Energy Efficiency Assessment Based on Field Measurements and Computational Simulations

A Swedish Hypermarket's case study

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Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

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October 2022

Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

Acknowledgements

Developing this project was a challenging but rewarding process. Hence, I am truly grateful to have had the conditions required to complete this master thesis.

First of all, I am grateful to Sweden. What an amazing country to have lived for one year and have developed the final project of my master! KTH provided me prosperous conditions to work, where I had the pleasure to find Professor Jaime Arias, a very dedicated professor and examiner, always ready to clarify any doubt I could have and provide very useful feedback. I would also like to present my gratitude to my supervisor Sotirios Thanasoulas, who believed in me from the beginning to develop this project and gave me a great support. Another important support on my thesis was provided by Enrique Mejia Solis, to clarify some questions regarding EnergyPlus, thank you so much! I would also like to give an appreciation word to ICA MAXI group, for providing me detailed data about the hypermarket I have been working with.

From KTH I was also inspired by amazing colleagues that cross my path, from which I would like to give a special word to Árpád Fodor, who was always ready to read and discuss about my project and Niraj Kunkulol, who was present in every moment of this journey.

From IST, my home university, where I studied for 4 years, I learnt to be resilient and patient, among many other technical knowledge I acquire which was useful to develop this thesis. Professor Tânia Sousa inspired me on her course in the end of my bachelor and, luckily, accepted to supervise this master thesis, always providing me with useful feedback.

Finally, I would like to thank my family, specially my parents Rita and Paulo and my sister Margarida, who always supported and inspired me unconditionally and without whom it would have been impossible to have taken this journey.

Abstract

Energy consumption in buildings is responsible for 36% of GHG emissions in European countries. To reach the net-zero emissions by 2050, it is essential to improve energy efficiency in the building sector. Food retail stores consume 3-4% of the total electricity in industrialized countries.

In this thesis, the software simulation tools EnergyPlus and CyberMat are tested by comparing their predicted annual energy consumption of a Swedish hypermarket with the energy consumed in 2021, according to field measurements. Afterwards, energy efficiency measurements are tested in EnergyPlus. For such purpose, an ICA MAXI hypermarket in Bålsta, Stockholm, has been under analysis. This hypermarket operates with a trans-critical CO_2 booster refrigeration system for cold climate countries, allowing to recover the heat from the refrigeration cabinets to the sales area.

Results from the field measurements showed a total energy consumption of 264 kWh/m^2, which is in accordance with several studies' conclusions. However, the values predicted by the simulation tools appointed a lower annual consumption.

In the end, EnergyPlus' model predicted an annual energy consumption of 205 kWh/m^2. Out of the 387 MWh gap, 219 MWh are due to the assumptions taken for the energy consumed by non-specified electrical appliances, 120 MWh resulted from the non-optimal control strategy used on the refrigeration system and the remaining 48 MWh were related to different outside temperatures, predicted on the model and measurements from 2021.

The final results from the CyberMart model were close to the EnergyPlus ones and this software was found to be much more user-friendly, but less detailed. The construction of different scenarios on the EnergyPlus model pointed out that the non-control of the indoor temperature during the night can save 1.3% of the annual energy consumption and, thus, avoid the emission of 522 kg of CO_{2e}.

Keywords

Hypermarket, Energy efficiency, Building's simulation tools, EnergyPlus, CyberMart

Resumo

O consumo energético em edifícios é responsável por 36% das emissões de gases com efeito estufa em países europeus. De modo a alcançar as zero-emissões em 2050, é essencial melhorar a eficiência energética em edifícios. As lojas de retalho alimentar consumem 3 a 4% da eletricidade produzida em países industrializados.

Nesta tese de mestrado, os softwares de simulação EnergyPlus e CyberMart são testados, ao comparar a sua estimativa do consumo energético anual do um hipermercado sueco com a energia consumida em 2021, de acordo com os medidores de energia. Posteriormente, medidas de eficiência energética são testadas com software EnergyPlus. Para isso, um hipermercado ICA MAXI em Bålsta, Estocolmo, é objeto de análise. Este hipermercado opera com um sistema de refrigeração centralizado trans-crítico, com CO_2 como refrigerante. Este sistema é usado em países frios e permite recuperar calor extraído das cabines de refrigeração para a zona de vendas.

De acordo com as medições realizadas em 2021, a energia total consumida foi de 264 kWh/m^2, enquadrando-se com as conclusões de vários estudos. Contudo, os valores estimados pelos software de simulação apontaram para um consumo energético mais baixo.

No final, o modelo construído no sofware EnergyPlus previu um consumo energético anual de 205 kWh/m^2. Da diferença de 387 MWh, 219 MWh deveram-se às suposições tidas em conta para o consumo energético de aparelhos eletrónicos não especificados, 120 MWh resultaram de uma estratégia de controlo não otimizada usada no sistema de refrigeração e os restantes 48 MWh estão relacionados com a diferença de temperaturas exteriores estimadas pelo modelo e as medições de 2021.

Os resultados finais obtidos pelo modelo construído no software CyberMart estão próximos do modelo do EnergyPlus, sendo que o software CyberMart demonstrou ser muito mais fácil de usar, ainda que com menos detalhes. A construção de cenários diferentes no modelo do software EnergyPlus concluiu que o não controlo da temperatura no hipermercado durante a noite leva a uma poupança de 1,3% do consumo energético anual e, dessa forma, evita a emissão de 522 Kg de CO_{2e}.

Palavras-chave

Hipermercado, Eficiência energética, Softwares de simulação, EnergyPlus, CyberMart

Acronyms

AC	air conditioning
ach	air changes per hour
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
CDD	Cooling Degrees Days
CFC	Chlorofluorocarbons
COP	Coefficient of Performance
DHW	Domestic Hot Water
EPW	EnergyPlus Weather
GHG	Greenhouse Gases
GWP	Global Warming Potential
HFC	Hydrofluorocarbons
HFO	Hydrofluoroolefins
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LHR	Latent Heat Ratio
LT	Low Temperature
MT	Medium Temperature
ODP	Ozone Depletion Potential
RPC	Representative Concentration Pathway
SMHI	Swedish Meteorological and Hydrological Institute
NZEB	Nearly Zero Energy Buildings

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Chapter 1

Introduction

1.1 Background

Back in 2015, the Paris Agreement was accepted by many countries in the world, aiming to keep the rise in the global average temperature to 'well below' 2 degrees above pre-industrial levels, ideally 1.5 degrees [6]. From that moment until today, those targets have been increasing. In order to have the chance of limiting warming to 1.5 degrees, global Greenhouse Gases (GHG) emissions must reach 'net-zero', by 2050 [7]

"Faced with the challenge of mitigating climate change, EU leaders have committed to saving 20% of the EU Member States' projected energy consumption by 2020 and 32.5% by 2030. Improving the energy efficiency of buildings is a key tool to achieving these targets. Buildings consume the greatest share of energy and have the largest energy savings potential." [8]

Energy used in buildings accounts for almost one third of the global final energy consumption, being responsible for 36% of GHG emissions in European countries [9]. Therefore, reducing energy use by all building types (residential, commercial, services and industrial) is essential to achieve Net Zero emissions by 2050 and to follow the Paris Agreement. Efforts are being made with demand pattern analysis and the use of building codes, which help to create efficiency measures to decrease the energy consumption. Much attention has been paid to the residential sector, whereas consumption in commercial and industrial buildings has been, somehow, under-investigated due to its diversity, lack of publicly accessible data, and the nature of property ownership [10]. However, the commercial sector accounts for 21% of the total final consumption of electricity. Amongst these, food retail stores (supermarkets) are the highest energy intensive ones (highest energy consumption per sales or total area), consuming almost the double of a standard office building. Supermarkets consume about 3-4% of the annual electricity production in industrialized countries. These numbers have been reported in different countries, namely 3% in Sweden and 4% in the USA [2], [11].

For the reasons mentioned above, it is relevant to further study and analyse the energy demand in supermarket buildings, aiming to decrease the demand, by implementing energy efficiency measures as much as possible. Today, different approaches and computational software can be used or adapted to predict the energy consumption in supermarket buildings.

It may also be interesting to understand how climate change can affect the buildings' energy demand, namely in supermarkets. Even in the best-case scenario of net zero emissions by 2050, temperatures are expected to rise globally and it will probably affect the energy demand of our buildings. According to several studies, including [3], the highest relative changes occur towards north-eastern Europe, like Sweden, and for high-altitude areas. The study shows that temperature changes lead to generally decreased heating demands and increased cooling needs. Therefore, it is important to adapt the heating and cooling appliances' capacities to this new reality.

According to the International Energy Agency (IEA), Sweden is a global leader in decarbonisation and aims to cut GHG emissions 59% by 2030 compared with 2005 and to have a net-zero carbon economy by 2045. Sweden was the first country to implement carbon tax and has the highest carbon tax in the world, which has proven to be effective at promoting decarbonisation. In addition, Sweden has reduced its CO_2 (Carbon Dioxide) emissions by almost 40% compared to 1990's levels [12]. Sweden has been achieving those promising results, not only by increasing the share of renewables year by year, but also by reducing the total energy consumption, without decreasing the consumers satisfaction. This, naturally, comes from the energy efficiency measurements that have been adopted. Sweden is, thus, making considerable efforts to reach the so important net-zero emissions before 2050, as agreed on the European Green Deal in 2019 by the European Commission [13]. It is important to take into consideration that, although the Swedish electricity mix rely considerably on clean sources of energy, each kWh still generates the equivalent of 29 g of CO_2 [14] [15] . Therefore, it is crucial to keep looking for energy efficiencies measures, aiming to achieve net zero emissions by 2045.

In this cold climate country, it has been extremely important to implement energy efficiency measures in the building sector, namely in commercial and residential buildings, due to the need for supplying space heating without emitting large amounts of GHG. Therefore, in order to limit the amount of GHG emissions, it is crucial to decrease the energy consumption of the country. With that aim, building codes have been adopted in the residential sector, such as the City of Stockholm initiative in Norra Djurgårdsstaden district. There, newly constructed buildings should have an energy intensity of 55 kWh/m^2, much stricter than the value of 75 kWh/m^2, as stipulated by the Swedish Building Code [16]. This regulation is aligned with directive created by the Directive on Energy Performance of Buildings, regarding Nearly Zero Energy Buildings (NZEB). A NZEB is defined as a building that has a very high energy performance. In addition, the nearly zero or very low amount of energy required shall be covered to a very significant extent from renewable sources, including sources produced on-site or nearby [17].

Moreover, efforts are being made, in Sweden, to reduce the energy intensity of buildings from the commercial sector, such as food retail stores. CyberMart software, developed by Jaime Arias, KTH Royal Institute of Technology, is an example of software being used to predict the energy demand on a supermarket building, taking into account different aspects such as the geographical location, floor area, building envelope, refrigeration, HVAC systems and opening hours. These kind of simulation tools allow to understand which characteristics of the building most influence its energy consumption.

1.2 Purpose

This thesis aims to create and validate computational models used for the energy consumption estimation of food retail stores (hypermarkets supermarkets etc.) and investigating possible measurements of energy efficiency. In that sense, The energy consumption as it is calculated by the computational tools is compared to field measurements from a hypermarket.

For such purpose, the sate-of-the-art of supermarkets' energy systems and its interactions will be performed, aiming to understand what are the best practices and find typical values for several parameters that influence a supermarket's energy consumption. Subsequently, the hypermarket used in this study, ICA MAXI in Bålsta will be presented and the field measurements will be analysed.

In that sense, a few simulation tools will be used to model the hypermarket's energy systems and boundaries. The main purpose is to understand what is the most accurate way of analysing the energy demand of a Swedish supermarket, using a model-driven approach. The supermarket under analysis is an ICA MAXI, located in Bålsta, (near Stockholm). After all, this study also intends to find the main challenges when measuring the energy consumption of a supermarket over one year and, if possible, purpose energy efficiency's measures to decrease the energy consumption.

1.3 Research Methodology

In order to achieve the objectives described above, this study has been divided in six different parts.

1. **Literature Review**: to acquire knowledge about the main sources of energy consumption in a supermarket, the main sub-systems and respective interactions. In addition, this part of the thesis also aimed to reveal and describe the most adequate simulation tools to predict the energy consumption of a supermarket, based on its specific characteristics.

2. **Case Study's Description**: where the supermarket under analysis will be described, in terms of store's and sub-systems' characteristics. Moreover, results from the field measurements from the energy consumption performed in 2021 will be presented.

3. **EnergyPlus' Model**: the creation of the model in EnergyPlus software will be presented and subsequently, the obtained results will be analysed and compared with the field measurements.

4. **CyberMart's Model**: The constructed of the model in CyberMart software will be presented and the simulation results will be analysed. At this point, a comparison between the results from the field measurements and both the simulation tools will be described.

5. **Creation of Different Scenarios in EnergyPlus**: This project had a great focus on EnergyPlus, as it revealed to be the most complex and detailed and freely accessible for this type of studies. Therefore, this software was chosen for the creation of different possible scenarios and the measurement of their energy consumption. This chapter aims to evaluate how changing some parameters of the supermarket would influence its energy consumption. In that sense, energy efficiency measures may be identified.

