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Energy Performance Gap of an Office Building

The influence of modelling assumptions and level of detail

Master's thesis in Structural Engineering & Building Technology

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Abstract

Building simulation software can be used to predict the energy use of buildings in the design phase. However, due to the importance of time efficiency in building projects today, energy models are often simplified. Numerous cases have been reported where the energy models are not performing in accordance with the actual building. One of these cases is an office building in Trollhättan, Sweden, where the predicted energy use was 37% lower than the average of the yearly total energy use during operation. The difference between a building's predicted energy performance and the actual energy performance is called *energy performance gap*.

This study investigated whether a more detailed energy model could decrease the energy performance gap of the building. The level of detail was increased by implementing the building's actual geometry and solar shading system, among other factors. Furthermore, the magnitude of various modelling assumptions was assessed by a sensitivity analysis of the model, where uncertain input data were varied one factor at a time.

The original design model led to a performance gap of 37%. This however includes post-simulation addition of template values for energy use due to heat losses not accounted for in the simplified model, e.g. for the hot water circuits. The performance gap based on the result from the simulation alone was 53%. The performance gap derived from the detailed energy model was 47%, i.e. only slightly decreased compared to the original model result, and even increased compared to the original model with post-simulation addition of template energy use values. Consequently, the energy performance gap of the building was not decreased by implementing a more detailed model.

Furthermore, the sensitivity analysis showed that incorrect modelling assumptions can be a reason for the performance gap. The chosen setpoints for heating and cooling had the largest impact on the energy use among the four parameters tested.

At last, important input data for energy modelling was emphasised, and proposals for increasing the level of detail further was presented.

Keywords: energy performance gap, office building, building energy simulation, IDA ICE, VIP Energy

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Julia Appelkvist
Victoria Ahlgren
Gothenburg, June 2024

Symbols, abbreviations & definitions

Symbols

A	Area	m^2
χ	Point thermal bridge	W/K
η	Efficiency	-
ψ	Linear thermal bridge	W/(m·K)
Q	Heat flow	Wh
U-value	Heat transfer coefficient	W/(m^2·K)
W	Electricity	Wh

Abbreviations

AHU	Air handling unit
BEN 2	Byggnadens energianvändning vid normalt brukande och ett normalår (eng: Building's energy use during normal use and one normal year)
BBR	Boverkets byggregler (eng: Boverkets building regulations, The Swedish National Board of Housing, Building and Planning)
BIM	Building information model
CAV	Constant air volume
COP	Coefficient of performance
DCV	Demand controlled ventilation
DH	District heating
DHW	Domestic hot water
DVUT	Dimensionerande vinterutetemperatur (eng. design outdoor temperature)
EPG	Energy performance gap
HVAC	Heating, ventilation, and air conditioning
PE	Primary energy number
SFP	Specific fan power
ST	Solar transmission
VAV	Variable air volume

Definitions

A_{temp}	The floor area inside a building envelope (incl. the inner walls, opening for stairs, shafts) that is heated to a minimum of $+10^{\circ}$C, excl. garages (Boverket, 2017a)
Activity energy	Energy or electricity that is used for activities, for example computers and copy machines (Boverket, 2017a)
Air infiltration	Unintentional leakage of outside air into a building
Blower door test	Method for testing the air tightness of a building
Free cooling	Utilising a free source of energy for cooling from the surroundings, for example cold outdoor air (Boverket, 2017a)
Property energy	Energy needed to be supplied to the building to power the HVAC system (fans, pumps, energy meters etc.) but also the energy needed in the public areas (lighting, elevators) (Boverket, 2017a)
Setpoint	The temperature that the control system is aiming for

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1

Introduction

This chapter presents the background, aim and limitations of the study. Furthermore, the method is also presented.

1.1 Background

A building's energy performance is dependent on several factors, such as climate, building envelope, building services, operation, maintenance, occupant behaviour and provided indoor environmental quality (Yoshino et al., 2017). The building services include for example ventilation, heating of spaces and hot water supply, which are needed to achieve a healthy and comfortable environment. These systems contribute to the building's energy use, highlighting the importance of optimising them to reduce the energy consumption.

During the design phase, simulation tools are often used to predict and optimise the energy performance of a building based on different design choices. However, these tools are highly dependent on input data and choice of accuracy level. Simplifications are often made during modelling, which makes it difficult to achieve an exact result that matches the actual energy use during the post occupancy phase. This difference between the calculated and the actual measured energy use is called the energy performance gap. Except for modelling assumptions, the difference between the calculated and real energy use of a building can be due to alterations during the design, installation and post-occupancy phases.

In a report made by Shi et al. (2019), several calculated ratios between the predicted and the measured energy consumption in buildings from previous studies were summarised. The average values presented of the reported gap varies in ratios between 0.29 to 2.5. These ratios are difficult to compare and analyse since no standard method for calculating the performance gap exists. However, the report indicates that performance gaps are common, and that cases exist where the buildings' energy consumption is more than twice the predicted consumption. In a Swedish study made by Karlsson et al. (2007), three different building energy simulation tools were used to simulate an existing residential house and the results were then compared to the measured energy use. The authors concluded that the simulation software gave similar results, with a deviation of maximum 2%. However, the difference between simulated and measured energy use was larger, with a deviation of 20%.

An example of a detected case of an energy performance gap in Sweden is a newly built commercial building in Trollhättan. The performance gap was detected when the building was to be certified according to the Swedish building certification Miljöbyggnad. When the measured energy use was studied during the certification process, a significant difference between the predicted and the actual energy use was identified. The building's energy use had been predicted in a software called VIP Energy, and the assumed energy use was lower compared to the measured data when the building was in use.

A work of investigating the differences and finding the sources of the energy performance gap has been introduced by PE Teknik & Arkitektur, in collaboration with the real estate company Kraftstaden. Several solutions to decrease the gap have already been identified, but there is still a difference between the modelled energy performance and the actual performance.

1.2 Aim

The purpose of this study is to investigate the energy performance gap of a newly built office building. The study will assess the significance of the level of detail within energy simulation models. In the end of the study, the aim is to broaden the perspective on the potential and limitations of building simulation modelling and propose ways to decrease the performance gap in a general matter.

1.3 Objectives

As a part of studying the energy performance gap, the following questions will be answered in this report:

- What is the size of the performance gap for the studied commercial building?
- How do different levels of detail of the building simulation affect the accuracy of the model?
- What input data does most strongly influence the accuracy of the energy model?

1.4 Limitations

The performance gap studied will only cover the building's energy performance during a limited time of three years since construction. Life cycle costs and life cycle assessments will not be considered in this study. Solar panels will not be included in the results section, as the scope is to estimate the energy use. Pump energy will be excluded due to measuring uncertainties and modelling limitations. Free cooling will not be modelled, also due to modelling limitations.

2

Theory

This chapter introduces the theoretical background to the thesis. The subchapters include the energy use in commercial buildings, energy performance gaps, computational tools, and green building certification, with focus on the Swedish Miljöbyggnad.

2.1 Energy use in commercial buildings

The energy balance in the building consists of the energy losses and energy gains (Abel & Elmroth, 2007). The different gains and losses in the energy balance of a non-residential building are described in this section. The annual heat balance is described as:

$$Q_{room} = Q_{tr} + Q_{V\,o} + Q_{V\,room} - Q_{int} \tag{2.1}$$

where:
Q_{room} is the heat energy required to heat the room air
Q_{tr} is the heat losses through the building envelope due to transmission
$Q_{V\,o}$ is the heat losses through the building envelope due to air leakages
$Q_{V\,room}$ is the heat required to heat the supply air if needed
Q_{int} is the internal heat transferred to the room air

The HVAC system needs energy and electricity to function:

$$Q_{V\,s} + W_{fans} + W_{pumps} + W_{cool} \tag{2.2}$$

where:
$Q_{V\,s}$ is the heat required to heat the supply air
W_{fans} is the electricity needed for the fans
W_{pumps} is the electricity needed for the pumps
W_{cool} is the electricity needed to run the cooling system

Internal heat gains are a part of the building's energy balance and affects the need for heating and cooling of the building. The heat comes from human bodies, equipment, and lightning. The activities in the building require energy, and can be summarised as:

$$Q_{DHW} + W_{light} + W_{eq} + W_{op} \tag{2.3}$$

where:
Q_{DHW} is energy needed for heating the hot tap water
W_{light} is the electricity for lighting
W_{eq} is the electricity for equipment
W_{op} is the electricity for the operation for the building, for example the elevators.

Energy is supplied to the building through for instance solar heat and internal heat. In contrast, energy is emitted from the building through transmission losses, heat leakage from hot water pipes and electricity required for lighting and technical equipment. The governing factors for transmission losses are the difference in outdoor and indoor temperature, and the U-value of the building envelope (Strandberg & Lavén, 2021).

The energy use of a building is described as the amount of energy delivered to a building during a normal year and normal occupancy, used for heating, cooling, hot water and the facility electricity in the building (Sveby, 2013). Specific energy consumption is another term for expressing the energy performance in a building. It is expressed in $kWh/m^2, A_{temp}$ and is calculated by dividing the total energy consumption with the heated floor area, A_{temp}.

When the energy use of a building is calculated, electricity consumption is commonly separated into property electricity and tenant electricity. The two categories are separated in the energy use calculation in Miljöbyggnad. The electricity needed to run the HVAC systems, elevators and lighting in common areas belong to property electricity. Examples of tenant electricity in commercial buildings are refrigerators, coffee machines, computers and ventilation needed for tenant activities, such as restaurant kitchen fans.

2.1.1 Building envelope

Transmission and air infiltration through the building envelope, as well as the thermal inertia of the building structure has an impact on the building's energy balance (Nilsson, 2003). Therefore, the choice of façade has a large impact on the required energy for heating, cooling and electric lighting in a building (Mahdavinejad et al., 2024). Office buildings today often consist of a glazed façade (Blomsterberg, 2008). A reason for the increased interest in constructing buildings with large glazing areas is the development of window's thermal performance. The accessibility of daylight and architectural purposes are other reasons. Daylight is an important factor for the occupants well-being (Lee & Boubekri, 2020).

One glazing construction type that has received increased attention when it comes to commercial buildings is the double-skin façade (Blomsterberg, 2008). The double-skin façade consists of a glass construction that is positioned in front of the building's external wall, with a gap in between (Bohne, 2023). The gap can be ventilated either mechanically and/or naturally. The sun heats the air in the air gap, creating the chimney effect, and the air moves via openings in the façade. The double-skin façade can be useful for noise reduction, reducing thermal loads, and it gives possibilities of adding external sun protection in the gap. During winter, the double-skin façade can reduce the heat losses as it can act as a buffer. Drawbacks of the construction are the investment cost, increased maintenance costs, larger building volumes and the risk of the air in the gap becoming too hot. This can create thermal discomfort for the occupants and cause higher cooling demands during the summer period.

BBR, the Swedish building code, presents maximum U-values that should be aimed for in the building envelope if the building does not meet the energy performance requirements set in the building code (Boverket, 2017a), presented in table 2.1.

Table 2.1: Maximum U-values for building envelope components set by BBR (Boverket, 2017a).

U_i	W=(m^2 K)
U_{roof}	0.13
U_{wall}	0.18
U_{floor}	0.15
U_{window}	1.2
U_{door}	1.2

Windows in office buildings often have U-values of 0.7 1.0 W/(m^2 K) including the window frames and with 3-fold glazing (Bohne, 2023).

2.1.2 Thermal bridges

Thermal bridges in a building can contribute to an increase of 30% in space heating (Alhawari & Mukhopadhyaya, 2018). They generally occur at junctions between different building envelope components (Swedish Standards Institute, 2017). Thermal bridges can occur in junctions between external elements, between external walls and intermediate walls or floors, between columns inside external walls and around windows and doors. Linear thermal bridges are commonly described as in W/(m K) and point thermal transmittance is described as in W/K.

There are several methods to determine the thermal bridges of a building. The -value can be estimated either by thermal bridge catalogues or default values, with a typical accuracy of 20% and 0 50% respectively (Swedish Standards Institute, 2017). A more precise estimation can be made through numerical calculations, which has a typical accuracy of 5%.

Catalogue values of and manual calculation can be made at stages in building design when there is information available about details in the envelope (Swedish Standards Institute, 2017). If the full details are given, all the methods can be used, including numerical calculations. However, in early stages of building design when the construction of details is not yet made but the main geometry of the building is known, only a rough estimation of thermal bridges can be made.

2.1.3 HVAC system

According to Boverket (2023), the main purpose for the ventilation system is to clean the indoor air from pollutants and to keep humidity to acceptable levels. In Sweden, the required air flow is governed by the area of the building and the number of occupants. The minimum allowed air flow in Sweden is 0.35 l/s/m^2 + 7 l/s/person (Arbetsmiljöverket, 2020). The ventilation can have constant air flow (CAV), variable air flow (VAV) or demand-controlled ventilation (DCV) (Warfvinge & Dahlblom, 2010).

Office buildings are often in need of cooling systems due to large internal heat loads during working hours. Chilled beams are commonly used and are placed in the ceiling. The chilled water used in the chilled beams can be from different sources, for example chillers, district cooling, or free cooling. Free cooling is a term for when the only energy needed to cool is the electricity needed to power the fans and pumps required, for example when using the outdoor air when the outdoor air temperatures are low (Warfvinge & Dahlblom, 2010).

Radiator systems can be used to heat a building. Hot water then gets distributed to for instance radiators and convectors in the building. With thermostats and radiator valves on every radiator, a correct water flow corresponding to the heating demand in each room can be ensured. The most common governing factor for the required water temperature in the heating system is the outdoor temperature (Abel & Elmroth, 2007).

To avoid long waiting time for hot water at tapping points, a circulation system is used where hot water is constantly circulating through the pipes of the building. There is also a health aspect of keeping the water in the system above 50C, as the bacteria Legionella Pneumophilia could spread through the distribution system if the water in the system is within the range of 25 50C (Kitzberger et al., 2019).

The energy losses from hot water circulation in offices can reach the same value as the energy use for hot water it self, with a value of 1.5 to 3 $kWh=m^2$ (Bengt Berqvist Energianalys AB, 2016). Hot water is not used to the same extent in offices as in residential buildings, but the hot water circuit is running constantly in all buildings. Peaks of hot water use often occur around noon, and the consumption during the weekends are low (Kitzberger et al., 2019).

Eleven non-residential buildings were analysed by Bengt Berqvist Energianalys AB (2016), and the results showed that the hot water consumption corresponded to 10–20% of the cold water consumption. To compare with residential buildings, the consumption of hot water is approximately 40% of the total water consumption.

According to the guidelines from Boverket (2017b) and Sveby (2013), the energy use for hot water, excluding the hot water circulation, should be assumed to 2 kWh/ $m^2; A_{temp}$ in office buildings. There is however no guideline for the energy losses of the circulating hot water. In contrast to the hot water use, the hot water circulation is not dependent on occupant behaviour but on the piping design, which makes it difficult to assume a specific value.

Pumps are required for water-based systems to pressurise the system and keep the fluid circulating (Warfvinge & Dahlblom, 2010). In an energy statistics report from Energimyndigheten (2007), the energy use of 123 office- and administrative buildings were mapped and analysed. The results showed significant variations in pump electricity, with values between 0.2–39.2 kWh/m^2 per year.

