018c). *2030 climate & energy framework.* https://ec.europa.eu/clima/policies/strategies/2030_pt [2018-02-22]

European Commission (2018d). *2050 low-carbon economy.* https://ec.europa.eu/clima/policies/strategies/2050_pt [2018-02-22]

EQUA Simulation AB (1995-present). *IDA Indoor Climate and Energy* (Version 4.8) [software]. Available: https://www.equa.se/en/ida-ice

Finja (2018). *EPS S60 Raka.* https://www.finja.se/storage/ma/e1e03701a1534a6aa99d66499dfd4d31/ba00519eceaa450285115dcff82c62eb/pdf/B4CA5CF5B9DD74ED11FF357B7CA2C973A6977B57/EPS%20S60%20Raka%20_PB_sv.pdf [2018-11-27]

Folkhälsomyndigheten (2014). *Folkhälsomynfighetens allmänna råd om temperatur inomhus*. https://www.folkhalsomyndigheten.se/globalassets/publicerat-material/foreskrifter1/fohmfs-2014-17.pdf [2018-05-18]

Government Offices of Sweden (2015). *Objectives for Sweden's climate and air quality policy*. http://www.government.se/government-policy/environment/objectives-for-swedens-climate-and-air-quality-policy [2018-02-22]

Government Offices of Sweden (2017). *The climate policy framework.* http://www.government.se/press-releases/2017/06/riksdag-passes-historic-climate-policy-framework/ [2018-02-22]

ISOVER Saint-Gobain (2018a). *Isolera yttervägg inifrån.* https://www.isover.se/isolera-yttervagg-inifran [2018-11-05]

ISOVER Saint-Gobain (2018b). *Isolera tak och vind.* https://www.isover.se/isolera-tak-och-vind [2018-11-05]

ISOVER Saint-Gobain (2018c). *ISOVER ULTIMATE UNI-skiva 36.* https://www.isover.se/products/isover-ultimate-uni-skiva-36 [2018-11-27]

Johansson, B. (red.) (2012). *Miljonprogrammet – utveckla eller avveckla?.* Stockholm: Edita AB

Kraftringen (2018a). *Fjärrmärmepriser.* https://www.kraftringen.se/Privat/Fjarrvarme/Fjarrvarmepriser/ [2018-05-09]

Kraftringen (2018b). *Rörligt elpris – elområde 4.* https://www.kraftringen.se/Privat/El/Vara-elpriser/Prishistorik/Rorligt-elpris--elomrade-4/ [2018-05-09]

Lunds Fastighets AB (No date). *Ombyggnad av kv Eddan.* https://www.lkf.se/Byggprojekt/Ombyggnadsprojekt/Upprustning-av-kv-Eddan-Havamal/ [2018-04-26]

Lunds Kommun (2017). *Faktatext om Lund*. https://www.lund.se/kommun--politik/press--och-informationsmaterial/faktatext-om-lund/ [2018-04-26]

Microsoft Corporation (1975-present). *Excel* (Version 2016). [software] https://www.microsoft.com/sv-se/store/d/excel-2016/cfq7ttc0k5f3?activetab=pivot%3aoverviewtab

Park, C. S. (2012). *Fundamentals of Engineering Economics: International Edition.* Essex: Pearson Education Limited.

Passive House Institute (2015). *Passive house requirements.* https://passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm [2018-10-23]

Philips Lighting (2018a). *CorePro LED tube Universal T8.* https://www.assets.lighting.philips.com/is/content/PhilipsLighting/fp929001869702-pss-global?fbclid=IwAR0Q4FZ6QTrno-6gqj_R0h6IsIQeHtEkL1lBMimux0f36TL5-x8gtoaMCHo [2018-11-13]

Philips Lighting (2018b). *MASTER LEDtube EM/Mains.* http://www.assets.lighting.philips.com/is/content/PhilipsLighting/comf2167-pss-sv_se?fbclid=IwAR1sTFKBpJ22JBeSNHyRkYSVHl8A7g99tcK8wWzb9UcqcDFLij-LdoF9eIY [2018-11-13]

Saltelli, A., Chan, K. & Scott, E. M. (2000). *Sensitivity Analysis.* Chichester: John Wiley & Sons Ltd.