6. **Conclusions**: In this chapter, a final analysis about the field measurements and the building's simulation tools accuracy and usability is discussed. In Addition, some recommendations are provided to continue working in the future.

Chapter 2

Literature Review

2.1 Energy Demand in Buildings

2.1.1 Overview

As stated in chapter 1, the building sector is a large contributor to GHG emissions. Therefore, it is essential to implement energy efficiency measures to decrease its energy consumption. The first step is, naturally, to understand which factors most influence the energy demand in buildings.

In European countries, the main sources of energy demand in buildings are space heating and cooling. In Nordic countries, District Heating and District Cooling are largely used, whereas in western countries, HVAC systems together make up 50–70% of the total residential energy use. Usually, it is important to analyse complex interactions, such as between heating sectors and electricity [3].

Building heating and cooling demands are determined by the inside temperature, exterior temperature, and the building's thermal properties, commonly measured by the U value (thermal transmittance). Other parameters that could be considered include snow cover, humidity, wind speed and cloud cover. Diverse underlying determinants, such as occupancy and heating patterns, ventilation behaviour, building aspect, window size, sun irradiation, have a significant impact on these characteristics as well. Typically, to achieve thermal comfort inside a building, the indoor temperature should be between 20 and 25$^{\text{o}}$C and the relative humidity in the range of 30-60%.

Improved thermal insulation, implementations within materials, such as energy storage, represent some of the current energy efficiency research areas. Improving heating and cooling systems and lighting also plays a vital role in achieving energy efficiency in buildings. Moreover, some market mechanisms, such as managing consumption in relation to fluctuating prices, which means that consumers save money on their energy bill, by using some electrical appliances during the off-peak periods, have been used. This last measure can lead to a larger share of renewables in the energy mix and, thus, less emissions [18].

2.1.2 Supermarkets

Food retail stores are energy intensive buildings, having one of the highest specific energy consumption among commercial buildings in European and developed countries around the world. As mentioned in chapter 1, supermarkets consume 3-4% of the annual electricity production in industrialized countries.

There are several characteristics that influence the energy demand of a supermarket:

- **Floor area** that is divided into several categories, namely sales area, storage rooms, office, chilled [1-14]$^{\text{o}}$C and frozen [-12-(-18)]$^{\text{o}}$C products and possibly cafeteria [19]

- **Geographical location**, which includes the weather conditions
- **Building Envelope**, representing the building's characteristics, namely insulation, shape, size and thermal conductivity of the windows, among others
- **Refrigeration system**, used to keep the chilled and frozen products at the desired temperatures. Usually, there is a centralized system responsible to cool down the refrigerator cabinets and the cold rooms, where those products are stored or displayed to the customers. There are different possible ways to design the system, depending on the outdoor conditions, some may be more efficient than others. Apart from this centralized system, in many cases there are plug-in refrigerator cabinets in the supermarket. These ones operate as an ordinary electrical appliance, since they not integrate the centralized system.
- **Heating system**, depending if the supermarket uses a gas boiler, district heating, ground source heat pumps, heat recovered by the refrigeration cabinets or a HVAC system.
- Opening hours, lightning system and average number of visitors and workers.

A supermarket should be seen as a large system, divided into several subsystems. In order to evaluate its energy demand, it is important to understand the interrelations between the different subsystems. Figure 2.1 shows different subsystems in a supermarket, such as the HVAC system, refrigeration system, cabinet system and heating sources and their respective interactions.

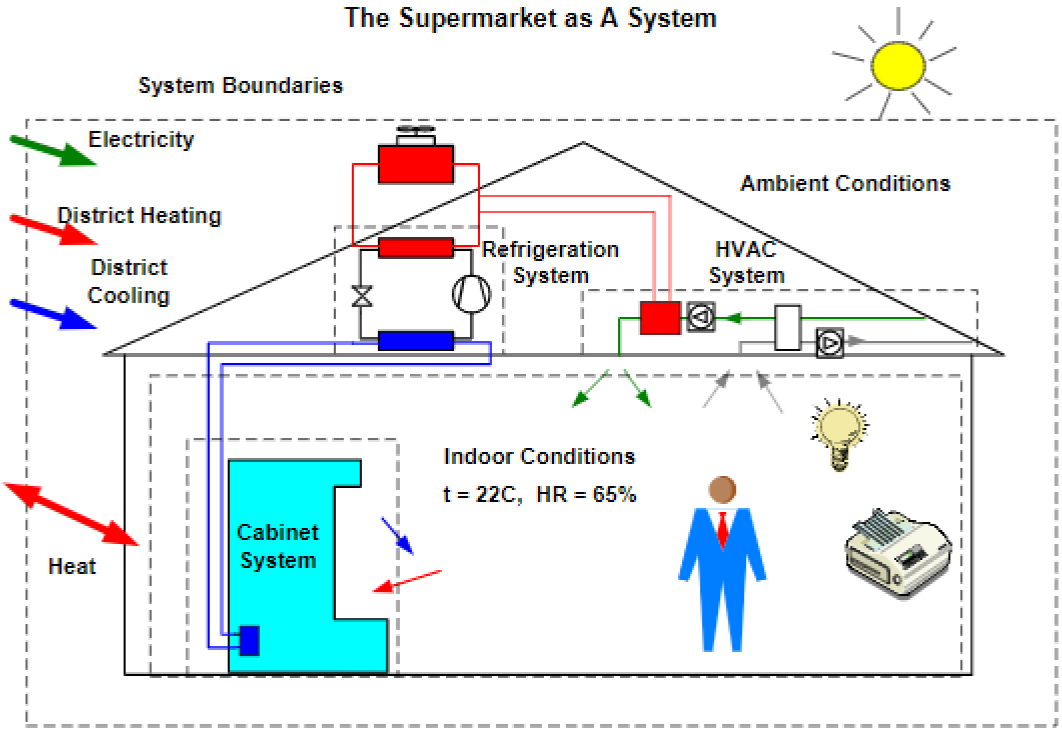


Figure 2.1: The Supermarket as a System [1]

The cabinet system represents the last storage stage in the cold chain prior to purchasing by consumers. It is naturally connected with the refrigeration system, which makes it at the desired temperature, so that the products can be kept in good conditions. Regarding the Indoor conditions, *t* stands for temperature, that is, in this example, equal to 22ºC and *HR* stands for relative humidity, which is equal to 65%. These indoor conditions set points are ensured by the electricity, district heating or cooling supply and the HVAC system. In the sales area, it is essential to keep the indoor temperature and relative humidity in a range of the thermal comfort described below. Moreover, the HVAC system is also used to ensure the inside air quality. Another example of the interrelations between the different subsystems is the influence that the cabinet system has on the indoor temperature of the supermarket.

The outdoor climate has a strong influence on the energy usage in a supermarket. It affects the indoor climate and, therefore, the performance of the refrigeration system. The outdoor temperature, relative humidity, solar irradiation and wind speed all influence the loads on the HVAC and refrigeration systems. The heat or cooling gains through the building envelope (the walls, floor, roof and windows) depend on the thermal properties of the components. Specific heat capacity, density and thermal conductivity of the walls, floor, roof and windows affect not only the heat transfer but also the storage of energy in the building structure. Occupancy and lightning also affect the indoor conditions of a food retail store.

The ventilation system performs air exchanges from the outside to the inside of the supermarket, aiming to provide comfort and acceptable indoor air quality. The air supplied to the supermarket is heated or cooled in the HVAC system according to the desired indoor conditions [1].

Typically, refrigeration systems take a 35-50% share of total energy use in food retail stores and they are usually the largest electricity consuming system in a supermarket [2]. As can be seen in figure 2.2, apart from refrigeration and lighting, HVAC systems are the other major energy consuming systems in Swedish supermarkets. However, it is important to refer that, even though this figure was obtained by a report from 2017, it was constructed with data from the year 2000, when lighting equipment used to be significantly less efficient. Nowadays, LED bulbs are typically used and therefore lighting might not account for 27% of the breakdown energy use in Swedish supermarkets.

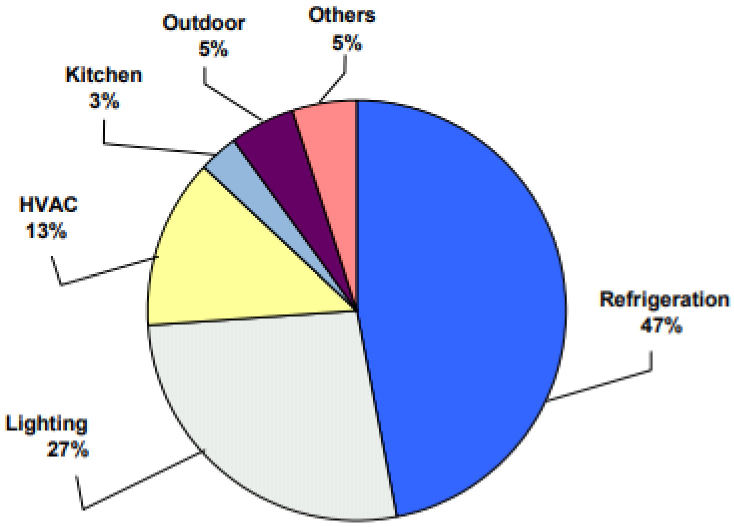


Figure 2.2: Energy use Breakdown in Supermarkets in Sweden (2000) [2]

A survey was carried out in 2010 comparing the specific energy consumption of 130 buildings in Sweden with "retail" function. This included 50 supermarkets, 30 shopping centres and 50 other types of shops. It has been found that the supermarkets' average annual specific energy consumption was about 400 kWh/m^2, whereas for other retail buildings, including shopping centres, the average was less than 265 kWh/m^2 [2].

Back in 1998, another survey made by a Swedish supermarket chain showed that the average consumption of 256 supermarkets was 421 kWh/m^2 annually. This suggests that from 1998 to 2010, there was a decrease in the overall energy consumption of supermarkets in Sweden. The 1998's survey also concluded that the total energy consumption of a hypermarket (approx 7000 m^2) is, on average, about 326 kWh/m^2 per year, while the total energy consumption in small neighbourhood shops (around 600 m^2) was near 471 kWh/m^2 annually [1]. From this, it is possible to conclude that, typically, the bigger the food retail store, the lower the energy intensity.

The research study [20] carried out in Portugal to 400 food retail stores from *Grupo Dia* in 2015 concluded that, in average, a convenience store with a sales area smaller than 280 m^2 has consumes 768 kWh/m^2. Whereas, the average energy intensity of a supermarket sized between 280 and 1400m^2 is equal to 481 kWh/m^2. These values also illustrate the tendency of decreasing the energy intensity of a food retail store with the increase of the sales area.

Some data from London in 2018 also indicates that supermarkets of around 300 m^2 sales area have an energy intensity of 840-1200 kWh/m^2 and year. These kinds of small supermarkets in the city have become more and more popular, in opposite from what is happening to hypermarkets outside the city [21].

An international workshop focused on international bench-marking of supermarkets was held in Beijing, China, in 2018, including some presentations and discussions. Results presented from the IEA HPT Annex 44 project pointed out that [22]:

- The most common performance indicators for supermarkets are size (total area or sales area), opening hours, refrigeration system type, installed refrigerating capacity and climate or geographical location. Less common performance indicators are sales volume, year of construction (or refurbishment), management attitude and system control and dynamics.

- Data sets from Denmark, Sweden and The Netherlands indicate the current value of average energy intensity to be 400 kWh/m^2 per year (based on gross floor area).

- Supermarket in the sample had an average gross area of 1360 m^2 and 73 opening hours per week.

- Energy intensity decreases with increasing supermarket size (-2% for each 100 m^2 sales area increase)

- Developments, especially in refrigeration systems and lighting, lead to an increase of energy efficiency in new or refurbished supermarkets ranging from 1 to 10%. Refurbishment is, therefore, an effective management decision to increase energy efficiency [21].

2.1.3 Climate Change's impact on energy demand in buildings

Even considering the efforts that are being made to achieve the Net Zero emissions by 2050, namely by the building sector, climate change is expected to be felt until the end of this century. The Intergovernmental Panel on Climate Change (IPCC), which is the United Nations body for assessing the science related to climate change, has adopted a Representative Concentration Pathway (RPC). A RPC reflects the GHG concentration (not emissions). For instance, even if we achieve the net zero by 2050, a concentration of CO_2 equivalent will continue existing in the atmosphere. In that sense, the RPC adopted by the IPCC are trajectories of GHG concentrations, year by year, until 2100.

Based on the predictions for the GHG concentration, scenarios for the temperature and sea level increase can be made. For example, RPC2.6 predicts a global temperature rising in the range of [1.5-2] Celsius degrees, whereas RPC4.5 suggests an increase of [2.5-3], compared to the pre-industrial levels [23]. This rising temperature will, naturally, lead to a change in the heating and cooling demand in buildings.