To connect all of the technical systems in a building to the indoor environment, control systems are used. The control system includes computers, microprocessors, storage devices and communication links (Shaikh et al., 2014). It can use information from sensors to adjust for instance ventilation rates and temperature setpoints (Esrafilian-Najafabadi & Haghighat, 2021). The ventilation rate can be controlled by parameters such as CO_2 levels and relative humidity (Hesaraki et al., 2015).

2.2 Energy performance gap

Examining the building's performance gap can focus on the difference between the assumed and the measured energy performance, but also other factors like indoor air quality, acoustical performance and similar (De Wilde, 2014). The reasons for the gap varies from case to case and is often a combination of issues.

This section will describe potential reasons for an energy performance gap (EPG) in three different stages of a building: the design stage, the construction stage and lastly the operational stage.

2.2.1 Design stage

During the design stage, there are several possible sources of an EPG (De Wilde, 2014). It can occur due to communication problems and misunderstandings about the performance targets between either the client and the building designers, or between building designers. The usage of the building might change from the design stage to the operational stage, which can cause the building not performing accurate for its actual purpose.

Modelling errors can be a source of the EPG (De Wilde, 2014). It is not only important to use the correct modelling tools, but the designer must also have the correct knowledge about how to use the tools and to analyse the results. De Wilde (2014) writes further that even for a correct energy model made by an experienced individual, there are still uncertain input data that can create the EPG. Examples of this data are the actual occupancy schedule, weather conditions and internal heat loads.

The EPG can also occur if information regarding the performance of technical devices in a building are given incorrectly (De Wilde, 2014). Buildings designed with energy saving technology have been reported to experience EPG due to the systems not being as efficient as it was expected during the design stage.

2.2.2 Construction stage

During the construction stage, there are several causes that can contribute to the EPG (De Wilde, 2014). It is common that the finished buildings do not perform exactly as specified in plans and drawings, affecting for example the performance of air tightness and insulation negatively. An explanation for the fact that buildings can perform differently from its design performance is due problems encountered during construction (van Dronkelaar et al., 2016). Changes and problem solving on site can be needed due to problems with for instance the site constraints, the budget or fitting of building components. De Wilde (2014) does also mention problem solving on site as a source for the EPG. The problem solving on site may occur if details are not specified properly in drawings, which could lead to consequences such as increased thermal bridges.

Additionally, there can be discrepancies between the building system designed in the design stage for heating, cooling, lights, etc., and what building systems that are actually installed later during the construction stage (Mahdavi & Berger, 2024).

Unaccounted distribution losses in the heating system can be one reason for EPG. These losses may be caused by wrong balancing of the heating system, wrong installation of thermostats or components in the substation and improper control of pumps (Kempe, 2020).

2.2.3 Operational stage

The actual operation of buildings are often different from the design stage, where assumptions about the building are made (De Wilde, 2014). A reason for EPG is due to the occupant behaviour. The occupant behaviour refers to all actions taken by the people that are occupying the building (Shi et al., 2019). Examples of these actions are window opening and operation of thermostats, lights and blinds. The way occupants move between spaces is also included in occupant behaviour. All these actions depend on environmental, social and physiological factors, for example the reasons of why a window is being opened or closed. During the summer season, the windows can be closed due to noise from the outside surroundings, while in the cold season windows can be opened due to poor indoor air quality. It can be concluded that occupant behaviour is difficult to predict, as it is a variable factor.

However, the theories on that the occupant behaviours have a large negative impact on the EPG does not have enough empirical evidence according to an article by Mahdavi et al. (2021), where the authors concluded that only 14% of the studies on occupancy behaviour had high-resolution data on both energy use and occupant behaviour. EPG in the operational stage can be caused by limitations in the methods, devices and documentation that should monitor the occupant's presence and behaviour. Also, errors and limitations of the energy metering and documentation of energy consumption in the building can cause EPG (Mahdavi & Berger, 2024).

In a study by Liang et al. (2019), a survey was answered by 117 facility managers of commercial buildings in USA. The facility managers were asked about the reasons for EPG in their facilities, and three primary reasons were identified by the authors. The reasons were that occupants use more energy than assumed in the design stage, that there are more occupants in the building post-occupancy than anticipated in the design stage, and due to failures of the energy efficient technology.

During the operational stage, problems with commissioning is a common reason for EPGs (Thompson et al., 2022). If the building is not commissioned properly, problems with operating and maintaining complex equipment can occur. Thompson et al. (2022) write further that energy measuring problems is a major issue during the operational stage of buildings. Problems with commissioning and measuring are often related to each other, both being potential contributors to the EPG.

2.3 Building energy modelling

Building energy simulations are used both during the design stage and during the operational stage for optimisation purposes (Coakley et al., 2014). They work as tools for predicting the behaviour of buildings and for performing calculations of the energy use required to achieve the desired indoor environment (Lara et al., 2017).

2.3.1 Computational tools for building simulations

In this study, two different software for simulating the energy use of a building were used, VIP Energy and IDA Indoor Climate and Energy (ICE). According to Sveby (2013), both are commonly used to calculate the energy use for offices. They are dynamic calculation tools, performing yearly simulations. A dynamic calculation is made in steps, typically per hour, and considers the storage and release of heat from the building's mass (Boverket, 2017b).

IDA ICE is a software developed by EQUA and it can simulate both indoor climate of individual zones within a building and calculate the energy consumption for the building as a whole (EQUA, 2013). The tool also provides visual 3D-graphics of the building. IDA ICE builds a single large simultaneous system of equations for all processes in the building. The software has three different user levels: Wizard, Standard and Advanced, depending on modelling level. According to the user manual made by EQUA (2013), it is important to be careful not to build the model too detailed, as this will increase simulation time. An addition of one zone in the model impacts approximately 2000 variables in the equations behind the simulation. The manual also brings up numerical instabilities and the fact that it is impossible to programme a completely bug-free code for a complex numerical programme like IDA ICE. The software has been validated according to several standards, such as ASHRAE 140-2007, EN15255, EN15265 and EN13791 (EQUA, n.d.).

VIP Energy, made by Strusoft, is another tool used to calculate the energy use in buildings. There is no simulation timer in the interface, but the simulations take around one second to complete. The energy consumption is typically calculated for one year, but it can also be calculated for shorter periods (Strusoft, 2020). The calculation model is dynamic and estimates the energy use, temperature, and relative humidity every hour. No visual graphics of the building are provided in the software. There is however a possibility of simulating 1D, 2D and 3D components in the programme. The software is validated according to ASHRAE 140-2007 and EN15265.

2.3.2 Recommendations from Boverket

The Swedish National Board of Housing, Building and Planning, Boverket, gives several requirements for energy calculations of buildings in the regulation called BEN 2 (Boverket, 2017b). It provides recommendations for what values to use in calculations if the factors are unknown, based on the type of activity in the building.

Advice for weather normalisation adjustments are also provided in the regulation. Table 2.2 presents the recommended values for offices that are given in BEN 2.

Table 2.2: Input data for office buildings in BEN 2.

Category	Description	Value
Indoor temperature	Minimum temperature [C]	+21
	Maximum temperature [C]	+23
Solar shading	Shading factor [-]	0.71
Hot tap water	Energy [kWh/m^2, $A_{temp;year}$]	2/ [1]
Property energy	Energy [kWh/m^2, $A_{temp;year}$]	50
	Internal gains [%]	100
Person heat	Occupant density [m^2,A_{temp}/person]	20
	Time [hours/days/weeks][2]	9/5/47
	Heat release [W/person]	108

[1] is the yearly efficiency of the heat source for hot tap water. For district heating equals 1.0.

[2] Hours per day / days per week / weeks per year.

For kitchens in schools, which was considered to be closest to restaurant activities in BEN 2, the recommendations are as presented in table 2.3.

Table 2.3: Input data for school kitchens in BEN 2.

Category	Value
Activity energy	22 kWh/(m^2,A_{temp},year)
Hot tap water	2 kWh/(m^2,A_{temp},year)

2.3.3 Recommendations from Sveby

A recommendation source for energy calculations in Sweden is Sveby, which stands for "Standardise and verify energy performance in buildings". It is a development programme in Sweden led by people in the building industry.

In Sveby's guide for energy calculations, it is mentioned that the ventilation airflow should primarily be based on the number of occupants (Sveby, 2013). Sveby however provide a recommendation if the calculation is made at such an early stage so that the needed airflows in the buildings are not yet known. The recommendation for normal office operation is 1.3 l/(s m^2,A_{temp}) for a occupancy density of one person per 20 m^2, and the operation times set to weekdays between 07.00-19.00.

Property electricity needed per year for elevators and entrances with curtain heaters can be estimated as presented in table 2.4 (Sveby, 2013).

Table 2.4: Property energy standard values.

Category	Value
Elevator	5.5 MWh/(year,elevator)
Entrance with curtain heater	4 MWh/(year,entrance)

2.4 Miljöbyggnad

One of the most commonly used environmental certification for buildings in Sweden is Miljöbyggnad. It is given in different versions and the relevant version for the studied building is version 2.2. This version has three different focus areas, which are energy, indoor environment quality and materials (Sweden Green Building Council, 2014). Energy usage is the first indicator of Miljöbyggnad 2.2 and is graded on the building's energy performance compared to the primary energy number recommended by Boverket's building regulations (BBR). For BBR version 25, the highest recommended primary energy number is 80 $kWh = m^2; A_{temp}$; per year (Boverket, 2017a).

The energy performance is calculated as the building's primary energy number EP_{PET} $[kWh = m^2; A_{temp}]$:

$$EP_{PET} = \frac{\sum_{i=1}^{6} \left(\frac{E_{uppv;i}}{F_{geo}} + E_{kyl;i} + E_{tvv;i} + E_{f;i} \right) \quad PE_i}{A_{temp}} \tag{2.4}$$

where $E_{uppv;i}$ $[kWh = year]$ is the heating energy, F_{geo} $[\ ]$ is the geographical adjustment factor, $E_{kyl;i}$ $[kWh = year]$ is the cooling energy, $E_{tvv;i}$ $[kWh = year]$ is the hot tap water, and $E_{f;i}$ $[kWh = year]$ is fan power. Depending on the energy carriers for each energy category, the number is multiplied with a primary energy factor PE_i $[\ ]$. The summation of this is divided by the heated floor area, A_{temp} $[m^2]$. The geographical adjustment factor for Trollhättan is $1:0 [\ ]$. The primary energy factor for district heating is 1.0 and 1.6 for electricity. When grading in accordance to Miljöbyggnad 2.2, the primary energy number per year needs to be 52 $kWh = m^2; A_{temp}$ for a GOLD grade, 60 $kWh = m^2; A_{temp}$ for a SILVER grade, and 80 $kWh = m^2; A_{temp}$ for a BRONZE grade.

2.5 Assessment of energy simulation tools

Both simulation software used in this study, i.e. VIP Energy and IDA ICE, include an energy balance of the model in the result of the simulation. The energy balance was used as a tool for comparing the simulation results in this study. The components of the energy balances are described in tables 2.5 and 2.6. In the table 2.5, the categories that are similar in both programmes are presented. The categories that differs are presented in table 2.6.

The two software appear to present transmission and solar heat loads slightly different. VIP Energy presents solar energy as supplied energy in the energy balance under Window solar heat. This includes only the heat gains through windows, while the heat losses through the windows are presented under the emitted energy category Transmissions. IDA ICE has another way of presenting it, as a net value of the solar heat gains through the windows. Transmissions through window glass and window frames are subtracted from the solar gains through the windows, including both long- and short-wave radiation. VIP summarises the internal heat gains in Person heat, while IDA presents them individually as occupants, equipment, and lighting Therefore, the energy balance differs slightly between the software.

Table 2.5: Components of energy balance in VIP and IDA ICE that are similar.

Category	VIP	IDA
Infiltration	Air infiltration: Energy leaving the building with the air leaving the building through leakages in the building envelope. This does not include the air entering the building through leakages.	Infiltration and openings: Heat gains supplied via the air flow from leaks and openings.
Building envelope transmission	Transmissions: Energy leaving the building through walls, windows, and similar.	Envelope & thermal bridges: Heat flux through external walls, floors, roofs, and thermal bridges. Presented as heat gains.
Ventilation system	Ventilation: Energy leaving the building as exhaust air through the ventilation system.	Mechanical supply air: The heat that is supplied by the mechanical ventilation.
Heating system	Heating: Energy supplied to keep the indoor temperature at the heating setpoint or higher, and the heating of the supply air to the supply air temperature.	Local heating unit: Heat gains from the controlled heating units, which includes radiators, fan coils, and similar.
Cooling	Cooling: Energy emitted to keep the indoor temperature at cooling setpoint or lower. This is done through airing, cooling with air or cooling systems. This category does not include the operation of the cooling machine.	Local cooling units: Heat gains from controlled cooling. Local cooling units. This includes chilled beams, fan coils, similar.
Internal heat gains	Process energy: Energy supplied to the building, without taking the heating setpoint into consideration. This category includes both process energy and person energy.	Occupants: Heat gains from occupants, excl. the heat gains from perspiration. Equipment: Heat gains from equipment such as computers, printers and similar. Lighting: Heat gains from lighting.

Table 2.6: Components of energy balance in VIP and IDA ICE that differs.

Category	VIP	IDA
Net losses	Not a separate energy category in VIP.	The heat gains that are defined in the module Extra energy and losses
Internal walls & masses	Not a separate energy category in VIP.	Heat gained through building components as internal walls, floors, ceilings, and other internal masses.
Windows and heat gains	Window solar heat Solar radiation entering the building via radiation through the windows. This does not include the solar energy through walls and roofs, this is included in energy emissions through Transmissions	External window & solar. The heat net gain through windows. Both short and long wave radiation and transmission through pane and frame. Advected heat through windows is included in Infiltration and openings. Transmissions through windows are presented in Transmissions
Hot water	Energy needed to heat the hot water. The program then estimated that the same amount of energy is emitted with the waste water.	Not a separate energy category in IDA ICE, but can be added as an energy meter.
Recovery	Energy supplied through heat recovery (heat exchanger, heat pump), and/or energy from solar collectors.	Not a separate energy category in IDA ICE.

3

Case study building

This chapter will present information about the building, based on drawings and documents provided.

3.1 General

The studied building was constructed in 2019 and is located in an industrial part of Trollhättan. It has a total heated area of approximately 9780 m^2. A bicycle garage is connected to the main building with an area of 225 m^2, which is included in the 9780 m^2. The garage is heated to a minimum of 10 °C.

The property has large glazing areas covering the facade and a double-skin façade towards southwest. The geometry of the building varies with different heights and angles. One part of the building consists of seven storeys and the other of five. The higher building part is referred to as Building part A and the lower as Building part B in this report. Figure 3.1 shows the BIM-model of the building.

(a) Façade towards north (b) Façade towards east

(c) Façade towards south (d) Façade towards west

Figure 3.1: BIM-model of the studied building, provided by PE.

The first floor has a lunch restaurant, a small grocery store and co-working office spaces, while floor 2-7 are offices only. The offices contains both cell and open offices, together with rooms for meetings, printers, lunchrooms, among others.

3.2 The building's envelope

There are different characteristics of the building's façade. It has a double-skin façade, glazed curtain walls and non-glazed curtain walls. The double-skin façade can be seen in figure 3.1d. The rest of the façade has cladding between windowpanes that are either titanzink, weathering steel or aluminium. On the inside of the cladding there is lath, insulation, and gypsum.

The glazing types on the façade are mainly the same glass type with alterations. The vision part is a three-pane window filled with argon gas and with low energy properties. The blind glass parts of the building are of the same window type but with two panes and two different grey coloured coatings, creating another visual look and reducing the g-value. It also gives the possibility to visually hide technical equipment and insulation. The outside layer of the double-skin façade consists of a laminated security glass.