Sartori, I. & Hestnes, A.G. (2007). *Energy use and the life cycle of conventional and low-energy buildings: A review article.* https://liveatlund.lu.se/departments/Building_Services/ABKF15/ABKF15_2017HT_100_1_NML__1281/CourseDocuments/5_Energy%20use%20in%20the%20life%20cycle%20of%20conventional%20and%20low-energy%20buildings.pdf?fbclid=IwAR025AVaXAFzzsOlLAGocIg-bBCM7iQk2SEv06KL2XzgdKNF2iXJRbxEZh0 [2018-11-22]

Sveby (2012). *Brukarindata bostäder*. http://www.sveby.org/wp-content/uploads/2012/10/Sveby_Brukarindata_bostader_version_1.0.pdf [2018-04-26]

Statistiska Centralbyrån (2018). *Inflation i Sverige 1831 – 2017*. https://www.scb.se/hitta-statistik/statistik-efter-amne/priser-och-konsumtion/konsumentprisindex/konsumentprisindex-kpi/pong/tabell-och-diagram/konsumentprisindex-kpi/inflation-i-sverige/ [2018-05-09]

Svenska Riksbanken (2018). *Search interest and exchange rates.* https://www.riksbank.se/en-gb/statistics/search-interest--exchange-rates/?g7-SEGVB10YC=on&from=05%2F09%2F2008&to=09%2F05%2F2018&f=Year&c=cAverage&s=Dot [2018-05-09]

VVS Företagen (2009). *Renoveringshandboken för hus byggda 1950 – 75.* Stockholm: Wallén Grafiska AB.

Wahlström, Å. (2014). *Teknikupphandling av värmeåtervinningssystem i befintliga flerbostadshus – utvärdering.* http://www.bebostad.se/library/1902/teknikupphandlling-av-vaermeaatervinningssystem-i-befintlig-flerbostadshus.pdf [2018-10-29]

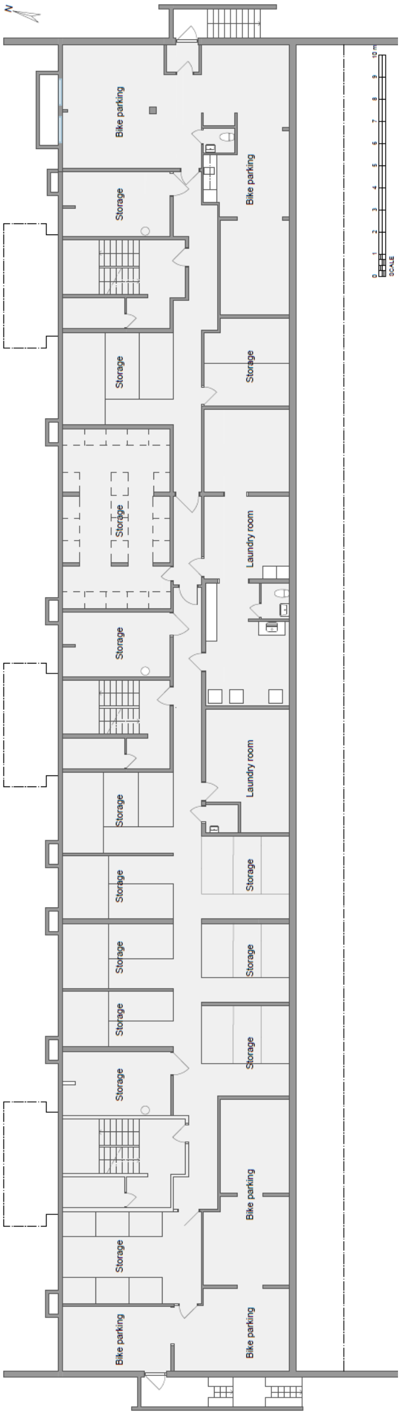
Warfvinge, C. & Dahlblom, M. (2015). *Projektering av VVS-installationer*. Polen: Dimograf.