A study, based on the RPC2.6 and RPC4.5, was conducted to predict the heating and cooling demands on buildings in Europe [3]. Models for predicting the future average and extreme temperatures were used, with the contribution of several climate institutions, namely the Swedish Meteorological and Hydrological Institute (SMHI). Regarding heating demands, the largest decrease is seen for Western and Northern Europe, whereas The Mediterranean and Eastern European countries experience a lower degree of change.

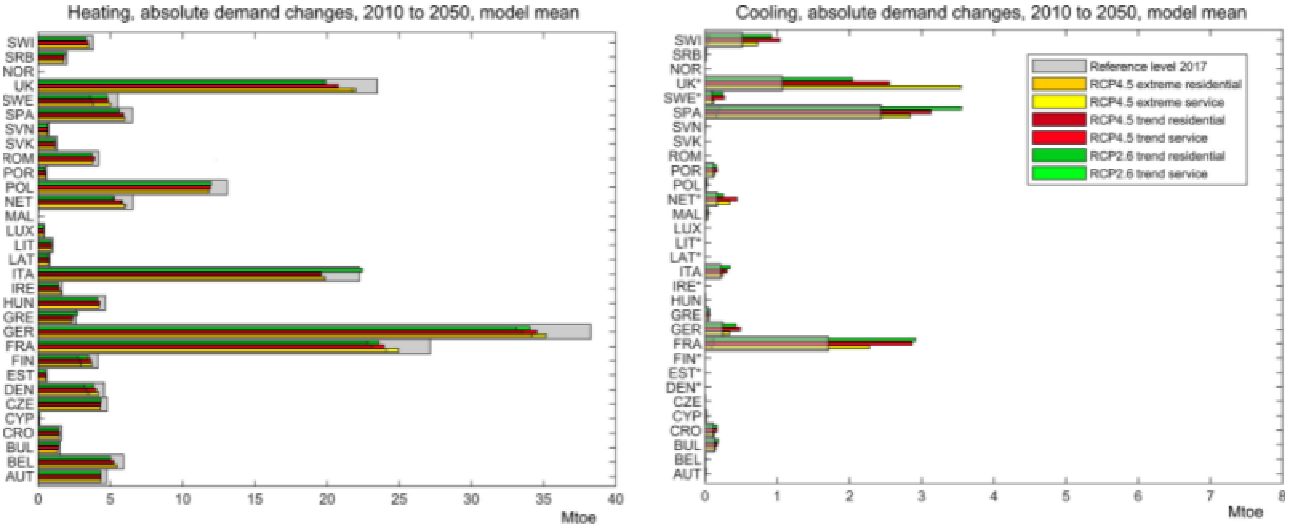


Figure 2.3: Heating and Cooling demand change, based on predictions for climate change [3]

Figure 2.3 shows the absolute change in heating and cooling demand in buildings per country until 2050, due to the expected temperatures increase, according to RCP2.6 and RCP4.5 scenarios (unfortunately, there are some countries with a lack of data availability). At first sight it may be strange that countries like Germany and France are likely to feel a much stronger impact on the heating and cooling demand in buildings due to climate change than Nordic countries, which are expected to be more strongly affected by climate change. However, as the graphs refer to absolute values, the results are also influenced by the dimension of the countries, including the population. Germany has 83 million of inhabitants, France has 63 million, whereas both Sweden and Portugal have about 10 million. By comparing Portugal and Sweden, which have the same population, it is possible to see that Sweden will feel a stronger impact on its buildings' heating and cooling demand. That is due to climate change, even though Swedish buildings are generally more resilient than Portuguese ones.

Considering that 1 Mtoe (million tonnes of oil equivalent) is equal to 11.63 TWh, according to the RCP4.5 trend for services, Sweden will save about 11.63 TWh of energy in heating demand of services buildings, from which supermarkets are part of. This change is stronger in the residential sector, where the energy demand in Sweden is expected to decrease about 52.3 TWh by 2050. In Portugal, a change of 11.63 TWh is expected to be felt in heating demand on residential buildings and this same effect on service buildings is neglected.

In what concerns the effect climate change will impose on cooling demand in European buildings, the absolute values are much lower than what happens with heating demand. This is positive from an energy management point of view, once rising temperatures are expected to decrease more the heating demand in buildings than increase the cooling demand. This effect of cooling demand change in buildings is almost the double in Sweden than in Portugal, but it does not go further than 3.5 TWh of increasing cooling demand in total until 2050. (Sweden is represented with a *, meaning that it is one of the countries with Cooling Degrees Days (CDD) lower than 10).

Changes in the outdoor temperature influence the profitability of heat saving measures. In that sense, an increase in the outdoor winter temperature can be seen as "free" heat savings and thus make additional heat savings more expensive. Another effect of increasing outdoor temperatures is an increase in the Coefficient of Performance (COP) of air-to-air heat (and cooling) pumps. On the other hand, the economics of both heat supply (e.g. boilers) and demand-side (e.g. insulation) measures are adversely affected by reduced winter heating demands, either in terms of length, magnitude, or both [3].

Although climate change's impact in buildings' heating and cooling demand is more strongly felt in the residential sector, this type of analysis should also be applied in other energy intensive buildings at relevant geographical levels, such as Sweden, with the aim to explore these phenomena in the context of rapidly-changing national energy systems.

2.1.4 Predict the Demand

In order to make an effective and efficient allocation of resources in buildings, it is useful to predict its energy demand. Based on the supermarket's characteristics, mentioned in chapter 2.1.2, it is possible to predict the heating and cooling loads of the building. Consequently, the HVAC can be modelled in accordance with the building's needs. For this process to happen smoothly, it is important to establish an integrated design process in which the different stakeholders, such as the supermarket's owner, property owner, consultants and subcontractors are involved.

In that sense, it is possible to plan and optimize the annual energy budget; negotiate energy supply contracts; and, if applicable, find measures to reduce the demand in existing buildings. Hence, if a supermarket ends up by using more energy than expected, investigations can be carried on with the potential of interventions to mitigate the additional energy use.

The main prediction methods can be classified in two ways: model-driven and data-based, regardless of the type of construction [10]. To simulate the building's future energy behaviour, the model-driven methodology employs sophisticated high-resolution engineering approaches based on the building's thermal, energy, architectural and utilization aspects. Whereas, in data-based approaches, the energy performance of the building is directly modelled with numerical and statistical methodologies.

Model-driven approaches are usually more accurate than data-driven ones. However, they are more complicated and computationally costly. On the other hand, model-driven studies compute their results for specific buildings, whereas data-driven models can be used for large sets of buildings. There are extensive reviews on methods to predict and benchmark energy use in buildings. Nonetheless, most of the reviewed works predict the electricity consumption of dwellings (uni-familiar houses) or office buildings [10].

In this thesis, a model-driven approach will be used, with the usage of two simulating tools: EnergyPlus and CyberMart. In theory, it should be possible to create a computer model that precisely represents energy transfers in a building and can accurately estimate its energy consumption. However, there is always a difference between prediction and performance in practice. This is referred to as the **Performance Gap** [24]. One of the biggest challenges in this thesis will be to minimize that gap.

Out of the several tools available in the market to predict buildings' energy consumption, not many of those are able to design a centralized refrigeration system, present in the large majority of the supermarkets. In that sense, EnergyPlus and CyberMart software were the selected simulation tools to carry on this study. A brief description of both of them is presented below.

EnergyPlus

EnergyPlus (US Department of Energy, 2011) is an open-source software used in energy analysis at design stage. This tool can be used to model a supermarkets' refrigeration system and accounting for the sensible and latent heat exchanges between the refrigerated cases and the HVAC system. It results from a collection of many program modules that work together to calculate the energy required for heating and cooling a building by using a variety of systems and energy sources. The operation mode consists of simulating the building and the associated energy systems when exposed to a certain environmental and operating conditions. The core of the simulation is a model of the building that is based on fundamental heat balance principles [25]. This software is able to make energy and mass balances with a hourly (or even lower time steps) resolution.

EnergyPlus uses measured outdoor weather with hourly data files, currently available for more than 2000 international locations [26].

In EnergyPlus, the HVAC system can be controlled by setting a schedule and specifying minimum, maximum, and delta temperatures. The temperatures can be set to a single value for the duration of the simulation, or they might follow a schedule that changes over time. The temperature difference between the inside and outside environments, as well as the wind speed, can affect the actual ventilation flow rate and heating or cooling supply.

In EnergyPlus, the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) load model (ASHRAE, 2006) has been adapted to simulate the cold storage rooms. The model includes infiltration through door openings and sensible loss through walls/ceilings described by the user for each zone. All equipment loads (fan, light, heaters) are also modelled. Sensible and latent exchange with multiple adjoining zones is included. EnergyPlus also uses a master schedule for the door opening operation, and additional schedules control the lights, defrost, and heater operation. Sensible heat loads are placed on a cold storage by fans, heaters, and lighting.

Although it is a very powerful tool, EnergyPlus is not user-friendly and may be very challenging to work with. There are several interfaces available to be connected to this software, however many are not free to access or do not have the option to design the refrigeration system. Hopefully, there are several series of supermarket models, useful for initiating a supermarket model for this investigation.

CyberMart

CyberMart is a building simulation tool created in KTH's energy department, designed specifically to simulate the energy demand of food retail stores in accordance with the required set points and store's characteristics [1]. CyberMart is a one-of-a-kind energy modelling program for supermarket energy efficiency and optimization. This software models the entire supermarket as a comprehensive system for calculating total energy consumption, taking into account energy-related parameters such as building design, opening hours, outdoor climate, and energy systems such as refrigeration, display cabinets, lighting, and equipment, among others. To validate the computer model, field measurements were taken in numerous supermarkets across Sweden [27]. This tool can access hourly climate data at any location in the world.

Different refrigeration system designs can be modelled in CyberMart with direct or indirect systems. The compressor power is dependent on the variation of the indoor and outdoor ambient conditions, which directly or indirectly influence the refrigeration load. The capacity and COP of the refrigeration system are also dependent on the boundary conditions of the condenser. CyberMart creates a database from manufacturer data, including the average air temperature, inlet and return air temperatures, evaporating temperature, electrical data for fans, heating wires, defrost heaters and light, coil volume, diameter of tubes, and refrigeration loads at 22°C and 65% RH and at 25°C and 60% RH for each cabinet.

CyberMart computes indoor conditions, heating and cooling loads from the building, refrigeration loads from cabinets and storage, compressor power and condenser heat from the refrigeration system, energy performance of lighting, equipment, plug-in cabinets, fans and pumps. The energy consumption from heating and cooling systems, lighting, rotary heat exchangers, fans, service water heating, and the refrigeration system of the first and last systems modelled are some of the data reported in CyberMart.

2.2 Energy Supply in Supermarkets

As mentioned in section 2.1, a supermarket is a large energy system, divided into several subsystems, interrelated with each other. Each subsystem has its energy needs and may influence the needs of other subsystems. The main sources of energy demand in a supermarket are related to the temperature of the different rooms (or zones) and indoor air quality in the sales area. It is, thus, necessary to keep part of the food chilled or frozen in the cabinets, while ensuring thermal comfort in the sales area, cafeteria and so one.

2.2.1 Refrigeration Systems

The refrigeration system is usually the way to enable the food to be stored at low temperatures by creating the cold environment required in cabinets. Supermarkets normally use one or several refrigeration units to provide the large amounts of cooling required in a limited space. A refrigeration system works by displacing heat from one area and moving it to another, meaning that the energy removed from the cabinets must be transferred elsewhere. This is based on the first law of thermodynamics, which states that the energy is always conserved and cannot be created or destroyed. The second law of thermodynamics expands on this, stating that heat cannot flow from a colder body to a hotter body without the application of external work.

Because a supermarket usually has a lot of cabinets and cold rooms, the refrigeration system is not as straightforward as the basic cycle. Each cabinet and cold room may have numerous cycles with additional compressors, a secondary refrigerant loop, or evaporators. In that sense, the refrigeration system needs to be adapted to the specific conditions of the supermarket, which vary from case to case [28].

Out of the refrigeration system described below, some of the heat provenient from the evaporator can be used to cover space heating needs in the sales area.