Two of the external wall types are the partition wall and the wall with aluminium cladding. The partition wall in figure 3.2a consists of a wall board, wind board, plastic sheet, insulation, wooden joists, and two gypsum boards. The exterior wall with aluminium cladding in figure 3.2b consists of an outer layer of a prefabricated aluminium wall element, insulation, wooden joists, plastic sheet, and two gypsum boards. The building's slab and roof consist of concrete and insulation.

(a) Exterior wall partition wall

(b) Exterior wall with aluminium cladding

Figure 3.2: Exterior wall sections, adapted from material provided by PE.

The air infiltration through the building's envelope was assumed to be $0.3\ l/s\cdot m^2_{ext.envelope}$ at a pressure difference of 50 Pa in the design phase. A blower door test was performed when the building was finished, resulting in an air infiltration of 0.51 $l/s\cdot m^2_{ext.envelope}$ at a pressure difference of 50 Pa.

3.3 Solar shading system of the building

Three different solar shadings are used in the building. Between the double-skin façade, facing the southwest direction, there is automatic external shading controlled by sun. The rest of the windows in the glazed façade have either internal blinds or curtains, both controlled by the occupants. The internal blinds are installed in the southeast and northeast direction. Windows facing northwest have curtains that were installed at a later stage.

3.4 HVAC system of the building

There are five air handling units serving the ventilation system of the building, called LA01, LA02, LA03, LA04 and LA05. However, LA05 has not been in use since 2021. A schematic picture of the air handling units and their location of operation is presented in figure 3.3.

Figure 3.3: Air handling units in relation to building parts.

The design air flows of each air handling unit are presented in table 3.1.

Table 3.1: Air handling units, the design air flows, and what floor they serve

Air handling unit name	Design air flow	Serves
LA01	5600 l/s	Building part A floors 2-7
LA02	5400 l/s	Building part B floors 2-5
LA03	2100 l/s	Building part A floor 1, restaurant and office
LA04	100 l/s	Bicycle garage
LA05	0 l/s	Building part B floor 1, closed restaurant

Measurements of the ventilation air flows have been made during the operational stage of the building. The measured air flows for LA01, LA02 and LA03 are presented in table 3.2

Table 3.2: Air handling units and their measured air flows.

Air handling unit	Supply air flow (max-min) [l/s]	Return air flow (max-min) [l/s]
LA01	7397-5037	7077-4807
LA02	5428	5586
LA03	2674-805	2412-604

CAV ventilation is used in a large part of the building and it runs between 07:00 19:00. DCV with CO_2-control is used in meeting rooms, break rooms, conference rooms, and the dining hall of the restaurant on the bottom floor.

The building is connected to district heating and is heated to a minimum of 21C initially. It has however been reported by the project team that the heating setpoint has been increased in several zones due to received complaints from occupants. Radiators are mainly used to heat the building, with system temperatures for supply and return water set to 55/45 C respectively. The restaurant is heated by radiators, convectors and ceiling heat panels and the bicycle garage has ceiling heat panels as well.

Chilled beams are installed to keep the indoor air temperature at a maximum of 23 C. The cooling system runs on electricity and the assumed COP of the chiller is 3.0. A free cooling tower is installed on the roof of building part B to utilise cool outdoor air for the cooling system. The free cooling coil operates only when the outdoor temperature is 8C or under. The chiller and the free cooling system is never in operation simultaneously, meaning that the chiller operates at outdoor temperatures above 8C.

Solar panels are installed on the roof of building part A, with a total area of approximately 270 m^2 and an efficiency of 18%.

3.5 Internal heat gains in the building

During the design phase, the property owner assumed that approximately 600 people would occupy the building. However, the occupancy has been reported to be lower due to changed occupancy behaviour during and after the COVID-19 pandemic because of both restrictions during the pandemic and office workers now working from home instead.

There are different types of equipment in the building contributing to the internal heat loads. The restaurant has several cooking appliances, such as ovens and deep fryers. A cold storage room is also used by the restaurant. The offices have internal heat loads due to computers, server rooms and printers.

The lighting system in the building consists of LED and is controlled differently in different parts of the building, some zones are controlled by presence and some with an on- and off switch.

3.6 Measured energy use statistics

Energy statistics for the years 2021, 2022 and 2023 were provided by PE and are presented in figure 3.4. There are also statistics for two months in 2020 and 2024, but these were excluded from this study as they were not complete years. The statistics for district heating are normalised in accordance with the actual weather conditions. District heating use has decreased by 37% between 2021 and 2023, while facility electricity has increased by 1.7%. "Other district heating" includes the hot tap water use, together with heat losses in pipes and ducts. "Other facility" includes facility electricity from for instance lights and elevators. A table with the measured energy statistic can be found in Appendix A.

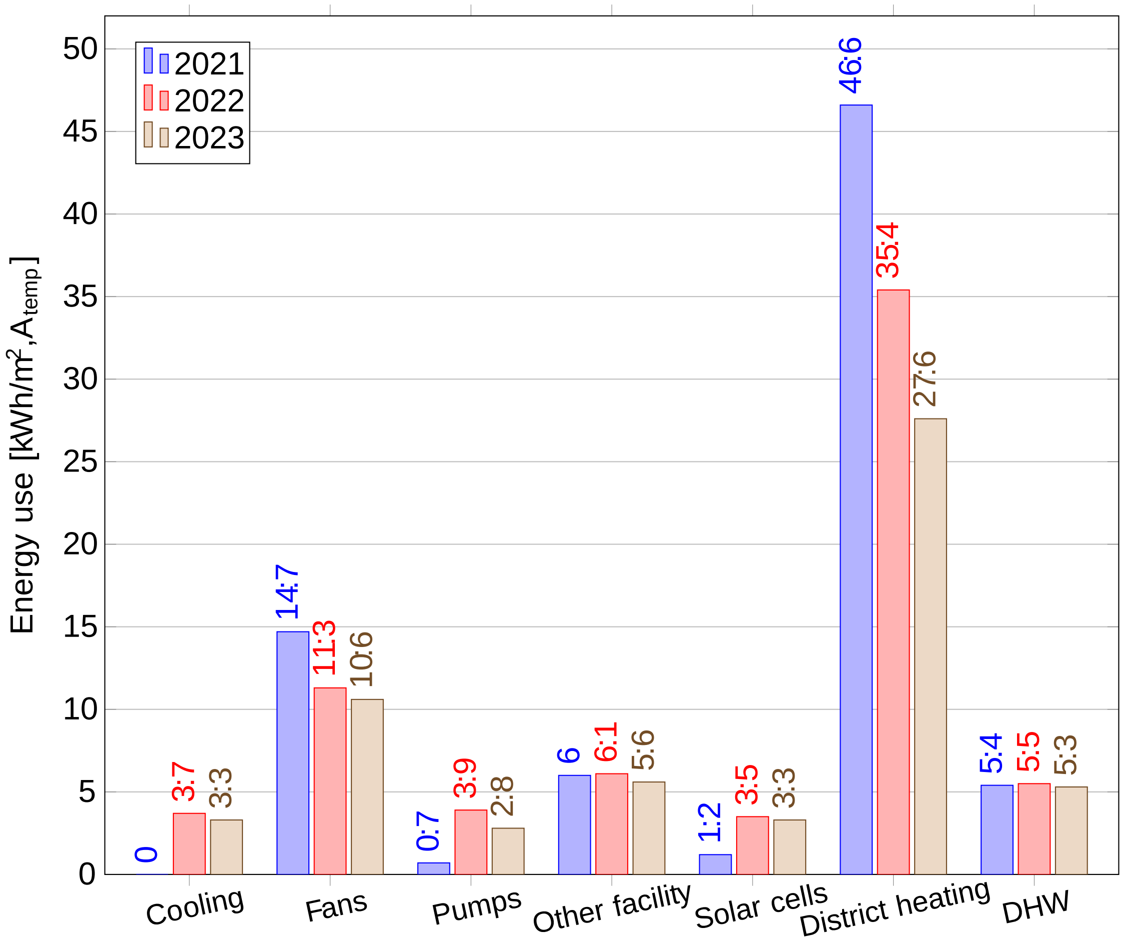

Figure 3.4: Energy use for the years 2021, 2022, and 2023.

The decrease in district heating use in the building post occupancy is due to a variety of reasons. One major factor is the non-occupancy of the second restaurant since 2021, leading to the fact that LA05 is not in use. The fine-tuning of the building service system is one additional contributor. Other reasons are due to changes in operational schedule for the air handling units. The adjustment of operational schedule involved ensuring that the air handling units do not operate during night and was made in the beginning of 2022. Hence, the adjustment is the reason for the decrease in fan electricity during 2022 2023, and it is also a contributor for the decrease in heating energy.

The reason for the low cooling and pump electricity during 2021 is that the separate energy meters for the chiller and pumps was not installed until the end of 2021.

3.7 Original design model [VIP Energy]

In the design stage, an energy model was created in VIP Energy to predict the energy use of the building. Several simplifications have been made in the VIP Energy model compared to reality. One reason for the need of simplifications is the fact that the model was developed before the building was in use. This requires assumptions regarding for instance the number of occupants, activities within the building, and the amount of internal heat gains. Additionally, the fact that a building project is limited by time generally forces consultants to simplify calculations to be able to finish within the given time limit.

3.7.1 Boundary conditions and geometry of the building

A weather file provided by Sveby with climate data for Trollhättan between the years 1981-2010 was used in the model. It gives a DVUT of -13.3C and a dimensioning ground temperature of 9.3C. The wind velocity was set to be 70% of the maximal wind velocity in the climate file, which corresponds to a partially sheltered building according to the VIP Energy manual (Strusoft, 2020).

Solar shading due to surrounding objects was simulated by inserting a horizon angle of 30 in the north, northwest and northeast direction. In the other directions, the horizon angle was set to 20. The angle is measured from the centre of the building's height. Solar shading connected to the windows, such as blinds, were excluded from the model. The solar reflection from ground was set to 20%.

In VIP Energy, the geometry of the building is inserted as given areas per component of the envelope. Each area is inserted with an orientation, a minimum height, a maximum height, U-value, and air infiltration. The areas in the given model have been based on measurements made in drawings of the building.

The main building and the bicycle garage were separated as two independent energy models in VIP Energy but were linked together with a built-in merge function. However, the first part of the comparison study will only cover the result from the simulation of the main building alone. The simplified model of the main building consists only of one thermal zone.

3.7.2 Building components

A summation of inserted building components is presented in table 3.3. Three different wall types and two different roof types were used. There are three different window types in the model, which are presented in table 3.4.

Table 3.3: Building components in the simplified model.

Building component	Total area [m ^{2}]	U-value [W/m ^{2}K]
Foundation slab 0-1 m	206	0.15
Foundation slab 1-6 m	905	0.13
Foundation slab >6 m	847	0.12
Roof general	1806	0.52
Roof terrace	117	0.52
Exterior wall 1	1439	0.13
Exterior wall 2	194	0.18
Exterior wall 3	834	0.57
Doors	75.2	1.0

Table 3.4: Window types in the simplified model.

Window type	Glass ratio [%]	Total g-value [-]	Direct ST [-]	U-value [W/(m ^{2}K)]
Curtain windows	100	0.35	0.12	0.57
Double windows	85	0.52	0.08	0.57
Other windows	70	34	0.10	1.3

As seen in table 3.3, a division of the foundation slab into three zones with different U-values was made in VIP Energy. This is to take into account the insulating capacity of the ground. Figure 3.5 illustrates the division of zones.

Figure 3.5: Principal drawing of zoning for the foundation slab in VIP Energy, viewed from above.

Table 3.5 presents the temperature amplitude and the time delay that VIP Energy uses for each part of the foundation slab in the simulation slab parts (Strusoft, 2020).

Table 3.5: The description of how slab on ground is calculated in VIP Energy

Part of the slab	Temperature amplitude [%]	Delay in days [-]
Foundation slab 0-1 m	70-100	11-13
Foundation slab 1-6 m	45-55	50-90
Foundation slab >6 m	25-40	85-125

3.7.3 Transmission

The linear thermal bridges ( ) of the original model were assumed in the design phase to have a value of 429 W/K. It is equivalent to about 15 % of the calculated building envelope's total thermal transmittance. The thermal bridges were inserted into VIP Energy as a building component with an area of 1 m^2 and a U-value of 429 W/m^2K. The air infiltration in the model was set to 0.3 $l/s,m^2$ envelope area.

3.7.4 HVAC system

Only scheduled ventilation with constant airflow was used in the VIP-model, meaning that the temperature- and CO_2-controlled ventilation has been disregarded as a simplification. The operating schedule for the ventilation in the main building is from 07:00 to 19:00 on weekdays all year. The ventilation is scheduled to start one hour before the occupancy schedule and stop two hours after.

The three air handling units, operating in the main building, LA01, LA02 and LA03 have been inserted in the model. A simplification was made where all units are assumed to provide ventilation within the same zone, as there is only one thermal zone in the model. Each air handling unit has been inserted in the model with an air flow, a supply temperature, fan pressure and an efficiency for the heat exchanger.

Cooling of the building is simulated as a chiller with a COP of 3.0 and a setpoint of 23 C. The model uses free cooling when the outdoor air is below 20 C. Using the free cooling option in the programme decreases the power needed for the chiller. There is no cooling during the weeks 28-31 in the model, as the building was assumed to be unoccupied during this period of time. Electricity for the circulation pump and fan was assumed to be 2% of the building's total required cooling power.

Heating is controlled by the outdoor air temperature in the model and the heating setpoint was chosen to 21 C. The circulation pump power was set to 5% of the building's total heating power. The supply- and return temperatures for the heating system was set in the model to 55 C and 45 C respectively.

Cold tap water temperature was set to 8 C and hot tap water to 55 C. There is no projected heat loss from the pipes in the model.

3.7.5 Internal gains

In the design phase, the client decided that the building should be dimensioned for a people density of 1 person per 12 m^2, and that 70% of the occupants are present during operational hours. Internal heat gains have been inserted in the model as activity energy and person heat in the unit W/m^2, both according to an operating schedule. The input value of activity energy was 20.75 W/m^2 and corresponds to the standard value from BEN 2 of 50 kWh/m^2,A_{temp},year. Internal heat gains from people were inserted as 7 W/m^2. Each person is assumed to have a heat loss of 108 W. The operating schedule has been set to 07:00-17:00 during weekdays, excluding the weeks 28-31 every year for summer vacation. During this period, it was assumed to be no internal heat gains from occupants or equipment in the building. Leakage of heat from the heating system to room air was set to 0 in the model.

3.7.6 Results from the simplified model

The resulting simulation time of the simulation in VIP Energy was approximately one second. The total average U-value of the building resulted in 0.353 W/(m^2K), including thermal bridges.

The energy balance is divided into supplied energy and emitted energy, as shown in figure 3.6. Tables of the data for supplied and emitted energy are found in Appendix B. The energy balance components are explained in section 2.5.