Westerbjörk, K. (2017). *Halvera Mera 1+2+3.* http://www.bebostad.se/library/2365/2017_03-halvera-mera-1plus2plus3.pdf [2018-05-18]

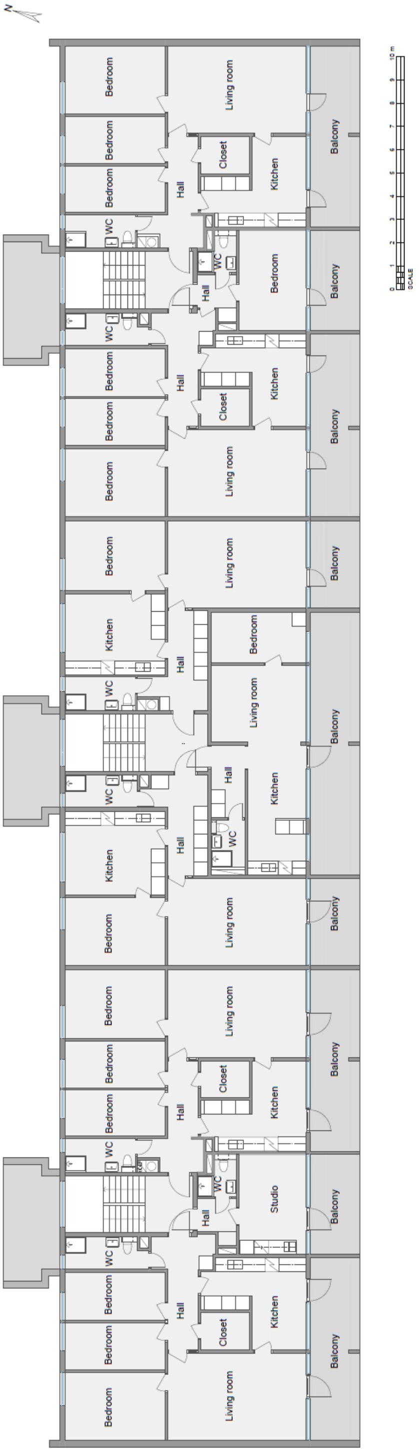
Wikells (2010). *Sektionsfakta – NYB 10/11.* Elanders.

Wikells (2010). *Sektionsfakta – VVS 15/16.* Elanders.

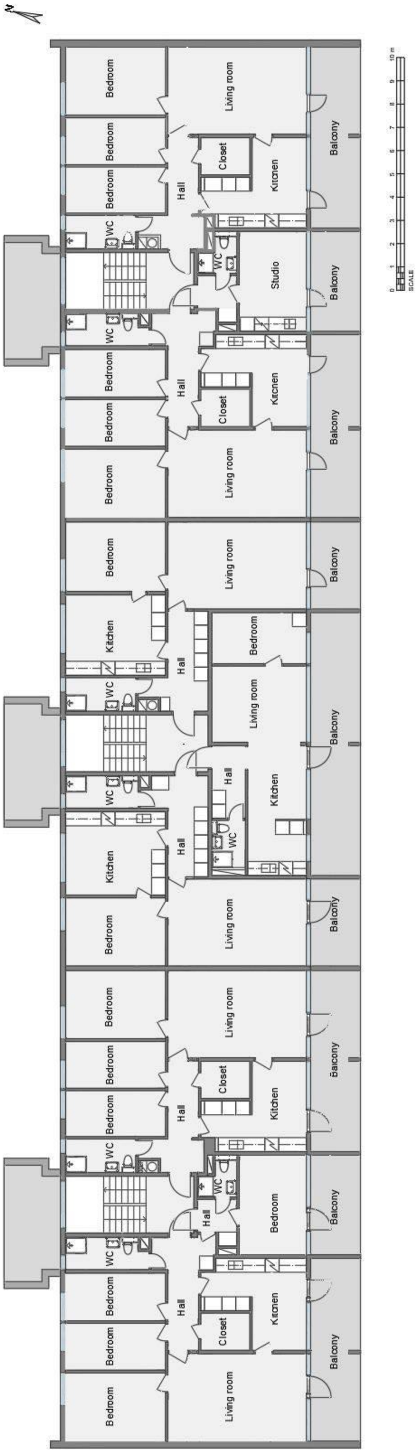
Appendix 1. – Floor plans



LEFT: Basement floor plan. *RIGHT: 1st floor plan*



LEFT: 2nd floor plan.