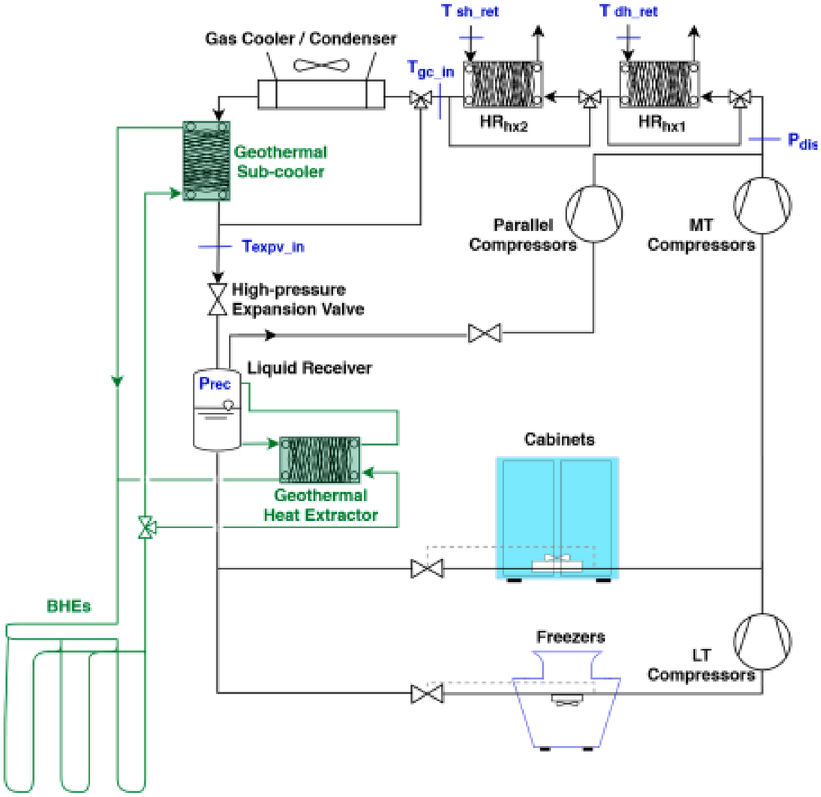


Figure 2.4: Schematic of a state-of-the-art CO_2 booster system and integrated geothermal storage, highlighted by green

Figure 2.4 shows an example of a geothermal storage, connected to a traditional refrigeration system in a supermarket in Stockholm, proposed in 2018. The heat that is obtained after the refrigerant is cooled down in the expansion valve is stored and can then be used for space heating purposes, namely in neighbourhood buildings, using CO_2 as the refrigerant. Conclusions pointed out that this kind of system can lead to an annual running cost decrease of 20-30% and a payback period of 3 years [29].

Refrigerants

Different types of refrigerants have been used in supermarkets' history. The most common ones can be split into halocarbons and natural refrigerants. Halocarbons consist of compounds where carbon atoms are linked to halogen atoms through covalent bonds. Halocarbons used as refrigerants have been developed as the demand has changed and can be divided into groups based on their properties.

Some of the most common halocarbons refrigerants are:

- Chlorofluorocarbons (CFC)s, which have been phased-out, as a consequence of the Montreal Protocol (1987), due to their high ozone depletion potential, if released in the atmosphere [30]

- Hydrofluorocarbons (HFC)s, were developed as an alternative to the phased out CFCs, with low ozone depletion potential. However they still have a significant global warming potential and are slowly being phased out.

- Hydrofluoroolefins (HFO)s are unsaturated as opposed to earlier mentioned halocarbons, meaning that they both have a lower Ozone Depletion Potential (ODP) and Global Warming Potential (GWP).

Properties of refrigerants vary significantly from each other, with favourable criteria depending on the usage behaviour. Switching from halocarbon refrigerants to natural refrigerants may seem an easy solution to the dangers of high GWP, though the properties of natural refrigerants typically differ from the conventional ones.

Ammonia, R717, was early used as a refrigerant in supermarkets due to its low cost and no risk of ozone depletion. It has an unpleasant smell, making it difficult to use in some places, even though the smell helps to identify leaks in the system quickly [28].

More recently, **Carbon Dioxide**, R744 refrigerant, has been widely used in Europe, as it allows to design systems that recuperate the heat from the refrigerator systems to be used with other proposes, as exemplified in figure 2.4. Depending on the region, the technology used and a supermarket's cooling needs, the total installation price for the entire CO_2 refrigeration system in the EU is currently 0 or 5-10 % higher than conventional HFC systems [11].

2.2.2 Carbon Dioxide Booster Systems

In cold climate countries, the booster system is the most widely used solution. The Low Temperature (LT) cabinets/evaporators are served by a separate smaller booster compressor, which lifts the pressure to the medium temperature level. The discharge gas from the booster is then merged with the gas coming from medium-temperature (MT) evaporators.

An increase in the outside temperatures leads to more work required by the compressor, which results in more energy consumed by the refrigeration system. A solution to this problem is to add an auxiliary parallel compressor to help relieve some of the strain caused by higher ambient temperatures (such as the example in figure 2.4). Booster systems with parallel compression are an example of that. The auxiliary compressor is only activated when required by the system and works like a typical booster system during the winter.

A supermarket's centralised refrigeration unit is a capital-intensive part of a building. Nonetheless, there are opportunities to integrate the heating and air-conditioning into the refrigeration system, reducing or completely eliminating the need for additional heating and air-conditioning devices. CO_2 trans-critical booster systems offer great heat recovery opportunities, which can be used to meet the store's hot water and space heating needs. The amount of accessible heat in CO_2 systems increases significantly when the discharge pressure of CO_2 is increased and the system transitions from sub-critical to trans-critical. To achieve an efficient heat recovery process and increase the heating capacity from the CO_2 booster system, a step-wise control of the refrigeration system is advisable.

In a study performed by several researchers from the KTH's energy department regarding supermarket refrigeration with heat recovery, extensive and detailed field measurement investigations were carried out. Some conclusions were obtained, namely: [27]

- Relatively new CO_2 trans-critical systems have comparable or higher COP than an advanced conventional system in mild-cold climates.

- Heat can be recovered from CO_2 trans-critical system with higher COP, about 3.5-5, comparing with a usual ground source heat pump for space heating where the typical heating COP is in the range of 3-4.5.

- Long and short-term thermal storage have been theoretically studied. Up to 6% in annual energy use reduction has been calculated. There is a potential for long-term thermal storage if the heating demand is much higher than the refrigeration demand in the supermarket.

In [4], a study was carried out to a medium-size Swedish supermarket, using a CO_2 trans-critical system with heat recovery and field measurements. In that supermarket, several features have been applied to improve its energy efficiency, including space and tap water heating, air conditioning and parallel compression. The results showed that the system provides the entire air conditioning (AC) demands and recovers a great share of the available heat, with high COP values. The comparative analysis shows that an integrated CO_2 system uses about 11% less electricity than stand-alone HFC solutions for refrigeration, heating and AC in the North of Europe.

Figure 2.5 illustrates the hourly-averaged and daily-average heating/cooling loads for January and July 2014. The cooling and heating loads are shown as negative and positive values, respectively. Q_{LT} is referred to the LT refrigeration load and varies in a narrow range of 10–15 kW in both months, independently of the hour of the day and T_{amb}. Q_{MT} stands for Medium Temperature (MT) refrigeration load and is higher in July than in January. There is an increase of demand during the working hours 8:00–22:00 mainly due to the presence of customers, higher indoor temperatures and humidity. This increase is not verified in Q_{LT} values. A major cause for this difference could be that the cold air is let out easier while opening the door of vertical MT cabinets compared with opening the glass lid of horizontal LT freezers.

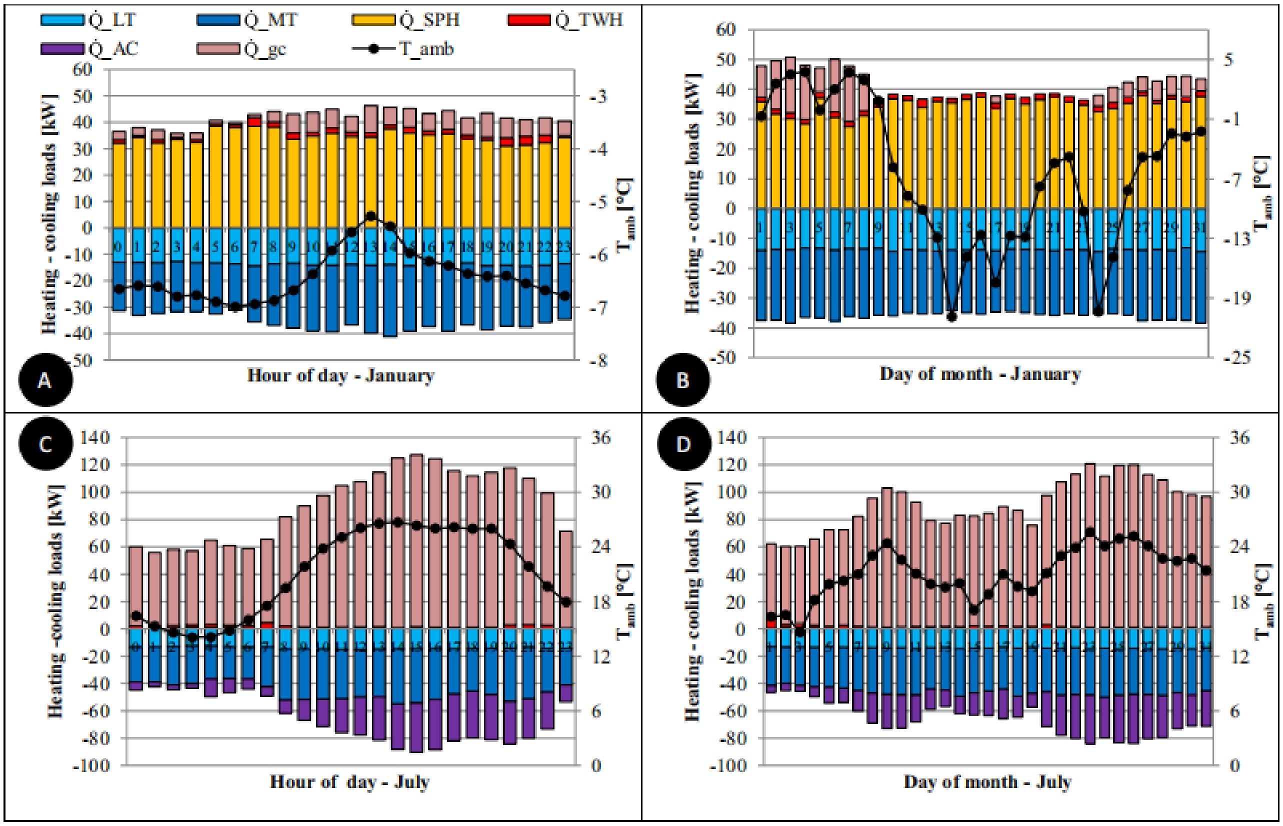


Figure 2.5: Hourly-averaged cooling and heating loads for (A) January 2014 and (C) July 2014. Daily-averaged cooling and heating loads for (B) January 2014 and (D) July 2014. Source: [4]

Q_{AC} refers to the AC load. It can be seen that in the month of January 2014, it was never needed and the authors believe that, in July, it is sometimes used in relatively low temperatures due to specific HVAC zones in the supermarket, such as the bakery. The clear relation between Q_{AC} and T_{amb} can be seen in figures 2.5C and D. It can be noted that when T_{amb} increases, Q_{AC} increases as well. In addition, the presence of the customers in the supermarket during the opening hours increases the CO_2 concentration in the air and more ventilation of the conditioned air might be required, specifically in the afternoon rush hours.

Q_{TWH} represents the load of Tape Water Heating and it does not change significantly throughout the year. However, in the daily profile, it can be observed that the early-morning food preparation and late-night cleaning in the supermarket resulted in peaks of Q_{TWH} up to 5 kW.

Q_{SPH} stands for the Space Heating load, which is zero for ambient temperatures higher than 15^{o}C. The hourly- and daily-averaged winter values of Q_{SPH} are within the 30–40 kW range and relatively independent of T_{amb} when it is lower than 0°C. This indicates that, for this supermarket, district heating is used as a supplementary heating source at sub-zero ambient temperatures.

Finally, Q_{gc} refers to the gas cooler load. Figure 2.5 allows to understand that the provided refrigeration and AC loads are rejected outdoors through the gas cooler during the summer.

It is, somehow, curious to notice that the thermal loads are higher in July than in January, considering that in July, the outdoor temperatures are much closer to the desired ambient conditions than in January. This suggests that this CO_2 trans-critical system is very efficient in recovering the heating. It is, thus, desirable in cold climate countries and perhaps not that effective for hot climate countries.

2.3 A Supermarket case study using EnergyPlus

A case study was carried out by Mylona, Kolokotroni and Tassou in 2016 to a British supermarket, using EnergyPlus software [5]. This supermarket, built in 2013, has a gross area of 450 m^2 and a sales area sized 315 m^2. It has the particularity of having a considerable amount of frozen food, counting for about one third of all the selling products. Some inputs for the EnergyPlus model were:

- Opening hours: 8:00 to 20:00 for weekdays and Saturdays and 10:00–16:00 for Sundays
- U-values: 0.35 W/m^2 K for the external walls, 0.25 W/m^2 K for the ground floor and the roof and 5.7 W/m^2 K for the (single glazed) windows.

Table 2.1: Summary of parameters input for customers density, lighting load and electrical equipment, used in [5]

Thermal zones	**Occupants' density [m^2/person]**	**Lightning load [W/m^2]**	**Electric Equipment [W/m^2]**
Tills area	7.6	32.9	15.9
Display area	16	16	n.a
Office control room	5.9	9.9	30.6 (PCs, printers and control equipment)
Office	4.2	13.8	17.85 (PCs)
Kitchen	3.9	36.7	274.2 (Fridge, microwave, kettles, dishwasher)
Restrooms	n.a.	10.6	137.4 (Heaters)
Storage area	31.6	1.9	n.a.