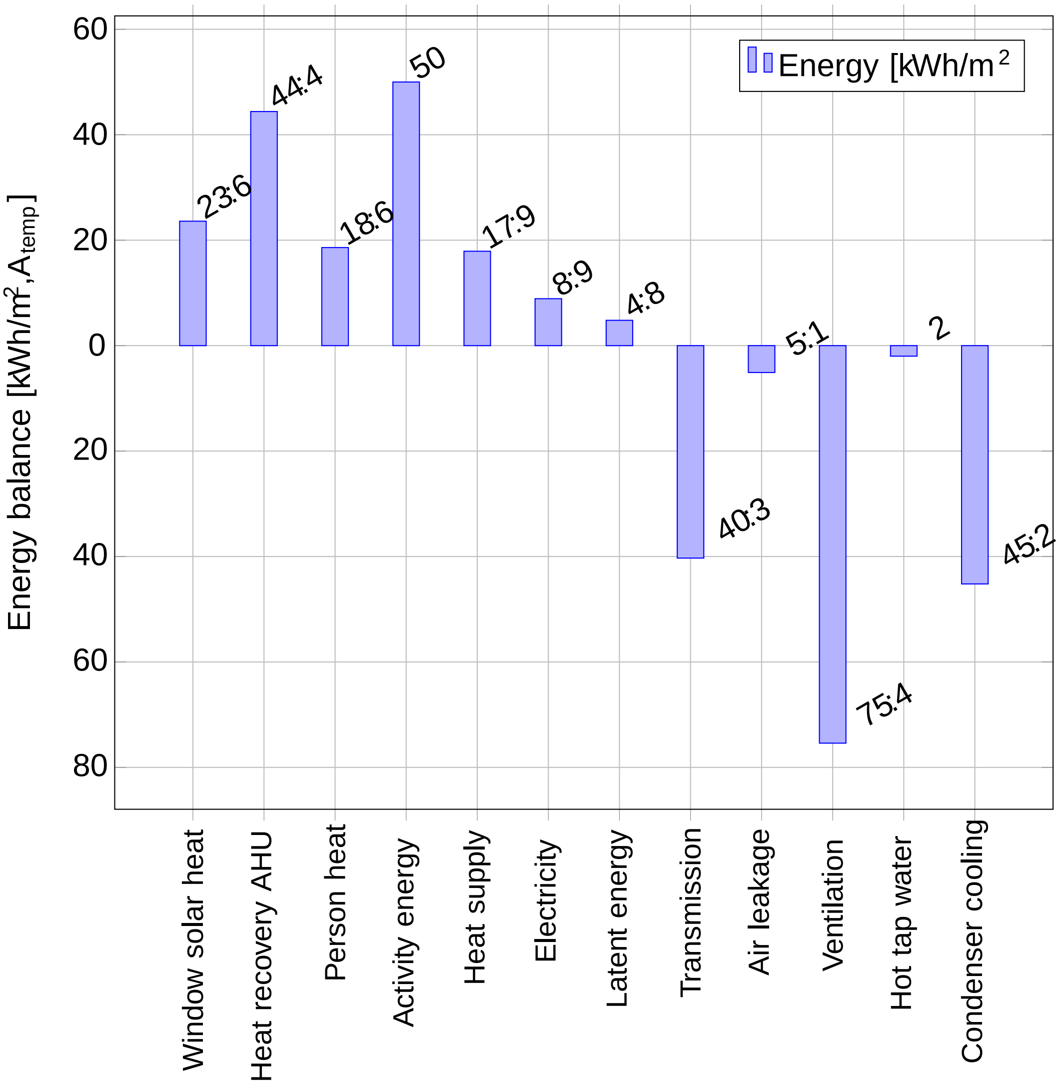

Figure 3.6: Energy balance in the original simplified model.

The resulting calculated energy use obtained from the original model in VIP Energy is presented in table 3.6.

Table 3.6: Energy use calculated in VIP Energy.

Category	[kWh]	[kWh/m^2,A$_{temp}$]
Total heating	172 447	17.9
Heating system	155 651	15.8
Hot tap water	19 303	2.0
Air handling unit	2 922	0.3
Total electricity	128 765	14.5
Cooling machine	24 863	4.0
Fans	58 074	5.9
Pumps	16 200	1.6
Other facility electricity	29 628	3.0

Two factors were added external to the VIP Energy calculation, heat losses due to airing and heat losses in the hot water circuit. These were added according to the recommendations in BEN 2 from Boverket, which are an addition of 4 kWh/m^2,A$_{temp}$ for airing losses and 6 kWh/m^2,A$_{temp}$ for hot water circuit losses. Table 3.7 presents the total predicted energy use of the building after the external addition of energy use due to heat losses.

Table 3.7: Total calculated energy use.

Category	[kWh]	$[kWh/m^2,A_{temp}]$
Total heating	276 635	28.1
Heating system	155 651	15.8
Hot tap water	19 303	2.0
Air handling unit	2 922	0.3
Heat losses due to airing	39 504	4.0
Heat losses in hot water circuit	59 256	6.0
Total electricity	128 765	14.5
Cooling machine	24 863	4.0
Fans	58 074	5.9
Pumps	16 200	1.6
Other facility electricity	29 628	3.0

The resulting energy use of the building was calculated to 42.6 $kWh/m^2,A_{temp}$, of which 28.1 $kWh/m^2,A_{temp}$ was heating energy and 14.5 $kW/m^2,A_{temp}$ facility electricity.

The primary energy number of the building was calculated to 45.3 $kWh/m^2,A_{temp}$,year, which would be classified with the grade GOLD for indicator energy use in Miljöbyggnad.

Comparing the calculated energy use to the measured energy use, the largest difference is in the heating energy use from district heating.

4

Methods

After reviewing the energy performance gap in literature together with the case building, two versions of energy models were developed in IDA ICE with different level of detail, to simulate the energy performance of the building. Version 5.0 of IDA ICE was used for the simulations. The first model was created based on the input data in the original design model from VIP Energy, and is referred to as Model A in this study. Furthermore, another version of model was made, referred to as Model B, where the IDA model was refined to increase the level of detail compared to the actual building. After the simulations, the calculated results from the two models was compared both with the original design model built in VIP Energy, and the measured energy data of the real building.

Subsequently, Model B was examined further by a sensitivity analysis, as a tool for detecting possible causes of the EPG. For this analysis, uncertain input data within the energy model were identified and then varied between simulations to evaluate their degree of impact on the calculated energy performance. The chosen input variables in the model that was assessed during the sensitivity analyses included:

- Thermal bridges of the building envelope
- Number of occupants in the building
- Heating temperature setpoint
- Cooling temperature setpoint

The methodology is summarised in figure 4.1.

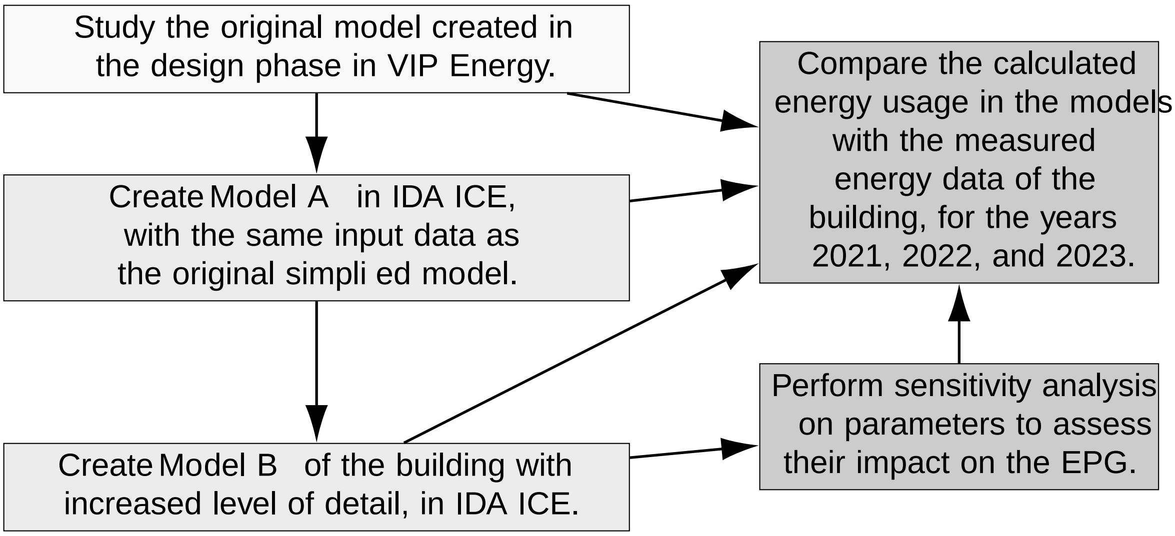

Figure 4.1: Workflow chart of the simulations.

4.1 Model A - Simplified [IDA ICE]

The first model created in this study, Model A, was built in IDA ICE with as close correlation as possible to the given original design model. Hence the input data from the original model was inserted into Model A. This included for instance schedules for occupancy and ventilation, air flows, efficiencies of the HVAC-systems and building envelope properties. For more details, see chapter 3.7.

Several adaptions were made in the original design model to facilitate the comparison. The solar panels and free cooling were excluded due to the chosen limitations of the study. The shading objects of the building, implemented as a horizontal shading in VIP, was removed from the original model as well, since it is not implemented in the same way between the two software.

When the building's geometry was obtained in IDA ICE, thermal zoning of the floor plans was created. Dividing the spaces into thermal zones was done to simplify the model and thereby decrease the simulation time. The lowest number of zones that could be used in Model A due to the geometry was five zones, compared to the simplified model only having one zone. Only one zone could not be obtained in IDA ICE if the correct building geometry would be used, due to the difference in the building's height. However, to increase the similarity of only having one zone, the zones were made with openings and leakages in between, which adds air flow paths. In accordance with the original model, all air handling units were set to run in all zones in IDA ICE.

During the process of matching the IDA ICE model to the VIP model, it was noted that the two software simulate heat transfer through the foundation slab differently. The same components with the same thermal properties were inserted for the foundation slab, which included a 100 mm thick concrete layer and a 200 mm insulation layer below. The U-value resulted in 0.173 W/(m^{2}K). Both software uses the climate file to also include the thermal properties of the ground, leading to a lower U-value than 0.173 W/(m^2 K), as the ground has insulating capacity. The resulting U-value in IDA ICE was 0.10 W/(m^2 K). VIP on the contrary splits the slab into three different zones with different U-values, see figure 3.5. The slab was manually measured on drawings, and the areas were then inserted into the three slab divisions in VIP. The first zone is a 1 meter wide border along the outer perimeter of the building body, the second is a strip 1-6 meters into the building and the third zone corresponds to the sum of the area which is more than 6 meters from the building body. The resulting U-values for the zones 0-1 meters, 1-6 meters, and >6 meters in VIP were calculated to 0.117, 0.154 and 0.125 W/(m^{2}K) respectively. In order to match this in IDA ICE, a weighted U-value was calculated based on the three zones in VIP Energy, and was then applied for the entire slab in IDA ICE.

IDA ICE measures the area of the foundation by excluding the area of the external walls connected to it. However, it was noticed that the inserted area for the foundation slab in VIP Energy had been inserted with the external walls included. This led to the fact that the slab area differed by 79 m^2. Furthermore, the total area of external walls ended up with a difference of 624 m^2 between the two models.

Table 4.1 presents the U-values and areas of the building envelope components in the two models.

Table 4.1: Building components in the original design model and Model A.

Building component	U-values [W/m^{2}K]		Areas [m^2]	
	VIP	IDA	VIP	IDA
Foundation slab 0-1 m	0.154	0.12	205.6	1874.1
Foundation slab 1-6 m	0.125		905.1	
Foundation slab >6 m	0.117		846.5	
Roof general	0.089	0.09	1806	1742
Roof terrace	0.153	0.15	117	131.2
Exterior wall 1	0.13	0.13	1439.2	2063.5
Exterior wall 2	0.179	0.179	194	194
Exterior wall 3	0.571	0.571	833.6	833.6
Doors	1.0	1.0	75.2	75.2
Curtain windows	0.57	0.57	1157	1157
Double windows	0.57	0.57	319.4	319.4
Other windows	1.3	1.3	420.1	420.2

Resulting key factors for the models are given in table 4.2.

Table 4.2: Key factors for the VIP Energy and IDA ICE models

	VIP Energy	IDA ICE
Envelope area [m^2]	8318	8811
Floor area [m^2]	9650	4410.7
U-value [W/m^{2}K]	0.362	0.344

The 3D-view of Model A in IDA ICE can be seen in figure 4.2.

(a) Façade towards north

(b) Façade towards east

(c) Façade towards south

(d) Façade towards west

Figure 4.2: 3D-view of Model A in IDA ICE

As presented in figure 4.2, the model has large areas where several floors were merged into one zone. This led to the fact that IDA excluded approximately half of the floor area in the building. To match the input data of the VIP model, a few recalculations had to be made. The calculations can be found in Appendix C.

The original model had one zone, where all the air handling units were active at the design ventilation flows. Because model A have 5 zones, the air handling units needs to be connected to all zones but at different ventilation rates. The portion of ventilation flows per zone is based on the volume of the zone, divided by the floor area of the zone to get the corresponding air flow from each AHU, in which zone. The adjustment is presented in table 4.3.

Table 4.3: Ventilation flows in Model A based on modelled volume and floor area.

Zone	Volume [m^3]	Share of volume [%]	Floor area [m^2]	LA01 [l/s,m^2]	LA02 [l/s,m^2]	LA03 [l/s,m^2]
Zone 1	2700	7	565.3	0.62	0.66	0.24
Zone 2	3300	8	818.5	0.53	0.56	0.21
Zone 3	11630	30	1069	1.42	1.51	0.56
Zone 4	15090	39	650.6	3.03	3.21	1.19
Zone 5	6290	16	1313	0.63	0.66	0.25

4.2 Model B - Detailed [IDA ICE]

An energy model with increased level of detail was made in IDA ICE to determine if it would decrease the building's performance gap.

4.2.1 Boundary conditions, geometry & zoning

An updated climate file from Sveby was used in the detailed simulation, with collected weather data from 1991-2020. The location was set to Torpabron. For the ground properties, the setting ISO-13370 was used. The air infiltration of the building at a was changed from 0.13 $l/s, m^2_{ext.surf}$ in the original model to the 0.51 $l/s, m^2_{ext.surf}$ that was measured in the blower door test.

The model was constructed by three building bodies, the 7-storey part (building part A), the 5-storey part (building part B), and the bicycle garage. The geometry of the building was obtained by creating zones on top of imported floor plan drawings from CAD. Due to differences on each storey, the building bodies were separated further in IDA ICE. The number of zones were increased significantly compared to Model A to increase the level of detail, resulting in a total of 163 zones compared to the five in Model A. The division of zones was mainly based on ventilation principle. Rooms with CAV were separated from rooms with DCV. Temperature setpoints, orientation of the rooms and adjacency to the building envelope and the type of activity in the room also played a role in the thermal zoning. Doors were placed between zones to connect them. Transfer air between rooms were simulated by a leakage area of 0.01m^2 in the door and the setting "Always closed". Between zones that has no door in reality, the setting "Always opened" was used for the door. The 3D-view of Model B in IDA ICE can be seen below in 4.3.

(a) Façade towards north

(b) Façade towards east

(c) Façade towards south

(d) Façade towards west

Figure 4.3: 3D-view of Model B in IDA ICE

4.2.2 Building envelope components in Model B

The number of building envelope components was increased for Model B to increase the level of detail. The glazing areas in Model A corresponding to the used areas in VIP were changed to the exact number of windows in reality. Hence, the envelope of the detailed model was built with respect to the BIM-model of the building. Additional information about the windows was found, including 12 different glazing types, which was implemented in Model B.

The final input data of the building components in Model B can be found in the table below.

Table 4.4: Building components in Model B.