RIGHT: 3rd floor plan.

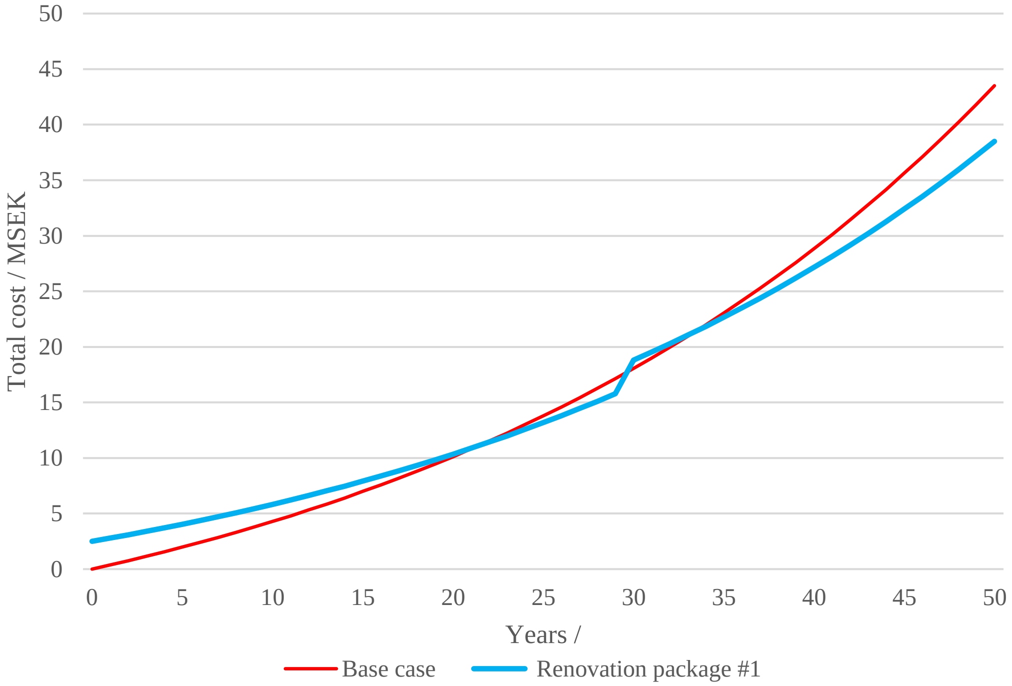
Appendix 2. – Internal heat gains for each zone

Heat gain	Lighting (Number of lamps)	Equipment		Occupancy (Persons per zone)
		Emitted heat (W)	Number of appliances	
Apartment Type 1	6	190	1	1.42
Apartment Type 2	10	260	1	1.63
Apartment Type 3	14	260	1	2.18
Apartment Type 4	16	260	1	2.79
Apartment Type 5	20	260	1	3.51
Stairwell (incl. entrance and circulation areas)	10	-	-	-
Basement	70	68.5	6	-

Appendix 3. – Apartment air flow

Zone	Air flow (l/s)
Apartment Type 1	16.6
Apartment Type 2	16.6
Apartment Type 3	16.6
Apartment Type 4	16.6
Apartment Type 5	24.0
Stairwell	-
Basement	64.0

Appendix 4. – Graphic explanation of the two occurring payback times



Growth rate: 5 %
Payback time after 22 and 34 years.

LUND UNIVERSITY

Dept of Architecture and Built Environment: Division of Energy and Building Design
Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services