EnergyPlus allows splitting the building into different zones with different characteristics and energy needs. The customers' schedule was also modelled, hourly. The weather input was obtained by a file that was constructed for the location, with data from the nearest meteorological station from Weather Underground to correspond to the period considered in the study.

- The design cooling requirements are estimated at 60 kW sensible. The HVAC system is operated 24 hours a day, with 20–21ºC set point temperature for both cooling and heating
- Ventilation rates for the exhaust system during trading hours have been set to 6 air changes per hour (ach) for staff areas and sales area, 10 ach for restrooms and 1 ach for the storage area. During the closed time, the exhaust fan is set to a lower speed of 0.75 m^3/s.

Table 2.2: Summary of refrigeration system input parameters, from [5]

	Cold Rooms		**Display Cabinets**		
	Chiller	Freezer	Open front multi deck chilled food	Lift up lid frozen food	Open top case frozen food
Number	1	1	7	58	3
Capacity [kW]	2.3	8	1.46	0.2	1.75
Operating temperature [°C]	0	-20.5	1 to 2	-20 to -22	-23
Refrigerant	R404a	R404a	R404a	R134a	R404a
Compressor COP	1.69	1.5	2.3	1.5	2.3

In the end, some results were obtained and then compared to the data provided by the building meters. The building's annual energy use from June 2014 to May 2015 is equal to 1143 kWh/m^2 of the sales area, whereas the final calibrated model prediction was 1104 kWh/m^2 of the sales area, resulting in a 3.4% deviation, which is a very reasonable energy performance difference.

Figure 2.6 shows the metered and simulated energy intensity for each of the 12 initial months of analysis (June 2014 to May 2015). It is possible to see that May 2015 is the only month in which the simulated consumption is higher than the real one. The authors believe it had to due with a sharp temperature rise in that period.

Finally, the calibrated model was run for the next available operating data for three months (June 2015–August 2015) in order to check its accuracy. It can be observed that the simulation error has decreased.

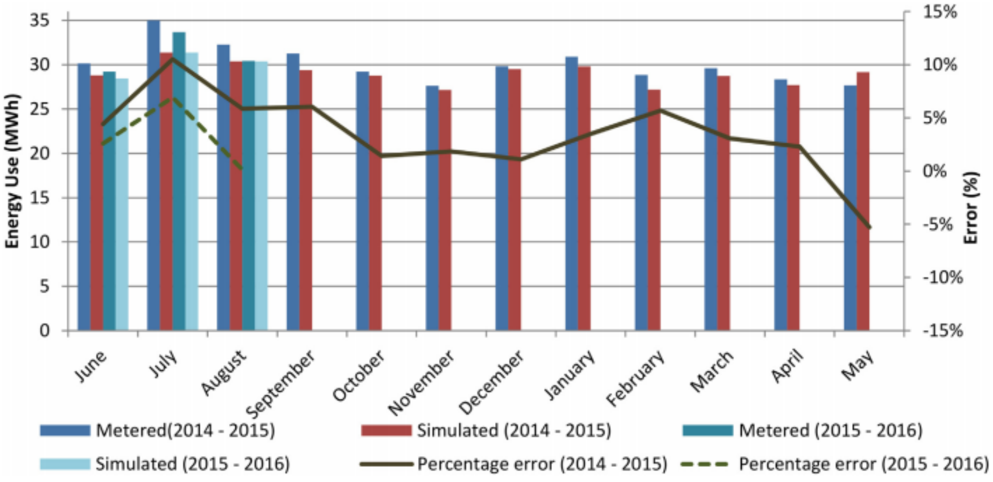


Figure 2.6: Monthly energy use comparison for metered and simulated data and percentage error [5]

The temperature set-point used in the model was 21ºC both in the Tills area and Display area. However, in reality, the inside temperature had fluctuations in the range of (19–22 ºC), with the lowest during December and the highest in July. This effect was more strongly felt on the tills area due to its proximity to the entrance. These results indicate that a more accurate model for the air infiltration through the entrance door should be developed in order to obtain a more accurate air temperature prediction in the tills area.

The final results also showed that the refrigeration system is responsible for 60% of the energy use, followed by the HVAC system (26%), lighting (8%) and electrical equipment (6%). Inside the HVAC parcel, 8% is due to cooling, 6% heating and 12% ventilation. These results differ from a typical supermarket's subsystems breakdown, mainly due to the refrigeration subsystem that has a significantly higher consumption, which might be related to the relatively small floor area in the referred supermarket.

Some scenarios were constructed, in which the authors realized that the most effective measures to optimize the energy consumption would be: 1) LED lighting system upgrade in Sales Area (35% less W/m^2), that would lead to a 2.5% reduction in the total energy consumption; 2) HVAC system in operation only during trading hours, would result in a 4% saving of energy consumption.

Chapter 3

Case Study: ICA MAXI in Bålsta

The food retail store used to construct and evaluate the computational models used in this research project is an ICA MAXI, defined as a hypermarket, since its floor area is bigger than 2500 m^2. This hypermarket is located in Bålsta, which is a locality at about 45 km away from the city of Stockholm. In this chapter, the main store's characteristics will be presented, as well as the main results from the field measurements performed in 2021.

3.1 Store's Characteristics

ICA MAXI in Bålsta has a total conditioned area of 6570 m^2 and is a stand-alone building with no other building connected to it. The sales area occupies 4860 m^2 and it is open 105 hours per week (from 7 am to 10 pm every day).

Inside this hypermarket there is a pizzeria, pharmacy and a post office's collector center, besides the "traditional" sales area. Outside, there is a parking place for the visitors, with lighting, car chargers and snow melters. ICA MAXI also offers the option of online commerce. Figure 3.1 presents some characteristics of the outside area of this hypermarket.

(a) Main entrance

(b) car chargers

Figure 3.1: Exterior area of the hypermarket

Electricity is the only source of energy supply in this hypermarket. A new trans-critical CO_2 refrigeration system was installed in in 2020. As explained in chapter 2, these kinds of systems allow to recover heat and thus, in this hypermarket, 6 boreholes are placed in the ground for energy storage. Since it was newly installed, some irregularities in the initial months' data were expected. The system is capable of providing refrigeration and freezing for the food products in the store (MT and LT loads), air conditioning (AC), heating for space heating and domestic hot water, via heat recovery and from the boreholes.

The large majority of the chilled and frozen products are placed in display cabinets or cold storage rooms, connected to the trans-critical CO_2 refrigeration system. Nonetheless, 18 plug-in cabinets were identified in the sales area. Those are not connected to the centralized refrigeration system and, instead, work as normal electrical appliances. This happens due to marketing purposes for some of the hypermarket's stakeholders.

(a) Display cabinets

(b) Plug-in cabinets

Figure 3.2: Refrigerator cabinets in the sales area

Figure 3.2 shows some of the display and plug-in cabinets in the sales area, where the customers have access. The plug-in cabinets are mostly used to store drinks and ice creams, whereas the display cabinets can contain any kind of chilled or frozen products. Inside all these cabinets there are lights and fans.

Electric auxiliary heaters provide additional heating for space heating and domestic hot water applications when needed. Energy meters placed across the store provide detailed information about energy consumption, namely for compressors, lighting, auxiliary heating and car charging [31].

3.2 Measured Energy Consumption

As explained previously, field measurements regarding this hypermarket's energy consumption were performed in 2021. In most cases, hourly data was provided regarding electricity consumption and outdoor temperature.

The owners divided the energy consumption in some subcategories, namely refrigeration system, which is responsible to cool down the products in the refrigerator display cabinets and cold rooms and also supply some space heating, hot water and space cooling to the desired locations inside the hypermarket; lighting on the sales area and outside parking; bakery equipment; ventilation; energy usage in the pharmacy and electric heaters to supply extra heating (besides the one supplied by the refrigeration system).

The building's thermal loads were also provided, as well as the power demanded by the compressors to keep the chilled and frozen products at the desired temperatures. These data will be analyzed in the next chapter to be directly compared with the simulation results.

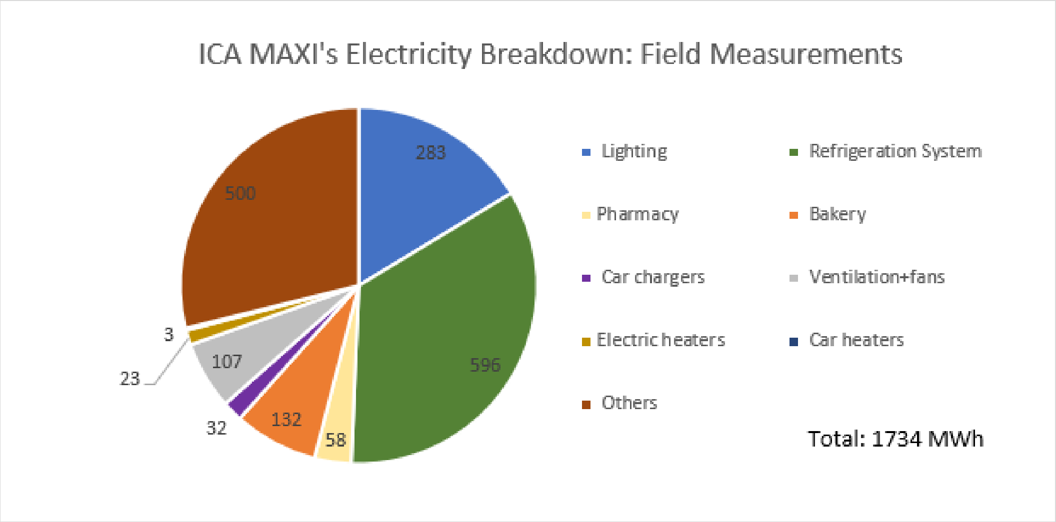


Figure 3.3: Energy Breakdown through field measurements (values in MWh units)

Figure 3.3 shows the energy breakdown of the hypermarket. "Other" stands for the energy used for several non-measured demands, such as cashiers, lift, security cameras, e-commerce or lighting not used on the sales area or the outside parking.

It can be seen that the total electricity consumed in 2021 was 1734 MWh, which corresponds to 264 kWh/m^2 of conditioned area and a total of 50.3 tons of CO$_2$e (equivalent emissions of CO$_2$), considering that in Sweden each MWh of electricity consumption generates 29 kg of CO$_2$e [15].

Chapter 4

EnergyPlus Model

In this chapter, the construction and main results of the hypermarket's model on EnergyPlus will be presented. Additionally, a comparison will be established between the model's results and the field measurements.

4.1 Construction of the model in EnergyPlus

After proceeding with the literature review and acquiring a better insight of energy consumption studies in supermarkets, EnergyPlus was believed to be the most complete and capable tool to predict the energy consumption of this hypermarket. Moreover, KTH's Energy Department was aiming to test EnergyPlus software in this kind of studies. In that sense, EnergyPlus was the most used and tested tool on this research project.

EnergyPlus version 9.6 was directly used in the IDF editor interface, to initiate the model, by editing the example file "SupermarketDetailed". Several categories of inputs were used, namely: Simulation parameters, Building location, Schedules, Building's construction, Internal Gains, Infiltration rates, HVAC and Refrigeration systems. As explained previously, EnergyPlus simulation operation allows modeling the interactions between these different components.

4.1.1 Simulation Parameters

This simulation considers the heat balance method, which is divided in four processes: outside surface heat balance, which is sensible to the outdoor climate conditions; through the wall conduction; inside surface heat balance, which is regarding the the different sub-systems inside the building and the respective interactions; and finally the air heat balance, that relates the internal loads and infiltration rates with the HVAC needs [32].

The heart of the heat balance method used in EnergyPlus is the internal heat balance involving the inside faces of the zone surfaces. This heat balance is generally modeled with four coupled heat transfer components: 1) conduction through the building element, 2) convection to the air, 3) short-wave radiation absorption and reflectance and 4) long-wave radiant interchange. The incident short-wave radiation is from the solar radiation entering the zone through windows and emittance from internal sources such as lights. The long-wave radiation interchange includes the absorption and emittance of low temperature radiation sources, such as all other zone surfaces, equipment, and people. Equation 4.1.1 intends to express the relation between these variables.

$$q"_{LXW} + q"_{SW} + q"_{LWS} + q"_{ki} + q"_{sol} + q"_{conv} = 0 \tag{4.1.1}$$

Where:

- $q``_{LXW}$: Net long-wave radiant exchange flux between surfaces in a zone or group of zones
- $q``_{SW}$: Net short-wave radiation flux to surface from lights
- $q``_{LWS}$: Long-wave radiation flux from equipment in a zone or group of zones
- $q``ki$: Conduction flux through the wall
- $q``_{sol}$: Transmitted solar radiation flux absorbed at surface
- $q``_{conv}$: Convective heat flux to zone air [33].

In conclusion, the building's energy balance is affected by the conduction from the outside air through the building's walls, ceiling, ground and leakages, solar radiation through the windows, the internal heat gains caused by the lights, people, electric equipment and also by the refrigeration systems and the heating or cooling and ventilation system of the hypermarket.

The model simulates the building energy balance in an one hour time step, along a full year.