Category	Building part	U-value [W/m ^{2}K]	Area [m ^{2}]
Foundation slab	Main building	0.11	1875.5
	Bicycle garage	0.125	225.1
Roof	General	0.089	1705.1
	Terrace	0.153	127.6
	Bicycle garage	0.177	224.7
Exterior wall	Wall 1	0.13	1608.0
	Wall 2	0.25	1157.7
	Wall 3	0.18	174.1
	Bicycle garage	0.22	197.9
Opening	Door	0.99	64.0
Window	G01	0.59	1085.8
	G03/G04/G20/G21	1.56	12.4
	G10	0.59	50.6
	G11	0.62	154.5
	G12	0.71	47.0
	G13	0.86	9.0
	G14	1.05	16.0
	G15	0.7	12.6
	G16	0.66	23.3
	G17	0.99	21.3
	G32	0.59	8.4
	G33	0.7	320.8

Resulting key factors for Model B are listed in table 4.5.

Table 4.5: Key factors for Model B

Envelope area [m^2]	9121
Floor area [m^2]	9905
U-value [W/m^{2}K]	0.278

4.2.3 HVAC system

All four air handling units that is in operation were inserted in the IDA ICE model with temperature setpoints, schedule, and efficiencies according to available information. The supply air temperature setpoint is connected to the heat exchanger, heating coil and cooling coil (EQUA, 2013). In the original design model and Model A, all zones had a heating temperature setpoint of 20°C. However, the staircases of the building do have a lower heating setpoint in reality, being 18°C. This was implemented in Model B and figure 4.4 illustrates the inserted setpoints in an example floor plan.

Figure 4.4: Setpoints for the heating system implemented in the building.

Air flows were inserted in each zone of the model according to measurements made in the building during inspection of the ventilation system. Most of the building has CAV that is active during the occupied hours on weekdays. The ventilation schedule for these zones was set to 7.00-19.00, as in the previous studied models. In meeting rooms, conference rooms, break rooms and similar rooms, the ventilation is in reality controlled by presence, air temperature, and CO_2 levels. This was simulated with separate ventilation schedules and occupancy schedules, see chapter 4.7. The total air flows of the air handling units increased significantly compared to the inserted value in the original simplified model and Model A. The resulting maximum and minimum air flows are presented in table 4.6 below.

Table 4.6: Air handling units and their modelled air flows.

Air handling unit	Number of served zones	Supply air flow (max-min) [l/s]	Return air flow (max-min) [l/s]
LA01	84	7785-4330	7385-4800
LA02	71	5753-4611	5347-4967
LA03	8	2676-581	2576-498
LA04	2	99	114

4.2.4 Occupancy

The number of occupants in each zone were estimated to be equivalent to the number of chairs in architectural floor plan drawings. Before running an energy simulation in IDA ICE, it is possible to set a percentage of the total inserted occupants. The value was set to 70% since the building is assumed not to be 100% occupied in reality.

Occupancy during 47 weeks of the year is recommended in BEN 2 for the office schedules (Boverket, 2017b). This is often achieved in energy models by putting occupants to zero for one week during Christmas holiday and four weeks during summer. In this case however, it was decided to put occupants to zero for two weeks during Christmas and reducing the occupancy to 50% for 8 weeks during summer instead. This was decided due to the current tenants of the building not being on summer vacation at the same time. Simulating a non-occupied building during summer would underestimate the cooling demand if this were not considered.

The building has different assumed occupancy schedules for different rooms in the detailed model. This was to simulate the movement of occupants during the workday, which affects the operation of the variable ventilation system. Break rooms and dining rooms were simulated to be occupied during breakfast, lunch and coffee breaks in the afternoon. Conference and meeting rooms were assumed to be in use for shorter meetings three times a day. To simulate that all meeting rooms are not used at the same time, two different occupant schedules were created. The air handling units were already assigned to each zone in accordance with the drawings.

Meeting room schedules were then evenly distributed among the meeting rooms. The opening hours for the food shop and the office spaces were set with information from the property owner. The schedules for the break rooms and meeting rooms were based on assumptions made together with the project team of when forced ventilation is needed.

Table 4.7 presents the time schedules for the different activities in the building. The distribution of the schedules can be seen in the zoning of the floor plans in Appendix D.

Table 4.7: Assumed occupancy schedules during weekdays.

Room type	Occupancy schedules during weekdays
Lunch restaurant	11:30-13:30
Food shop	05:30-23:00
Office spaces	08:00-17:00
Break rooms	09:00-10:00 12:00-13:00 14:30-15:00
Meeting room schedule, type 1	08:00-09:00 13:00-14:00 15:30-16:00
Meeting room schedule, type 2	10:00-11:00 14:00-14:30 16:00-17:00

4.2.5 Equipment & lights

For the equipment and lights in the building, recommended values from BEN 2 were used. This was a simplification of reality, but calculating the actual values would require knowledge of the number of computers, printers, lights and coffee machines etc. that is used in the building, together with their energy performance. Due to the fact that this was not known, 50 kWh/m^2,year was used for the office spaces. No recommended value for restaurants and shops was found in BEN 2. The value for a high school kitchen was found to be the closest, which corresponded to 22 kWh/ m^2,year (Boverket, 2017b). However, no equivalent value for a small food shop was found, leading to the fact that 50 kWh/m^2,year was used for the shop as well. The energy meters for office spaces, restaurant and food shop were all set to tenant electricity in the model.

In common areas, such as the entrance hall with the main staircase and common corridors, lighting was added as facility electricity, corresponding to an energy use of 12 kWh/m^2,year. This value was based on a calculation made by Sveby (2013), where 12 kWh/m^2,year was estimated for lights in an office. Elevators and the curtain heaters were added to the facility electricity in the section "Extra energy losses" in IDA ICE, with values according to Sveby (2013), see table 2.4. There are two elevators and two air curtain heaters in the building meaning that the resulting values was 11 000 kWh and 8000 per year respectively.

In zones where no equipment is used, such as toilets, the value of equipment and lights was set to zero. There are also three staircases in the building that are assumed to be used only in case of emergency and are therefore assumed to have no equipment or lighting either.

4.2.6 Heat losses

Hot tap water consumption was assumed to contribute to 2 kWh/m^2,A_{temp} per year. Heat losses in the hot water circuit system can be assumed to 3 kWh/m^2,A_{temp} in office buildings according to Sveby (2013). According to Svensk Byggtjänst (2015), the heat loss from hot water pipes is between 3.8-5.9 W/m for a 20 mm pipe with medium performance insulation. It was concluded that a better approximation was to measure the total length of the hot water circuit pipes based on pipe drawings and then multiply with a value chosen value of 5.0 W/m. This resulted in a total heat loss of 7760 kWh per year, which is equal to 0.78 kWh/m^2,A_{temp}.

4.2.7 Solar shading

The properties for the three different solar shadings used in the building were implemented in the model. External solar shading was applied on the windows behind the double-skin façade. The shading was set to be controlled by sun with a default limit of 100 W/m^2 in solar heat and a schedule that closes the shades during the nights to decrease heat losses through the windows.

The rest of the windows in the building, except for windows facing northwest, have internal blinds, controlled by the occupants. These were implemented in IDA ICE as controlled by sun with a limit of 100 W/m^2 for solar heat, similar to the solar shading in the double-skin façade. The windows facing northwest have curtains, which was implemented in IDA ICE as well.

The two buildings next to the building in question was inserted in the model as "Shading building" with the real distance and an estimated height. The high vegetation located southeast to the building was simplified as a lower shading building as well.

4.2.8 Free cooling

The free cooling was not modelled in IDA ICE, but it could be approximated by exporting the simulation results to Excel, together with the weather data. An estimation of the savings from free cooling was thereby done by excluding the cooling energy use for "Ideal coolers and other local units" when the outdoor air temperature was below +8 C.

4.3 Sensitivity analysis

The detailed model included the input data that was assumed to correspond closest to the building in reality. However, some values were estimated or assumed due to lack of information. The impact from different parameters in the energy simulation was therefore studied in this section. According to Tian (2013), sensitivity analyses are important in the process of performing building simulations. Tian writes further that one type of sensitivity analysis is called local sensitivity analysis, which involves changing one parameter while keeping other factors fixed. The method was conducted for sensitivity analyses in this study.

4.3.1 Occupants

One of the most uncertain input values of the model was the number of occupants in the building, as there is no available data regarding the real occupancy of the building today. It was therefore decided to make a sensitivity analysis where the internal heat gains from occupants, lights and occupants were varied, to analyse what impact it had on estimated energy use.

For the simulation of Model B, 70% of the inserted number of occupants were assumed to be in the building at the same time, and that 100% of the lighting and 100% of the equipment generated internal heat could be accounted for as internal heat gains. For the sensitivity analysis, these additional settings were tested:

- 30% occupants, 50% lighting, 50% equipment
- 50% occupants, 70% lighting, 70% equipment
- 90% occupants, 100% lighting, 100% equipment

4.3.2 Thermal bridges

Thermal bridges were set to 15% of the total transmission losses of the building envelope in all of the energy models. This was based on an assumption made in the design phase, hence it is possible that the number of thermal bridges is higher in reality. Therefore, simulations with thermal bridges corresponding to 20%, 25% and 30% of the transmission losses was made.

4.3.3 Heating setpoint

The heating setpoint of the building was set to +21C for the majority of zones in the design phase, with exception for three staircases and the bicycle garage. Since it has however been reported that the heating setpoint has been increased in several zones due to complaints, simulations with increased heating setpoints was tested. The heating setpoint was simulated to be either +21C, +22 C and +23 C. 22.9 C was inserted in the model for simulation of setpoint +23C, to avoid simulation problems, since the cooling setpoint is +23C as well.

4.3.4 Cooling setpoint

The design cooling setpoint was +23C in the zones with cooling. This value is based on recommendations from Boverket and it is possible that zones in the building have a higher cooling setpoint than +23C. Changes in the cooling setpoint was therefore tested, more specifically +24 C and +25 C.

4.3.5 Heating setpoint with no cooling

Two additional simulations were conducted regarding the heating setpoint, where cooling was removed from the model. The cooling setpoint was thereby set to a value of +40 C, and this was made to limit the risk of simultaneous heating and cooling in the model. Consequently, simulations were made with the following input data:

- Heating setpoint +21 C and no cooling
- Heating setpoint +22 C and no cooling

5

Results

Results from the simulations of Model A and Model B are presented in this chapter. Lastly, the results from the sensitivity analysis of Model B are presented.

5.1 Model A

The results from Model A is presented in 5.1 together with the results from the original design model, without free cooling and horizontal shading. It could be concluded from the graph that the results of the models correlate well to each other. The total simulation time for Model A was 4 minutes and 29 seconds.

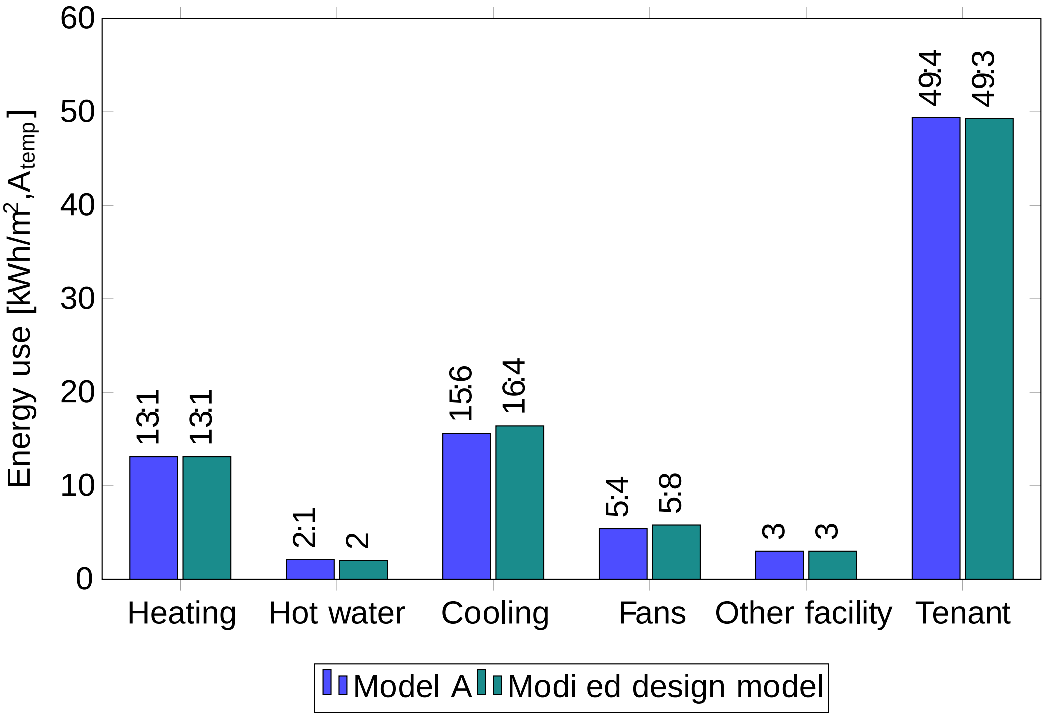

Figure 5.1: Comparison between results for bought energy in Model A and original simplified model.

5.2 Model B

The result of Model B compared with the original design model, is presented in figure 5.2. The results between Model B and the original model differed, in contrast to Model A and the original model. This was however expected, since input data had been changed for Model B, e.g. the implementation of equipment loads being dependent on activities within the zones. The simulation time for Model B was 11 hours and 49 minutes.

The resulting division of energy use between the air handling units is presented in Appendix E.

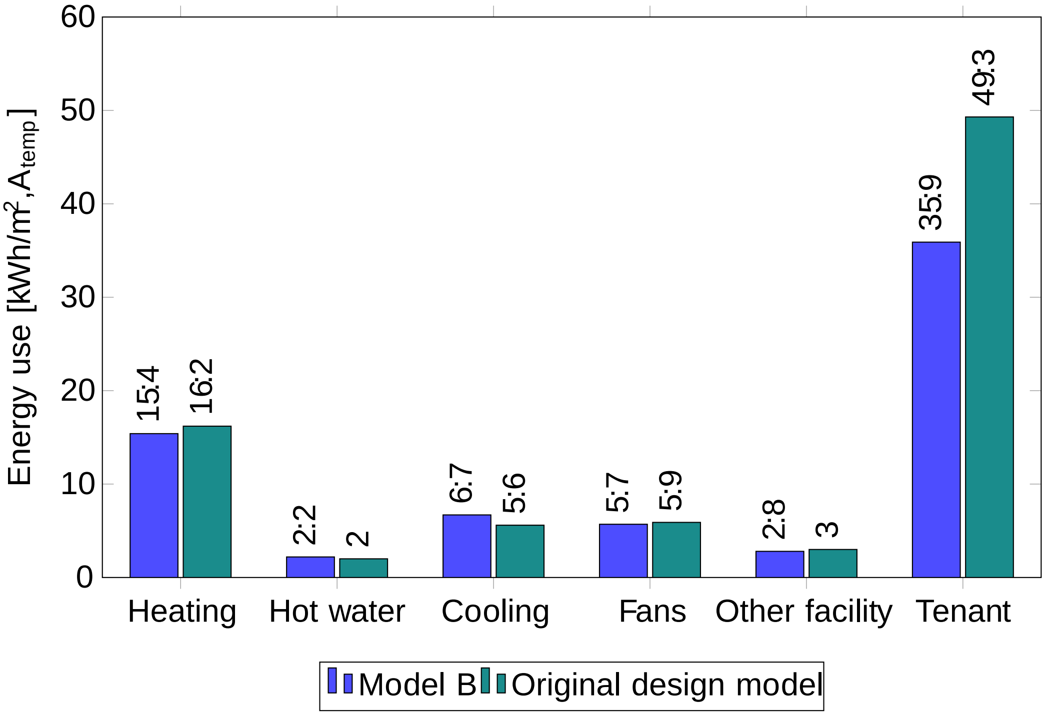

Figure 5.2: Comparison between results for bought energy in Model B and original simplified model.