4.1.2 Building's Location and Climate

The hypermarket under analysis is located in Bålsta, a locality in Håbo, Uppsala County, Sweden at around 45 Km Northwest of central Stockholm. This hypermarket's main entrance is facing the Northwest.

For the model in EnergyPlus, an EnergyPlus Weather (EPW) was used, referring to Stockholm, Arlanda location, which stays at, roughly, 30 Km East from Bålsta. This weather file contains information such as longitude, latitude, time zone, elevation, annual design conditions, monthly average ground temperatures, typical and extreme periods and holidays/daylight saving periods. It also contains hourly information regarding the outside air temperature and relative humidity for a full year in that specific location. The Stockholm, Arlanda EPW file was downloaded directly from EnergyPlus Website [26].

4.1.3 Building's Components

The building was constructed by setting the coordinates of each wall, window or door and the respective materials. From Skanska's report, the company responsible for the hypermarket's construction, some values for thermal transmittance (also known as U-value) of external walls, ceiling, ground, door and windows were provided. The U-value parameter has a strong influence on the $q``ki$ variable, in equation 4.1.1. The higher the thermal transmittance of the building's envelope, the higher the heat conduction flux through it.

EnergyPlus allows to choose the thickness and conductivity for each construction material and based on that, the modelled external walls have an U-value of 0.19 W/m^{2}K, ceiling and ground of 0.11 W/m^{2}K, windows with an U-value of 1.7 W/m^{2}K and door 1.3 W/m^{2}K. The entrance door is a glass door and the building has a total of 21 m^2 of windows and glass door, which corresponds to 13% of the building's envelope. All these values were obtained from the Skanska, the company responsible for this hypermarket's construction.

In reality, this hypermarket has many different zones inside the building, not only the sales area, but also several storage rooms, a kitchen, offices, a pharmacy, several toilets and offices. However, it would be extremely time consuming and difficult for EnergyPlus to process all these different zones and, as many zones have similar number occupants and HVAC system control strategies, they were grouped in bigger zones, in order to simplify the model. Therefore, the hypermarket was divided in six different zones, as represented in table 4.3.

The hypermarket is considered to have a total internal area of 6840 m^2, from which 6570 m^2 are conditioned, which means that the inside temperature and air quality are controlled by the HVAC system.

Table 4.1: Building's thermal zones

Zone	Area [m^2]	Height	Conditionated	Floor
DisplayArea	4860	5	yes	0
Offices	459	2.5	yes	1
Toilets	28	5	yes	0
BackRoom	729	2.5	yes	0
ColdRoom	495	2.5	yes	0
MachineryRoom	270	2.5	no	1

The **Display Area** represents the zone where the selling products are displayed and bought. It also includes the pharmacy, a pizzeria, with available seats and, apart from the toilets, it is the only place where costumers can enter. The **Offices**' zone includes all the offices in the building and resting rooms for the workers and it is placed on the first floor, above the Back Room and the Cold Room. The **Back Room** zone includes the storage and preparation rooms, whereas the **Cold Room** zone contains the actually cold rooms, both chillers and freezers to store the products that must be kept in lower temperatures. Finally, the **Machinery Room** has the machines required for the function of the hypermarket. Since this last zone is not a place for people to be on a constant basis, its temperature is not controlled.

4.1.4 Internal Gains

As presented in equation 3.2.1, there are loads inside a building that affect its energy balance. Those are generally referred as *Internal Gains*, since these components add energy to the zones, not only in terms of lighting or useful work, but also as heat sources.

Table 4.2 qualitatively illustrates the main components of internal gains to the conditioned zones of the building.

The values for occupancy, lighting and electric equipment were estimated by the data available from ICA MAXI [34] or assumed by similar cases found in the literature.

People inside the building constitute an important source of heat in this hypermarket. In this model, based on EnergyPlus 9.6 reference documentation [35] it is estimated that each person on the building contributes to 120 W of additional heat.

Lighting was estimated both from data provided from the hypermarket and also from some typical values for offices [36].

Table 4.2: Building's Internal gains for conditioned thermal zones

Thermal Zone	**Occupants' Density [m^2/person]**	**Lightning load [W/m^2]**	**Electric Equipment [W/m^2]**
DisplayArea	12 for peak hours	9 for opening hours 0.9 for closing hours	Max 19.9
Offices	15 from 8 am to 5 pm during the week	7.6 from 8 am to 5 pm during the week	Max 3.8
Toilets	4 for peak hours	7 for opening hours	
BackRoom	20 for peak hours	9 for opening hours	Max 5.5
ColdRoom	49 for peak hours	6 for opening hours	

The electric equipment integrates several components, such as bakery equipment, oven for the pizzeria, cashiers, maintenance equipment, security cameras and plug-in cabinets. These last ones are fridges and freezers that companies provide to the hypermarket, for marketing purposes. These Plug-in cabinets are not part of the refrigeration system of the supermarket and, instead, work as a regular electric equipment. According to observations on the hypermarket, there are 12 Medium Temperature and 6 Low Temperature plug-in cabinets. Based on a survey carried out to several supermarkets, these plug-in cabinets were estimated to have an average power consumption of 4 kW [37]. Details about this calculations can be found in the appendix, as well as the power consumption of all the electrical appliances input in EnergyPlus' model. Table 1 on the appendix specifies the power consumption and times of daily usage for each type of electrical appliances considered in the model.

Figure 4.1 illustrates the schedule of several parameters that most influence the Internal Gains of the hypermarket. For the hours which the value is 1, it means that the parameter is at its maximum. For example, from 5 to 8 pm, the occupancy density is equal to 12 m^2/person, whereas from 2 to 5 pm 24 m^2/person, since 50% of the maximum occupancy is estimated for those hours.

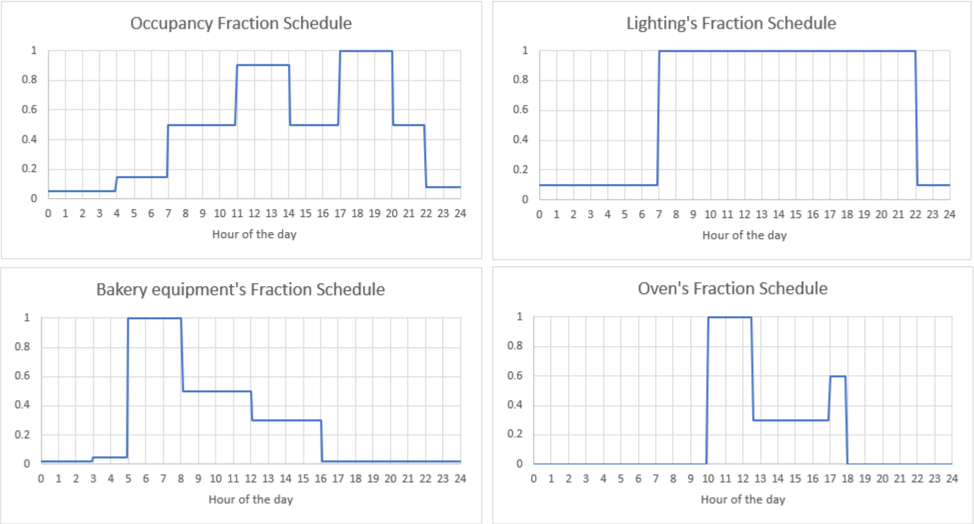


Figure 4.1: Occupants, electric equipment and lighting schedules

Figure 4.1 also indicates that the values presented in table 4.2 for lighting are verified from 7 am to 10 pm and for closing hours are equal to 10% of the maximum value. The fraction schedule for the oven operating in the pizzeria and the bakery's equipment are also shown in figure 4.1, since these equipment have a strong influence on the internal gains of this hypermarket. The bakery equipment has a maximum capacity of 55.5 kW and the oven 13.4 kW.

Estimating these schedules was a challenging task, because it is very difficult to know exactly how many people are inside the building and at what time. Probably, in reality, the fluctuations reflected in figure 4.1 are smoother, but in the model there are strong variations in some hours and it may influence the space heating and cooling loads.

4.1.5 Infiltration Rate and HVAC System

Initially, the hypermarket was modelled in EnergyPlus by a simple system that would provide enough heating, cooling and mechanical ventilation, in order to satisfy the required temperature set points and indoor quality.

According to the report from Skanska, the company responsible for constructing this ICA MAXI, [34], there is a constant infiltration rate of 0.3l/outside m^2. Moreover, a door to connect the outdoor with the sales area and another to the BackRoom are supposed to be opened several times within a day, which, naturally, affects the heat balance of the building. In the first case, the door is revolving, in order to minimise these heat losses to the outdoors. Nonetheless, in the model, a "tradition" door was considered.

Figure 4.2 illustrates how the schedule for door openings were created. For example, from 11 to 14, the entrance door is opened 40% of the time, while the back door is opened 20% of the same time period. Naturally, the entrance door is mainly used by consumers and it is opened more frequently, whereas the back door is for the hypermarket's workers and selling products to enter the building.

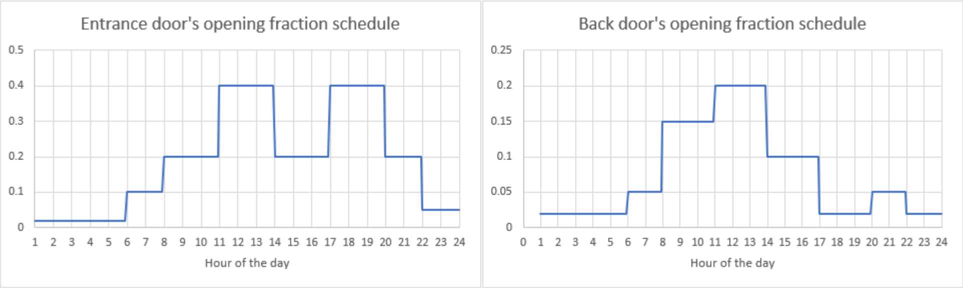
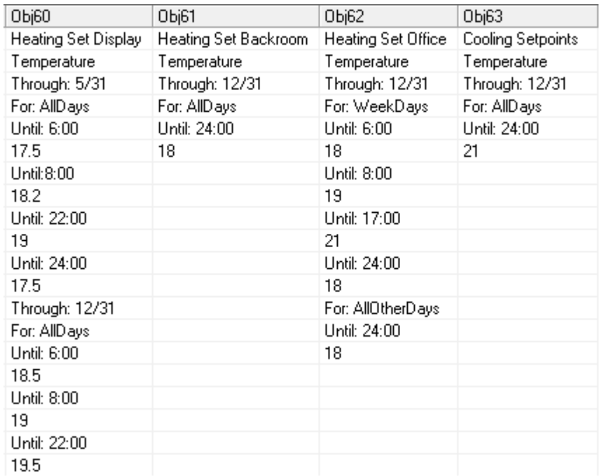


Figure 4.2: Door's opening schedules

For the entrance door, a leakage of 2 m^2 is considered when the door is opened and for the back door, this value is higher and equal to 4 m^2, due to the entrance of the products. Moreover, by taking into account the geometry of the building and its surroundings, the software is able to compute how these openings affect the energy balance of the whole system. There is, however, a high uncertainty on estimating when and for how long these doors are opened.

In what concerns the mechanical ventilation, a requirement of 9.44 liters of fresh air per person inside each zone was used, following a default value from EnergyPlus. In that sense, the maximum occupancy of 489 persons inside the hypermarket was used to calculate the mechanical ventilation requirement during opening hours and, during the night, 10% of this value was used.

Finally, aiming to reflect the reality of this hypermarket, the heating and cooling set points, for the different zones, were defined as showed in figure 4.3. The "Heating Set Display" is applied on the Display Area and the Toilets. During opening hours, from January until the end of May, the temperature should be between 19 and 21ºC, whereas during the night, without customers, the temperature can be lower, with a minimum of 17.5ºC. At some point, the model was calibrated in such a way that the inside temperature would be at least 18.2ºC from 6 am onward, to avoid a larger gap between closing and opening hours in the heating system. The control strategy changed from June onwards, meaning that the inside temperature was set to be between 19 and 22ºC all day long. For the BackRoom and ColdRoom, the temperature might be above 18ºC all year long. For the offices, there were some adjustments, to ensure the workers are thermally comfortable during working times, taking into account typical values reported in [36], for offices in Sweden. In that way, during working hours (week days from 8 am to 5 pm), the temperature should be 21ºC. In the other periods of the week it should be at least 18ºC.



Obj60	Obj61	Obj62	Obj63
Heating Set Display	Heating Set Backroom	Heating Set Office	Cooling Setpoints
Temperature	Temperature	Temperature	Temperature
Through: 5/31	Through: 12/31	Through: 12/31	Through: 12/31
For: AllDays	For: AllDays	For: WeekDays	For: AllDays
Until: 6:00	Until: 24:00	Until: 6:00	Until: 24:00
17.5	18	18	21
Until:8:00		Until: 8:00	
18.2		19	
Until: 22:00		Until: 17:00	
19		21	
Until: 24:00		Until: 24:00	
17.5		18	
Through: 12/31		For: AllOtherDays	
For: AllDays		Until: 24:00	
Until: 6:00		18	
18.5			
Until: 8:00			
19			
Until: 22:00			
19.5			

Figure 4.3: Temperature set points defined in EnergyPlus

In this hypermarket there is no humidifier or dehumidifier to control the inside relative humidity. Therefore, in this model, there are no set points for the inside relative humidity.

4.1.6 Refrigeration System

In this hypermarket, the HVAC system is connected to the refrigeration system. Consequently, with the adequate control, the space heating and cooling and domestic hot water heating needs should be entirely fulfilled by the refrigeration system. This allows the COPs for heating and cooling to be higher and, thus, having less energy consumption.

As the connection of this two systems is complex and innovative, it was simulated separately in a Python tool developed by Sotirios Thanasoulas at KTH Energy Department. In that sense, the building's loads will be obtained through the EnergyPlus model and subsequently, ICA MAXI's refrigeration system will be modelled in the Python tool, to compute the energy consumed by the system to fulfil the loads defined previously in EnergyPlus.

As a common practice in any supermarket, this ICA MAXI in Bålsta has both display refrigeration cabinets and cold rooms. The display cabinets are located in the display area, where customers can access, whereas the cold rooms, also called *Walk ins*, are located in a storage place where only staff can have access. Typically, the cold products arrive by truck and go directly to the cold rooms. Later on, when appropriated, those are placed in the display cabinets.

Table 4.3 summarizes the different types of refrigeration cabinets in the supermarket. The plug-in cabinets were excluded, since they are not integrated in the refrigeration system of this hypermarket.

Table 4.3: Summary of ICA MAXI's refrigeration system

	Display Cabinets		**Cold Rooms**	
	Medium Temperature	**Low Temperature**	**Chillers**	**Freezers**
Total Capacity [kW]	64.62	20.37	47.9	15.4
Quantity	22	7	7	2
Operating Temperature [ºC]	2 to 6	-18	2 to 6	-18
Refrigerant	R744			

Refrigeration Cases

The chiller and freezer display cabinets placed on the Display Area not only consume electricity themselves, but also influence the surrounding environment. Therefore, there is a large number of parameters that might be taken into account when modelling the refrigeration cases.

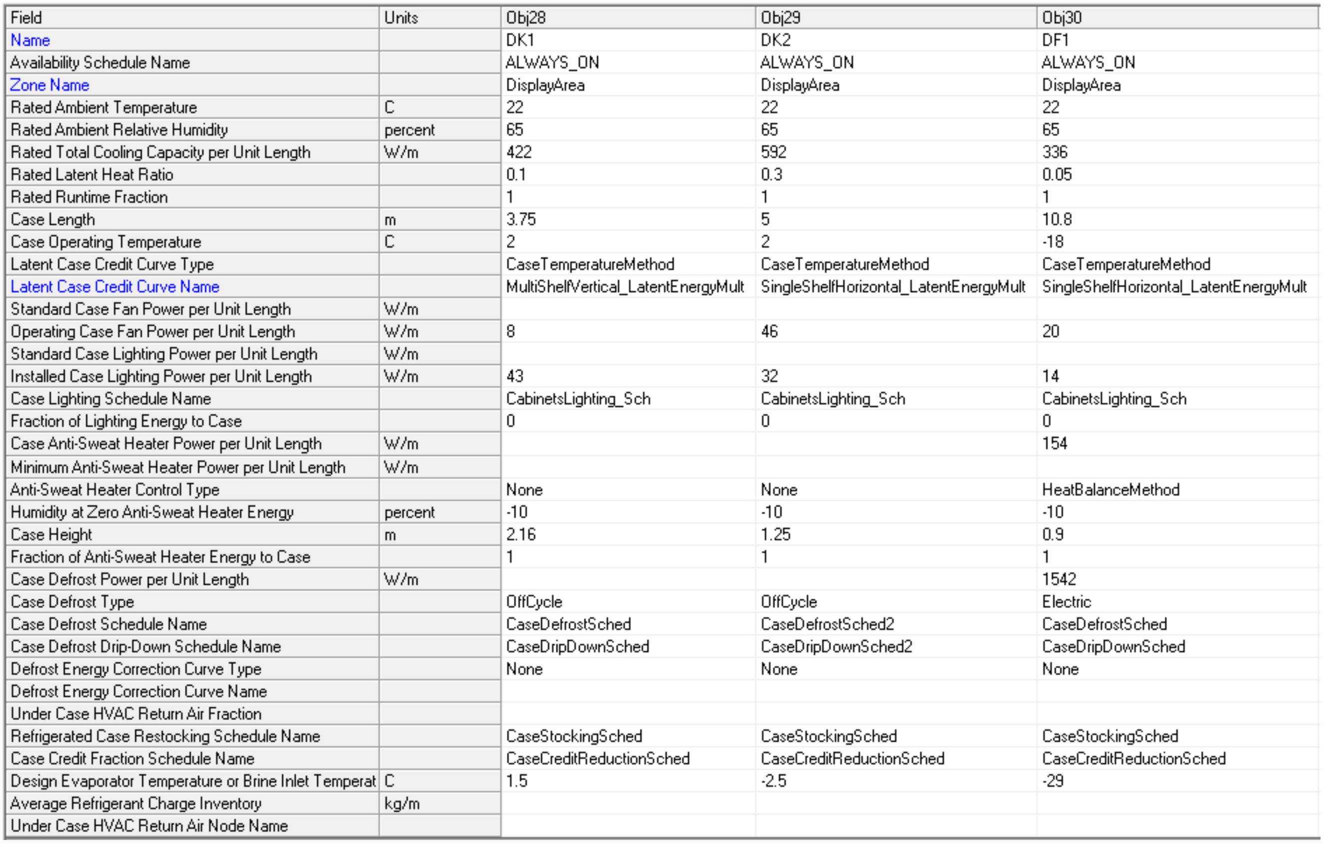
At this point, it is important to understand which factors influence the total load of the refrigerated cases in EnergyPlus.

$$Q_{case} = Q_{walls} + Q_{rad} + Q_{inf,sens} + Q_{inf,lat} + Q_{lights} + Q_{as} + Q_{def} + Q_{fan} + Q_{restock} \tag{4.1.2}$$

Where:

- Q_{case}: total load on the refrigerated case evaporator [W]
- Q_{walls}: heat transfer through case walls due to difference between the refrigerated case operating temperature and the zone temperature [W]
- Q_{rad}: radiant heat transfer to the refrigerated case [W]
- $Q_{inf,sens}$: sensible heat transfer by air infiltration through the air curtain or door openings [W]
- $Q_{inf,lat}$: latent heat transfer by air infiltration through the air curtain or door openings [W]
- Q_{as}: anti-sweat heater load [W]
- Q_{def}: defrost heat load [W]
- Q_{fan}: fan heat load [W]
- $Q_{restock}$: sensible load on the refrigerated case, caused by restocking products at a higher temperature than the case [W]

Figure 4.4 shows how 3 different display cases were modelled in Energyplus. *DK1* and *DK2* refer to a vertical and a horizontal chiller, respectively, whereas *DF1* refers to a horizontal freezer.



Field	Units	Obj28	Obj29	Obj30
Name		DK1	DK2	DF1
Availability Schedule Name		ALWAYS_ON	ALWAYS_ON	ALWAYS_ON
Zone Name		DisplayArea	DisplayArea	DisplayArea
Rated Ambient Temperature	C	22	22	22
Rated Ambient Relative Humidity	percent	65	65	65
Rated Total Cooling Capacity per Unit Length	W/m	422	592	336
Rated Latent Heat Ratio		0.1	0.3	0.05
Rated Runtime Fraction		1	1	1
Case Length	m	3.75	5	10.8
Case Operating Temperature	C	2	2	-18
Latent Case Credit Curve Type		CaseTemperatureMethod	CaseTemperatureMethod	CaseTemperatureMethod
Latent Case Credit Curve Name		MultiShelfVertical_LatentEnergyMult	SingleShelfHorizontal_LatentEnergyMult	SingleShelfHorizontal_LatentEnergyMult
Standard Case Fan Power per Unit Length	W/m			
Operating Case Fan Power per Unit Length	W/m	8	46	20
Standard Case Lighting Power per Unit Length	W/m			
Installed Case Lighting Power per Unit Length	W/m	43	32	14
Case Lighting Schedule Name		CabinetsLighting_Sch	CabinetsLighting_Sch	CabinetsLighting_Sch
Fraction of Lighting Energy to Case		0	0	0
Case Anti-Sweat Heater Power per Unit Length	W/m			154
Minimum Anti-Sweat Heater Power per Unit Length	W/m			
Anti-Sweat Heater Control Type		None	None	HeatBalanceMethod
Humidity at Zero Anti-Sweat Heater Energy	percent	-10	-10	-10
Case Height	m	2.16	1.25	0.9
Fraction of Anti-Sweat Heater Energy to Case		1	1	1
Case Defrost Power per Unit Length	W/m			1542
Case Defrost Type		OffCycle	OffCycle	Electric
Case Defrost Schedule Name		CaseDefrostSched	CaseDefrostSched2	CaseDefrostSched
Case Defrost Drip-Down Schedule Name		CaseDripDownSched	CaseDripDownSched2	CaseDripDownSched
Defrost Energy Correction Curve Type		None	None	None
Defrost Energy Correction Curve Name				
Under Case HVAC Return Air Fraction				
Refrigerated Case Restocking Schedule Name		CaseStockingSched	CaseStockingSched	CaseStockingSched
Case Credit Fraction Schedule Name		CaseCreditReductionSched	CaseCreditReductionSched	CaseCreditReductionSched
Design Evaporator Temperature or Brine Inlet Temperat	C	1.5	-2.5	-29
Average Refrigerant Charge Inventory	kg/m			
Under Case HVAC Return Air Node Name				

Figure 4.4: Exemple of refrigeration cases modelled in EnergyPlus

All the cabinets are considered to be working all the time and they are placed on the Display Area, where the rated conditions were set with a temperature of 22ºC and relative humidity of 65% (given values by the manufacturer). Inputs such as total cooling capacity, case length and height, operating temperature, evaporator temperature, fan and lighting power were provided by the manufacturer. It was assumed that during the night the lighting power inside the cabinets would be 10% of the one used during the opening hours of the hypermarket. This was modelled within the *CabinetsLighting_ Sch*. The parameters *Fraction of Lighting Energy to Case* was challenging to model. It could handle an input from 0 to 1 where 0 means that none of the lighting power of the cabinet is giving energy to outside the cabinet. In that sense, the lights of a cabinet increase the energy inside the cabinet, which leads to a need for using more cooling power to keep the desired temperature inside, as shown in equation 3.2.2.

Some parameters required some extra research to estimate. Namely the Rated Latent Heat Ratio (LHR), which consists on the latent capacity divided by the total cooling capacity of a refrigeration case [35]. This parameter influences the latent air infiltration load, presented in equation 3.2.2. In the EnergyPlus model, it was assumed that for the vertical doors' chillers the LHR would be 0.1 and for the horizontal doors' chillers, 0.3. For all the freezers, this value was set at 0.05. The choice of these values was based on the EnergyPlus Engineering reference [35]. It also follows the principle that the freezers are better isolated from the surrounding environment than the chillers and chillers with vertical doors are less exposed to the surroundings than the ones with horizontal doors.

The case credit curve refers to the "credits" that the refrigeration case provides to the ambient (in this case, to the Display Area). It happens because, as mentioned before, these subsystems in the supermarket influence each other and the cabinets can decrease not only the temperature, but also the relative humidity of its surrounding area. The latent parcel affects the relative humidity. In that sense, the input *Latent Case Credit Curve Type* was chosen to be "Case Temperature Method", as a default choice from EnergyPlus, meaning that the variation in latent case credits depends on the case operating temperature. For the parameter *Latent Case Curve Name*, a pre-existing curve on EnergyPlus example file "Supermarket Detailed" was used and was selected in accordance with the type of cabinet, as can be seen in figure 4.4.

The *Rated Runtime Fraction* parameter refers to the additional cooling capacity that the refrigerated cases typically include, even in rated conditions, usually due to stocking products. The entered value for this parameter must be between 0 and 1. Both for the MT and LT cabinets, a value of 1 was modelled. Due to a considerable uncertainty regarding this parameter, several simulations were run and the value of 1 led to a more accurate result.

The Anti-sweat heater is used mainly on the LT cabinets to warm up the refrigerated rails or doors to avoid moisture condensation. Its capacity was provided by the manufacturer and was input in the model accordingly. There is no certainty regarding the *Anti-sweat control type*, when the heater power is different than zero. However, it was assumed to be in accordance with the Heat Balance Method, which means that the power load can vary according to the zone temperature and relative humidity. Using this method is more energy-efficient than using a heater that supplies a constant power [35].

The manufacturer has provided the defrost power of each LT cabinet, whereas the defrost for the MT cabinets was assumed to be "Off Cycle", which means that, for the cabinet to defrost, the cooling supplying stops. It is assumed, also based on data given by the hypermarket, that each cabinet defrosts twice a day for 20 minutes each time. Five different schedules were made, in order not to have all the cabinets defrosting at the same time. The *Drip Down* consists on the extra time that a cabinet may need to return to the rated conditions after defrosting. In this model, the Drip Down Schedule was set in such a way that the drip down starts at the same time as the defrost and lasts for 5 more minutes.