5.2.1 Free cooling

Due to the fact that the chiller in the building does not operate when the outdoor air temperature is above +8C, up to 1.57 kWh/m^2,A$_{temp}$ can be saved annually by free cooling, according to extracted results from Model B. This amount was estimated by exporting cooling electricity together with weather data from IDA ICE.

5.3 Model B compared to original design model and measured energy statistics

The graph below presents the total energy use of the original design model and Model B, in comparison with the measured energy statistics of the building. The original design model is presented with values from 3.7 and "Added heat losses" stands for template heat losses for circulating hot water and due to airing. Heat losses from hot water circuits are included in the heating energy for Model B, see section 4.2.6. The estimated amount of free cooling in section 5.2.1 was added to the bar of Model B as a part of the calculated cooling energy.

It could be concluded from the graph that the original design model was closer to the measured energy statistics compared to Model B. It can also be seen that the measured energy statistics are decreasing annually, towards the computed energy performance of the building.

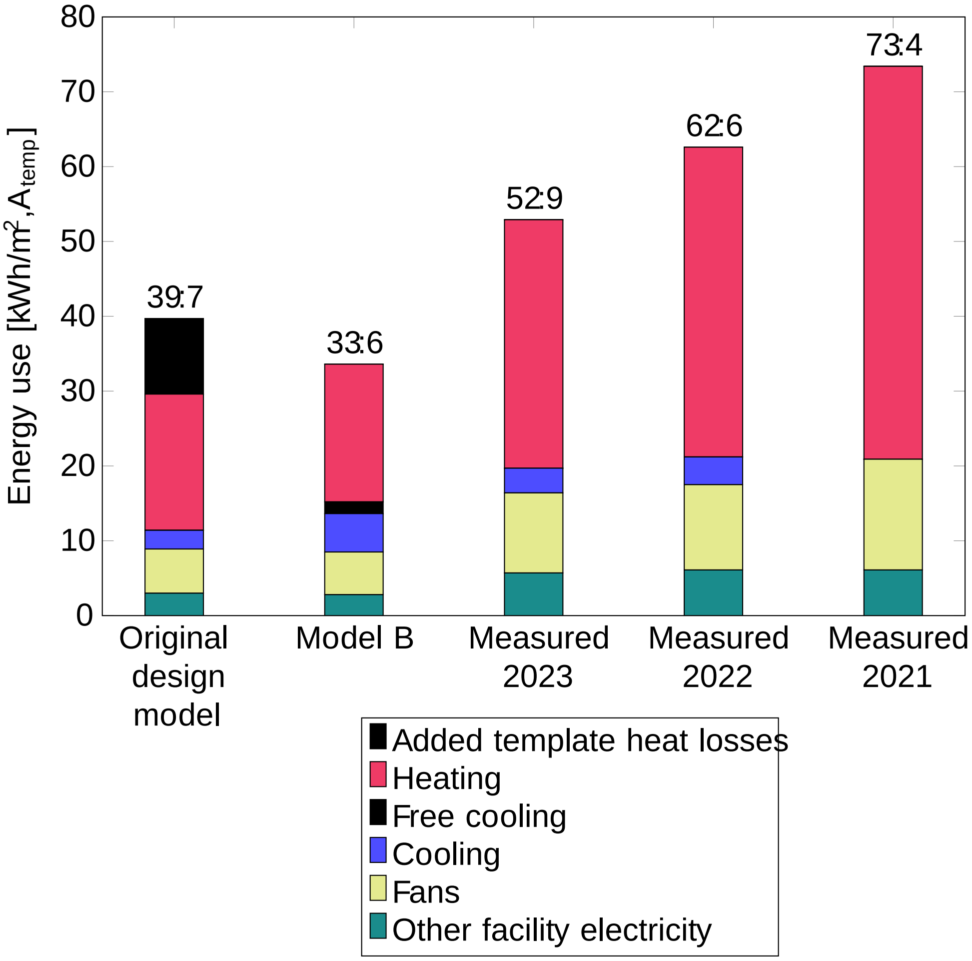

Figure 5.3: Resulting energy use in original design model, Model B and measured data.

5.4 Sensitivity analysis

The results from the sensitivity analysis are presented in this section. The hatched bar in the following graphs represents the original values used in Model B.

5.4.1 Impact of thermal bridges

Thermal bridges were initially assumed to correspond to 15% of the transmission losses through the building envelope. Different percentages of thermal bridges were tested and the energy use for heating and cooling are presented in figure 5.4. The heating energy use increased about 1 kWh/m^2,A$_{temp}$ per 5% increase of thermal bridges. The cooling energy use decreased by 0.1 kWh/m^2,A$_{temp}$ per 5% increase of thermal bridges.

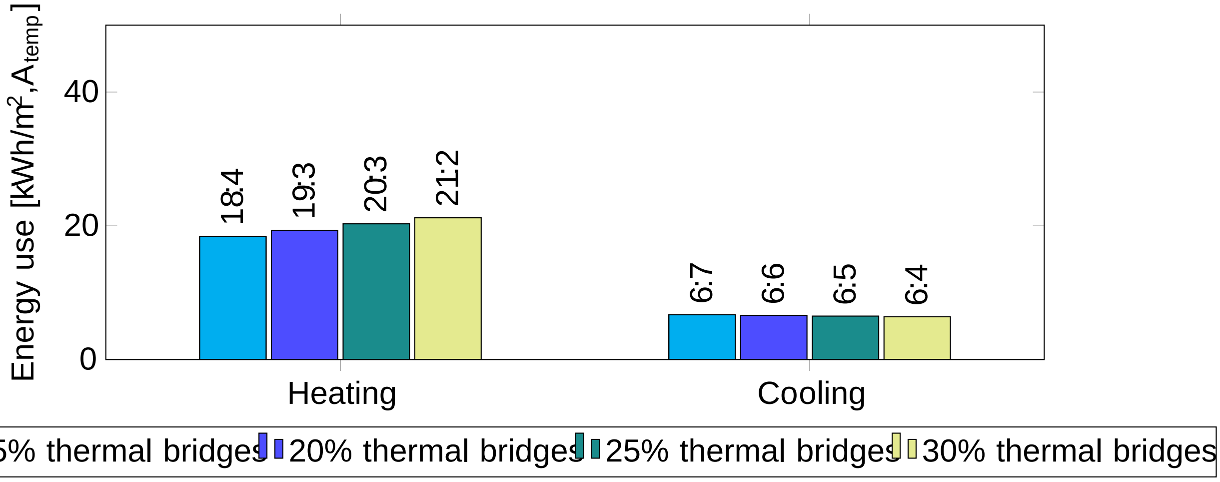

Figure 5.4: Energy use for heating and cooling for different percentage of heat transmissions due to thermal bridges in the building envelope.

5.4.2 Impact of occupant generated heat

The impact that the percentage of occupancy in the model had on the heating and cooling energy use is presented in 5.5. The heating energy use decreased while the cooling energy use increased.

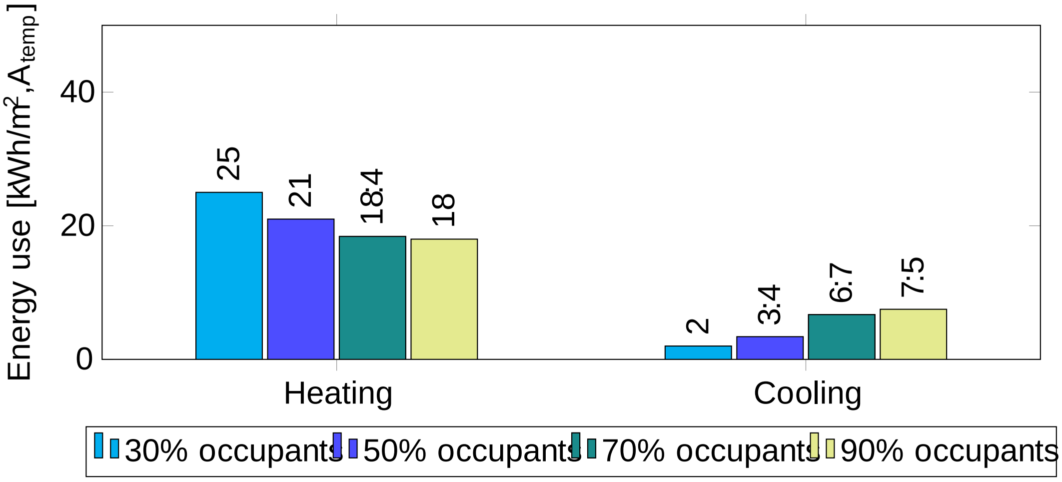

Figure 5.5: Energy use for heating and cooling with different occupancy percentages.

5.4.3 Impact of heating setpoint

Increasing the heating setpoint had a significant impact on the energy use for heating. It can be seen in the left figure above that a 2C increase doubled the heating energy use. This however also had an impact on the cooling energy use of the building, where the cooling use increased by 55% when the heating setpoint was increased by 2C.

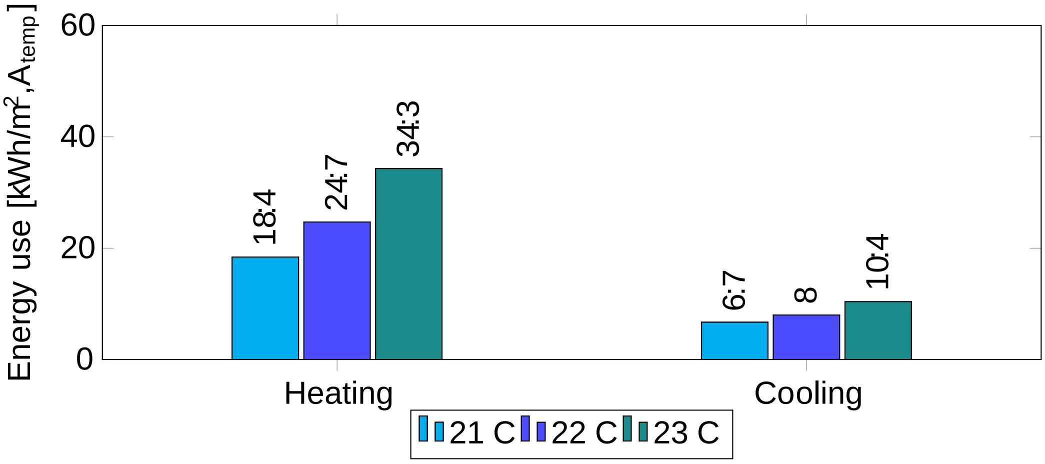

Figure 5.6: Resulting energy use with 21C, 22 C and 23 C as the heating setpoint.

5.4.4 Impact of cooling setpoint

Increasing the cooling setpoint lead to a decrease of energy use for cooling, where a 2 C increase of setpoint decreased the cooling energy use by half. This had an effect on the heating use as well, reducing the heating use by 18%.

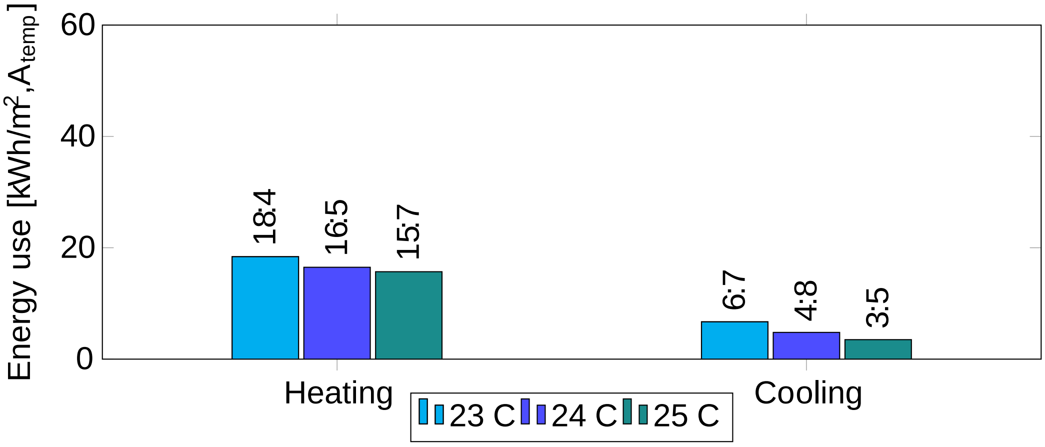

Figure 5.7: Resulting energy use with 23 C, 24 C and 25 C as the cooling setpoint.

5.4.5 Impact of heating setpoint with no cooling

Removing the cooling from the model resulted in a lower difference in heating energy between various heating setpoint temperatures. This reveals that the model at certain times had heating and cooling of the building at the same time.

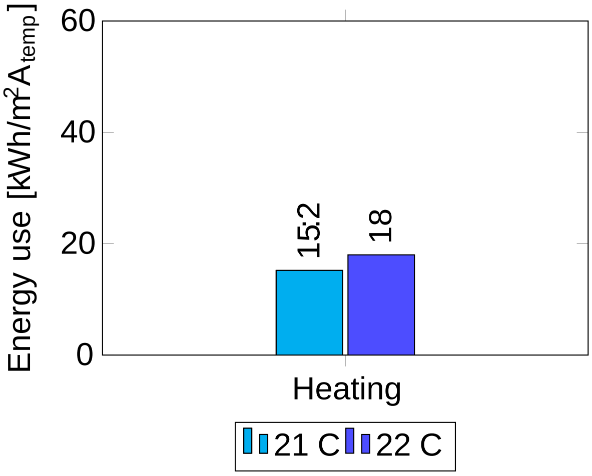

Figure 5.8: Resulting energy use for heating after cooling was removed.

6

Discussion

The energy performance gap between calculated and measured energy use was not closed by implementing a more detailed energy model in this study. However, the resulting total energy use was closer in the detailed model compared to the original design model. More specifically, the gap between total energy was decreased from 53% in the original model to 47% in the detailed model when comparing to the average of the total energy use between 2021–2023. However, when considering external added energy use for the original design model, it was closer to the measured energy, with a deviation of 37%.

One of the main differences between Model B and reality is the energy use for heating of the building, where IDA ICE simulated approximately a 56% lower use of district heating compared to the average of the measured values. There can be several reasons for this, either that the model underestimates the heating use or that the heating system of the building does not perform as expected. All three energy models calculated approximately the same heating energy use. However, for the original design model, a large amount of heat losses was added outside of the energy model, as template values. This led to the fact that the total calculated heating use was closer to the measured values. The heat losses in the circulating hot water were calculated with respect to pipe lengths for Model B, but reaching only a yearly value of approximately 0.78 $\text{kWh/m}^2,\text{A}_{temp}$ compared to the used template value of 6 $\text{kWh/m}^2,\text{A}_{temp}$ in the original design model.

The simulated energy use for the chiller in the building is not according to the measured values either. One reason for this is that the free cooling was not implemented in IDA ICE, leading to an overestimation in calculated energy use. There is no meter in the building that measures how much free cooling that is utilised, which creates a challenge when comparing to the actual cooling energy. Therefore, an approximation of the amount of free cooling that could be utilised in Model B was made, which resulted in a saving of 1.5 $\text{kWh/m}^2,\text{A}_{temp}$ per year. The estimation was made by excluding the cooling energy used when the outdoor temperature is +8 °C or below, since this is when the free cooling tower operates. Excluding the amount of approximated energy saved by free cooling did however not close the gap entirely, which indicates on either errors in the model, in the cooling system or in the measuring. The calculated energy use for cooling was closer in the original design model, but it had four weeks of no cooling at all during summer. Free cooling was also accounted for in this model.

Fan electricity is higher in reality compared to what was calculated in all of the energy models in this study. The measured fan energy data has reached yearly values of around 12 kWh/m^2,A$_{temp}$ throughout the three years of energy statistics, while the energy models calculated between 5.7 5.9 kWh/m^2,A$_{temp}$ per year. One source of error can be that the control system of the ventilation was simplified in all models. In the original design model, only CAV ventilation was used with an early approximation of airflows. For the detailed model, both CAV and VAV was used, but the VAV ventilation was simplified to only be controlled by schedule, instead of the CO_2-control in reality. This led to the fact that the ventilation was not dependent on the simulated number of occupants in the zones, which also became evident during the sensitivity analysis where the fan electricity was unaffected. Furthermore, it is possible that the reason for higher fan electricity in reality is due to the ventilation system contributing to a part of the cooling in the building. This would also explain the fact that the cooling electricity is higher for the IDA ICE model, since the model has ideal coolers and the majority of the cooling is thereby provided by the cooling system.

Pump electricity is excluded from the comparison between measured and simulated data in this study. It was decided partly due to that the pump energy meter in the building has been reported to not measure only pump electricity. This is a source of error since by excluding this, a part of the fan electricity and other factors was missed as well. The portions of the categories that this meter measures are unknown, but the yearly value of the excluded amount was approximately 3 kWh/m^2,A$_{temp}$. Moreover, it was decided to use ideal heaters and coolers in IDA ICE due to modelling limitations, which results in no simulated pump power.

Model B was created and simulated with more available information than in the design stage. However, a lot of information was still missing and numerous assumptions made in the design stage had to be kept. For instance, no additional information was found for thermal bridges and U-values of the doors. Internal heat gains from equipment were also kept as the template value of 50 kWh/m^2,year in the BEN 2 standard. This is due to the equipment in an office being complex, as the internal heat gains do not only come from personal equipment like computers, but other contributions i.e. printers, servers, coffee machines and similar devices that use electricity even during non-occupied hours. Although template values for equipment were used in Model B, the correlation to reality was improved by setting the equipment load to zero in zones with no equipment and decreasing the equipment load in non-office zones, such as the restaurant and small grocery store.

The consequences regarding time consumption for increasing level of detail in a building energy model cannot be neglected. First of all, it takes time to manually build up the model's geometry in IDA ICE for a building with complex structure. This could be avoided if a BIM-model is imported into IDA ICE instead, giving all the information about the geometries of the building. Nevertheless, BIM-models often include additional information which are not useful in an energy simulation, making the model heavier than necessary. This was the case for the created BIM-model of the building in this study. Several input data were also inserted incorrectly when importing the BIM-model into IDA ICE, for instance the elevations of the building floors. Considering this, it was not efficient to use the available BIM-model of the building, and the structure was therefore built manually with imported floor plans instead. Secondly, the simulation time was increased from seconds in VIP Energy and under five minutes for the corresponding Model A, to around 12 hours for the detailed Model B. This becomes substantially inefficient if several simulations are required. Lastly, Model B ended up being demanding for the computer and the software crashed when loading floor plans or the 3D-view every time it had been closed and then reopened, which was a time consuming factor as well.

The sensitivity analysis showed that several input data have various impact on the results. An increasing step of 5% for thermal bridges lead to a small increase of approximately 1 kWh/m^2,A$_{temp}$ per year. Cooling was not affected to the same extent, with a decrease of approximately 0.1 kWh/m^2,A$_{temp}$ per increase step. The amount of generated heat due occupants, lights and equipment impacted the energy use for both heating and cooling in the model. Increasing the occupancy led to a lower heating energy use and a higher cooling energy use, while a decrease of occupants instead led to a higher heating and lower cooling energy. Hence, the total computed energy use was not significantly impacted.

The heating setpoint had the largest impact on the energy use results among the parameters tested in the sensitivity analysis. Increasing the heating setpoint by 1°C led to 6.3 kWh/m^2,A$_{temp}$ higher heating energy. Furthermore, an increase of 2°C in heating setpoint resulted in an increase of 15.9 kWh/m^2,A$_{temp}$ for heating, which means that it was nearly doubled. However, as the cooling energy was also impacted by the increase of heating setpoint, it could be concluded that the model at certain times had heating and cooling simultaneously. Therefore, two additional simulations were made, with heating setpoints of 21 and 22°C, where the cooling was removed in order to facilitate the comparison. This resulted in a reduced difference between two heating setpoints, but the difference was still considerable, being approximately 3 kWh/m^2,A$_{temp}$. Therefore, it can be concluded that the heating setpoint can contribute to the energy performance gap.

7

Conclusion

This thesis investigated the energy performance of an office building by developing two models with different levels of detail and performing a sensitivity analysis. The original predicted energy performance led to a performance gap of 37%, when comparing to the average of the total measured energy use in the building between 2021 2023. However, the performance gap was 53% for the original energy model alone, when excluding template values for heat losses that were added post-simulation. The detailed energy model resulted in an energy performance gap of 47%. Hence, the detailed model decreased the gap for modelled energy use, but not for the predicted energy performance as a whole.

Building energy simulations are complex, with a lot of information required and several input data can involve uncertainties. In this case, thermal bridges, occupancy, and setpoints for heating and cooling were identified as uncertain parameters that were evaluated further in a sensitivity analysis. It became evident that the chosen setpoint for the heating and cooling system has a considerable impact on the result, and thus can contribute to the performance gap. During the simulation process, it also became apparent that the average U-value of the building significantly influences the energy use of the building.

In general, Model B ended up underestimating the energy use in all categories except for cooling, compared to the measured data. The study did therefore suggest that a more detailed model does not necessarily increase the accuracy of the overall energy performance. However, due to the limitations of the study, Model B is not the most detailed model that could be made. The level of detail could be increased further by for instance implementing the building's specific heating and cooling units in the model. The long simulation time also needs to be taken into consideration. Further work to achieve a more detailed energy model would facilitate the addressing of whether a detailed model could decrease the gap.

Even if the results from the detailed model did not correspond to the actual energy performance, there are other aspects of a building that could benefit from a detailed building simulation, such as analyses of daylight and thermal comfort. With this aspect in consideration, a detailed model could be crucial for the process of analysing and optimising a building's overall performance.

Bibliography

Abel, E., & Elmroth, A. (2007). Buildings and energy (1st ed.). Formas.

Alhawari, A., & Mukhopadhyaya, P. (2018). Thermal bridges in building envelopes - An overview of impacts and solutions. International Review of Applied Sciences and Engineering, 9(1), 31–40. https://doi.org/10.1556/1848.2018.9.1.5

Arbetsmiljöverket. (2020). Arbetsplatsens utformning Arbetsmiljöverkets författningssamling. https://www.av.se/globalassets/filer/publikationer/foreskrifter/arbetsplatsens-utformning-afs2020-1.pdf

Bengt Berqvist Energianalys AB. (2016). VVC-förluster i kontor och lokaler - mätningar i 11 byggnader (tech. rep.). Bengt Bergqvist Energianalys AB. https://www.energi-miljo.se/sites/default/files/vvc_lokaler_slutrapport_20161129.pdf

Blomsterberg, Å. (2008). Möjligheter med kontorsbyggnader i glas i Norden (tech. rep.). Lunds universitet, Lunds tekniska högskola. Lund.

Bohne, D. (2023). Building Services and Energy Efficient Buildings. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-41273-9

Boverket. (2017a). BFS 2017:5 - BBR 25 (tech. rep.).

Boverket. (2017b). BFS 2017:6 - BEN 2.

Boverket. (2023, May). Ventilation. https://www.boverket.se/sv/PBL-kunskapsbanken/regler-om-byggande/boverkets-byggregler/ventilation/

Coakley, D., Raftery, P., & Keane, M. (2014). A review of methods to match building energy simulation models to measured data (tech. rep.). Elsevier Ltd. https://doi.org/10.1016/j.rser.2014.05.007

De Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation. Automation in Construction, 41, 40–49. https://doi.org/10.1016/j.autcon.2014.02.009

Energimyndigheten. (2007). Förbättrad energistatistik för lokaler - "Stegvis STIL" Rapport för år 1 (tech. rep.).

EQUA. (n.d.). Validations & Certifications. https://www.equa.se/en/ida-ice/validation-certifications

EQUA. (2013). User Manual IDA Indoor Climate and Energy (tech. rep.). http://www.equaonline.com/iceuser/pdf/ICE45eng.pdf

Esrafilian-Najafabadi, M., & Haghighat, F. (2021, June). Occupancy-based HVAC control systems in buildings: A state-of-the-art review. https://doi.org/10.1016/j.buildenv.2021.107810

Hesaraki, A., Myhren, J. A., & Holmberg, S. (2015). Influence of different ventilation levels on indoor air quality and energy savings: A case study of a single-family house. Sustainable Cities and Society, 19, 165–172. https://doi.org/10.1016/j.scs.2015.08.004

Karlsson, F., Rohdin, P., & Persson, M. L. (2007). Measured and predicted energy demand of a low energy building: Important aspects when using building energy simulation. Building Services Engineering Research and Technology, 28(3), 223–235. https://doi.org/10.1177/0143624407077393

Kempe, P. (2020, November). Förstudie - Förutsättningar för analyser av energieeffektiva flerbostadshus funktioner och energianvändning (tech. rep.). BeBostad.

Kitzberger, T., Kilian, D., Kotik, J., & Pröll, T. (2019). Comprehensive analysis of the performance and intrinsic energy losses of centralized Domestic Hot Water (DHW) systems in commercial (educational) buildings. Energy and Buildings, 195, 126–138. https://doi.org/10.1016/j.enbuild.2019.05.016

Lara, R. A., Naboni, E., Pernigotto, G., Cappelletti, F., Zhang, Y., Barzon, F., Gasparella, A., & Romagnoni, P. (2017). Optimization Tools for Building Energy Model Calibration. Energy Procedia, 111, 1060–1069. https://doi.org/https://doi.org/10.1016/j.egypro.2017.03.269

Lee, J., & Boubekri, M. (2020). Impact of daylight exposure on health, well-being and sleep of office workers based on actigraphy, surveys, and computer simulation (tech. rep.). http://meridian.allenpress.com/jgb/article-pdf/15/4/19/2678962/i1943-4618-15-4-19.pdf

Liang, J., Qiu, Y., & Hu, M. (2019). Mind the energy performance gap: Evidence from green commercial buildings. Resources, Conservation and Recycling, 141, 364–377. https://doi.org/10.1016/j.resconrec.2018.10.021

Mahdavi, A., & Berger, C. (2024). Ten questions regarding buildings, occupants and the energy performance gap. Journal of Building Performance Simulation, 1–11. https://doi.org/10.1080/19401493.2024.2332245

Mahdavi, A., Berger, C., Amin, H., Ampatzi, E., Andersen, R. K., Azar, E., Barthelmes, V. M., Favero, M., Hahn, J., Khovalyg, D., Knudsen, H. N., Navarro, A. L., Roetzel, A., Sangogboye, F. C., Schweiker, M., Taheri, M., Teli, D., Touchie, M., & Verbruggen, S. (2021, March). The role of occupants in buildings' energy performance gap: Myth or reality? https://doi.org/10.3390/su13063146

Mahdavinejad, M., Bazazzadeh, H., Mehrvarz, F., Berardi, U., Nasr, T., Pourbagher, S., & Hoseinzadeh, S. (2024). The impact of facade geometry on visual comfort and energy consumption in an office building in different climates. Energy Reports. https://doi.org/10.1016/j.egyr.2023.11.021

Nilsson, P. E. (2003). Achieving the desired indoor climate (P. E. Nilsson, Ed.; 1st ed.). Studentlitteratur AB.

Shaikh, P. H., Nor, N. B. M., Nallagownden, P., Elamvazuthi, I., & Ibrahim, T. (2014). A review on optimized control systems for building energy and comfort management of smart sustainable buildings. https://doi.org/10.1016/j.rser.2014.03.027

Shi, X., Si, B., Zhao, J., Tian, Z., Wang, C., Jin, X., & Zhou, X. (2019). Magnitude, Causes, and Solutions of the Performance Gap of Buildings: A Review. Sustainability, 11(3), 937. https://doi.org/10.3390/su11030937

Strandberg, B., & Lavén, F. (2021). Bygga hus - illustrerad bygglära (4th ed.). Studentlitteratur AB.

Strusoft. (2020, July). VIP-Energy Manual Version 4. https://www.vipenergy.net/Manual_ENG.htm

Sveby. (2013, June). Brukarindata kontor (tech. rep.). Sveby. Stockholm. https://www.sveby.org/wp-content/uploads/2013/06/Brukarindata-kontor-version-1.1.pdf

Svensk Byggtjänst. (2015). RA VVS & Kyl 16. Edita Bobergs AB.

Sweden Green Building Council. (2014). Miljöbyggnad 2.2 - Bedömningskriterier för nyproducerade byggnader (tech. rep.). Sweden Green Building Council. Stockholm.

Swedish Standards Institute. (2017). SS-EN ISO 14683:2017 (tech. rep.). www.sis.se

Thompson, D., Burman, E., Mumovic, D., & Davies, M. (2022). Managing the risk of the energy performance gap in non-domestic buildings. Building Services Engineering Research and Technology, 43(1), 57 88. https://doi.org/10.1177/01436244211008319

Tian, W. (2013). A review of sensitivity analysis methods in building energy analysis. Renewable and Sustainable Energy Reviews, 20, 411 419. https://doi.org/10.1016/j.rser.2012.12.014

van Dronkelaar, C., Dowson, M., Spataru, C., & Mumovic, D. (2016). A Review of the Regulatory Energy Performance Gap and Its Underlying Causes in Non-domestic Buildings. Frontiers in Mechanical Engineering, 1. https://doi.org/10.3389/fmech.2015.00017

Warfvinge, C., & Dahlblom, M. (2010). Projektering av VVS-installationer (1st ed.). Studentlitteratur AB.

Yoshino, H., Hong, T., & Nord, N. (2017). IEA EBC annex 53: Total energy use in buildings Analysis and evaluation methods. Energy and Buildings, 152, 124 136. https://doi.org/10.1016/j.enbuild.2017.07.038

A

Measured energy statistics

Table A.1: Facility energy statistics post-occupancy for each year.

Category	2021 [kWh/m^2]	2022 [kWh/m^2]	2023 [kWh/m^2]
Cooling electricity	0	3.7	3.3
Fan electricity	14.7	11.3	10.6
Pump electricity	0.7	3.9	2.8
Facility electricity	6.0	6.1	5.6
Solar cells	-1.2	-3.5	-3.3
Total facility electricity	17	19	17
Heating, district heating	46.6	35.4	27.6
Other district heating	5.4	5.5	5.3
Total district heating	52.0	41.0	32.9

B

Energy balance of design model

Table B.1: Supplied energy in energy balance.

Supplied Energy	[kWh]	[kWh/m^2,A$_{temp}$]
Solar energy (windows)	227 383	23.6
Heat recovery AHU	428 275	44.4
Person heat	179 075	18.6
Activity energy	482 572	50.0
Heat supply	172 447	17.9
Electricity	85 555	8.9
Latent energy	46 513	4.8
Total supplied energy	1 621 830	168.1

Table B.2: Emitted energy in energy balance.

Emitted Energy	[kWh]	[kWh/m^2,A$_{temp}$]
Transmissions	389 224	40.3
Air leakage	49 444	5.1
Ventilation	727 625	75.4
Hot tap water	19 303	2.0
Condensor cooling	436 234	45.2
Total emitted energy	1 621 830	168.1

C

Adaptions of input data for VIP to IDA model conversion

Hot water:

$$9650\,\mathrm{m}^2 \cdot 2\,\mathrm{kWh/m}^2 = 4410.7\,\mathrm{m}^2 \cdot X \Rightarrow X = 4.3757\,\mathrm{kWh/m}^2 \tag{C.1}$$

Tenant electricity:

$$9650\,\mathrm{m}^2 \cdot 50\,\mathrm{kWh/m}^2 = 4410.7\,\mathrm{m}^2 \cdot X \Rightarrow X = 109.39\,\mathrm{kWh/m}^2 \tag{C.2}$$

Facility electricity:

$$9650\,\mathrm{m}^2 \cdot 3\,\mathrm{kWh/m}^2 = 4410.7\,\mathrm{m}^2 \cdot X \Rightarrow X = 6.5636\,\mathrm{kWh/m}^2 \tag{C.3}$$

Infiltration:

$$8318\,\mathrm{m}^2 \cdot 0.3\,\frac{\mathrm{l}}{\mathrm{s} \cdot \mathrm{m}^2\,\mathrm{ext.surf}} = 8811\,\mathrm{m}^2 \cdot X \Rightarrow X = 0.2832\,\frac{\mathrm{l}}{\mathrm{s} \cdot \mathrm{m}^2\,\mathrm{ext.surf}} \tag{C.4}$$

D

Occupant schedules of the building

Figure D.1: Schedule types on floor 1

Figure D.2: Schedule types on floor 2

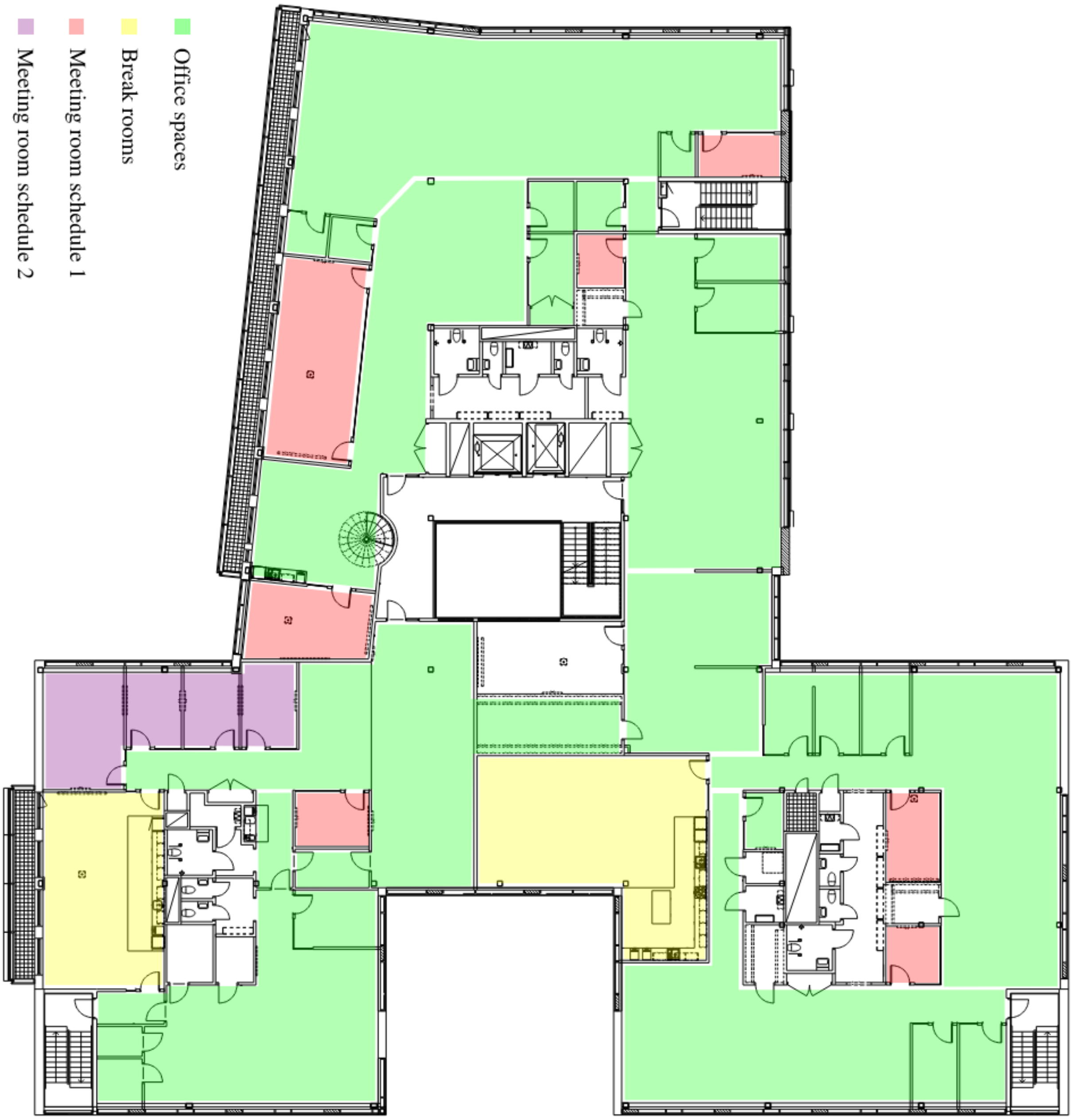

Figure D.3: Schedule types on floor 3

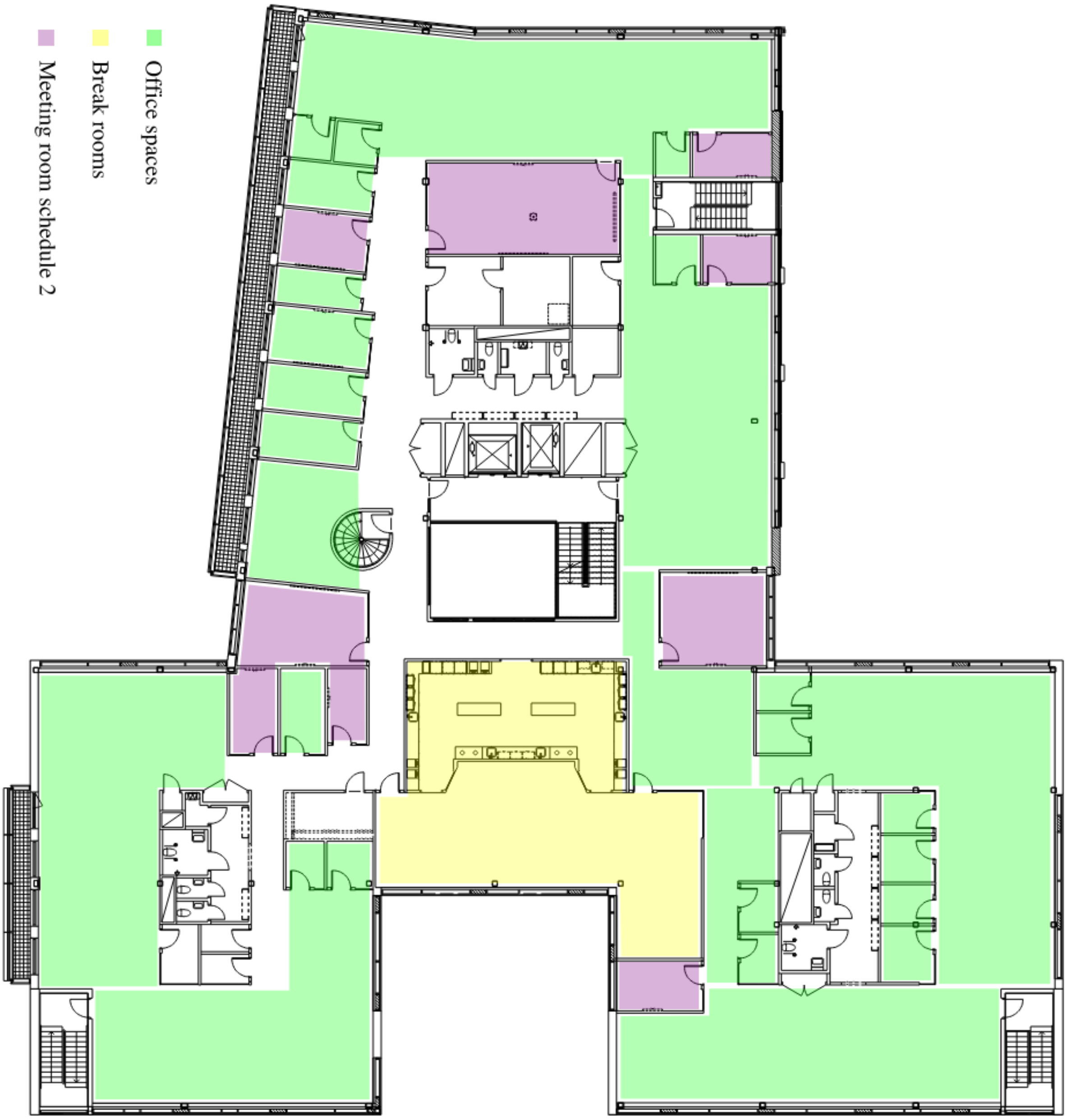

Figure D.4: Schedule types on floor 4

Figure D.5: Schedule types on floor 5

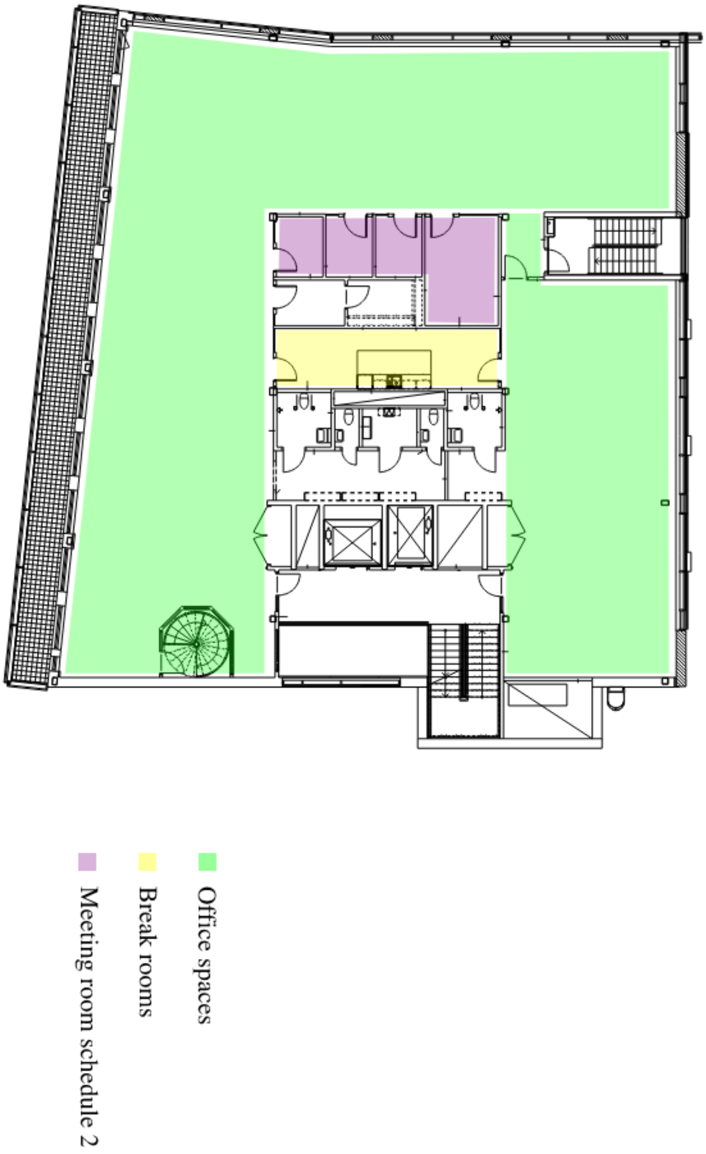

Figure D.6: Schedule types on floor 6

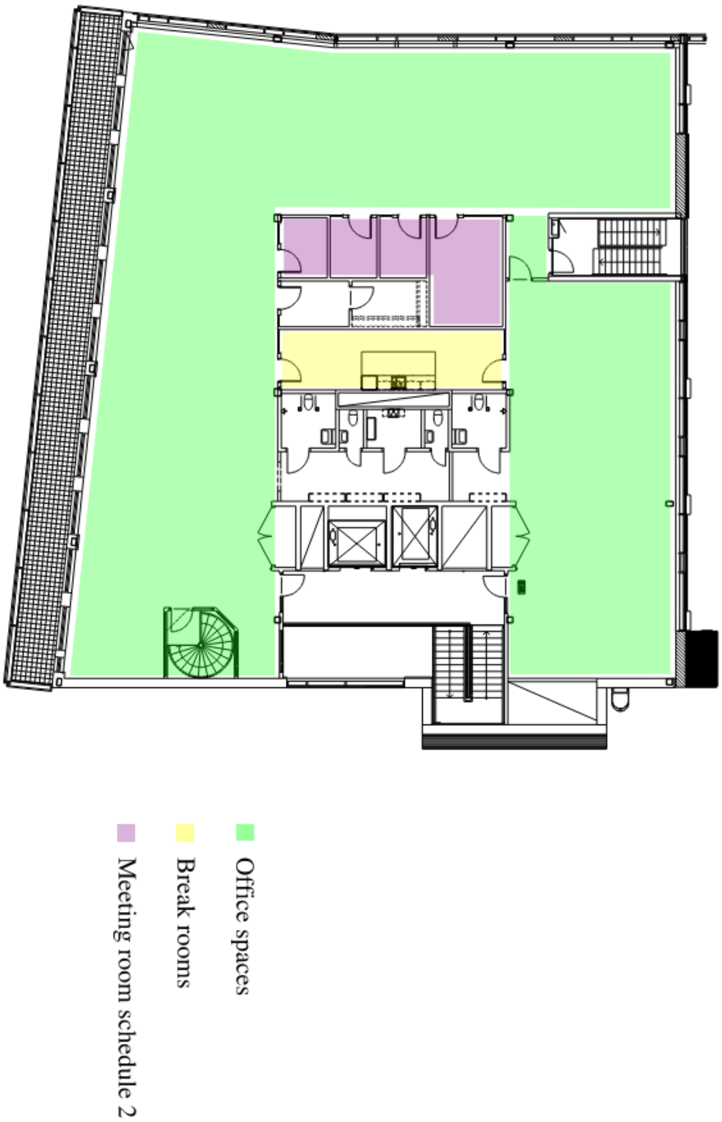

Figure D.7: Schedule types on floor 7

E

Calculated fan electricity in Model B

Table E.1: Calculated fan electricity in Model B

Air handling unit	Fan electricity [kWh/year]
LA01	26 213
LA02	22 584
LA03	4 317
LA04	2 095

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