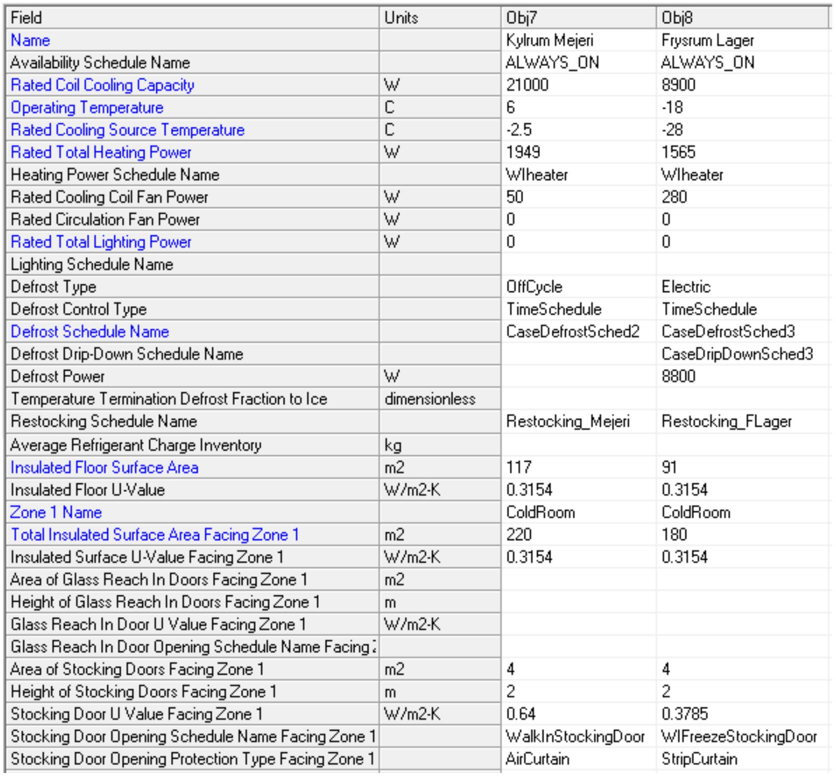
The *Case Restocking Schedule* relates the extra load on the cabinet by introducing products at a higher temperature than the case's operating temperature and the input values are in Watts per case length units [W/m]. Once again, this parameter was not given by the manufacturer, therefore it was estimated based on EnergyPlus default values. On the "Supermarket Detailed" example file, it was assumed to be 35 between 1 pm and 2 pm and 50 between 2 pm and 3 pm. Initially those values were kept in this hypermarket's model. However, after some iterations and comparison with the field measurements, this schedule was adjusted for a value of 45 between 1 pm and 3 pm. It is important to clarify that the products introduced in the cabinets that provide these extra loads are mainly coming from the cold rooms, so the temperatures difference are not significant, but opening the cabinets to introduce them also adds an extra load to the cabinets.

The input *Case Credit Fraction Schedule* is related to a reduction on the sensible and latent credits that are released by the cabinets to their surroundings. Usually, the cooling power provided by the manufacturers already accounts for the doors openings that happen during the opening hours of the supermarket. However, during the night, typically, the doors remain closed, which leads to a reduction on the credit cases from the cabinets. To take this aspect into account, this schedule was settled with the value of 1 from 7 am to 10 pm and 0.8 for the remaining hours. This means that during the day the case credits from the cabinet occur at 100% and during the night they are decreased to 80%.

Refrigeration Walk-In Coolers and Freezers

The coolers and freezer rooms are placed in the Cold Room zone are typically named "Walk In" cabinets, once it is possible to walk inside them. The majority of the cold products are stored in this kind of places. Only the cold products to be showed to the costumers are in the refrigeration cases, described before.

Once again, some parameters were fairly described by the manufacturer, whereas others required further research and taking some assumptions. Cooling capacity, operating and cooling source temperatures, fan and defrost power and cases' dimensions were given inputs by the manufacturer and were directly input, as exemplified in figure 4.5.



Field	Units	Obj7	Obj8
Name		Kylrum Mejeri	Frysrum Lager
Availability Schedule Name		ALWAYS_ON	ALWAYS_ON
Rated Coil Cooling Capacity	W	21000	8900
Operating Temperature	C	6	-18
Rated Cooling Source Temperature	C	-2.5	-28
Rated Total Heating Power	W	1949	1565
Heating Power Schedule Name		WIheater	WIheater
Rated Cooling Coil Fan Power	W	50	280
Rated Circulation Fan Power	W	0	0
Rated Total Lighting Power	W	0	0
Lighting Schedule Name			
Defrost Type		OffCycle	Electric
Defrost Control Type		TimeSchedule	TimeSchedule
Defrost Schedule Name		CaseDefrostSched2	CaseDefrostSched3
Defrost Drip-Down Schedule Name			CaseDripDownSched3
Defrost Power	W		8800
Temperature Termination Defrost Fraction to Ice	dimensionless		
Restocking Schedule Name		Restocking_Mejeri	Restocking_FLager
Average Refrigerant Charge Inventory	kg		
Insulated Floor Surface Area	m2	117	91
Insulated Floor U-Value	W/m2-K	0.3154	0.3154
Zone 1 Name		ColdRoom	ColdRoom
Total Insulated Surface Area Facing Zone 1	m2	220	180
Insulated Surface U-Value Facing Zone 1	W/m2-K	0.3154	0.3154
Area of Glass Reach In Doors Facing Zone 1	m2		
Height of Glass Reach In Doors Facing Zone 1	m		
Glass Reach In Door U Value Facing Zone 1	W/m2-K		
Glass Reach In Door Opening Schedule Name Facing			
Area of Stocking Doors Facing Zone 1	m2	4	4
Height of Stocking Doors Facing Zone 1	m	2	2
Stocking Door U Value Facing Zone 1	W/m2-K	0.64	0.3785
Stocking Door Opening Schedule Name Facing Zone 1		WalkInStockingDoor	WIFreezeStockingDoor
Stocking Door Opening Protection Type Facing Zone 1		AirCurtain	StripCurtain

Figure 4.5: Example of Walk In Cooler and Freezer modelled in EnergyPlus

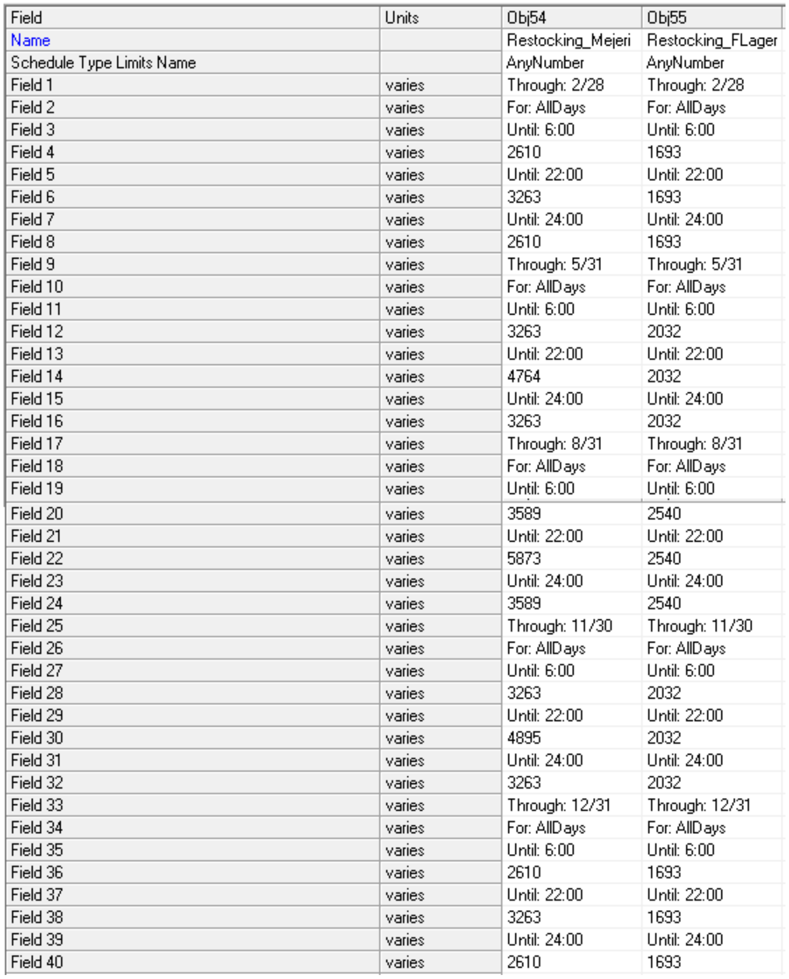
The manufacturer did not provide information about the number of workers, lighting or restocking products inside the cabinets and cold rooms. These parameters naturally influence the heating loads of this cold rooms. In that sense, some estimations were taken into place. The extra heating load provided by lights was assumed to be equal to 15 W/m^2 of the case and the extra load by the workers was assumed as 200W constantly, based on Jaime Arias' PhD thesis [1]. This effect was modelled in the *Rated Total Heating Power* input and the schedule "WIheater" was set to be at 100% rate all the time.

The defrost and drip down were modelled as the same way as in the refrigeration cases. However, the restocking was modelled differently. Here, it should be considered that the products come generally from truck to the hypermarket. It is not easy to predict their temperatures, as they can vary significantly. Due to the limitations on data availability, default values from the EnergyPlus example file "SupermarketDetailed" were adapted.

That example file considered different values for the restocking schedule of a walk in cabinet, for each time of the day. The volume of that cabinet was also known. Therefore, for the real cabinets, the example file's values were adapted to the ratio of volumes between the example cabinet and each real cabinet. Moreover, the restocking was considered to impact the system at night, as well, in the same way that the *Rated heating power* was assumed to be.

After analysing the results of several simulations and making further researching, it was assumed to be more accurate to increase the restocking schedule for the summer and spring/autumn, compared to the winter. In reality, the cooling power of the walk in cabinets depends on the indoor relative humidity, which is affected by the outside temperature and whether it is day or night. Unfortunately, EnergyPlus does not allow to model the walk ins in accordance to the outdoor temperature. Therefore, modelling the Restocking schedule as explained previously, was found to be the best solution. Two examples are presented on figure 4.6, where the values are in Watt units. The *Mejeri* is a chiller, while the *FLager* is a freezer. In both cases, it was considered that the Winter would last from December until the end of February, the Summer is from June to the end of August and the remaining time refers to Spring/Autumn season. From the information provided by the manufacturer, the chillers are more sensitive to the period of the day, whereas such factor barely influence the chillers.

Information from figure 1 in appendix 3 was used to set the differences between the times of the day and seasons.



Field	Units	Obj54	Obj55
Name		Restocking_Mejeri	Restocking_FLager
Schedule Type Limits Name		AnyNumber	AnyNumber
Field 1	varies	Through: 2/28	Through: 2/28
Field 2	varies	For: AllDays	For: AllDays
Field 3	varies	Until: 6:00	Until: 6:00
Field 4	varies	2610	1693
Field 5	varies	Until: 22:00	Until: 22:00
Field 6	varies	3263	1693
Field 7	varies	Until: 24:00	Until: 24:00
Field 8	varies	2610	1693
Field 9	varies	Through: 5/31	Through: 5/31
Field 10	varies	For: AllDays	For: AllDays
Field 11	varies	Until: 6:00	Until: 6:00
Field 12	varies	3263	2032
Field 13	varies	Until: 22:00	Until: 22:00
Field 14	varies	4764	2032
Field 15	varies	Until: 24:00	Until: 24:00
Field 16	varies	3263	2032
Field 17	varies	Through: 8/31	Through: 8/31
Field 18	varies	For: AllDays	For: AllDays
Field 19	varies	Until: 6:00	Until: 6:00
Field 20	varies	3589	2540
Field 21	varies	Until: 22:00	Until: 22:00
Field 22	varies	5873	2540
Field 23	varies	Until: 24:00	Until: 24:00
Field 24	varies	3589	2540
Field 25	varies	Through: 11/30	Through: 11/30
Field 26	varies	For: AllDays	For: AllDays
Field 27	varies	Until: 6:00	Until: 6:00
Field 28	varies	3263	2032
Field 29	varies	Until: 22:00	Until: 22:00
Field 30	varies	4895	2032
Field 31	varies	Until: 24:00	Until: 24:00
Field 32	varies	3263	2032
Field 33	varies	Through: 12/31	Through: 12/31
Field 34	varies	For: AllDays	For: AllDays
Field 35	varies	Until: 6:00	Until: 6:00
Field 36	varies	2610	1693
Field 37	varies	Until: 22:00	Until: 22:00
Field 38	varies	3263	1693
Field 39	varies	Until: 24:00	Until: 24:00
Field 40	varies	2610	1693

Figure 4.6: Example of Walk In Cooler and Freezer Restocking schedule on EnergyPlus

4.1.7 Domestic Hot Water and Lights on the outside Parking

Based on an assumption of 300 liters of Domestic Hot Water (DHW) use per day in this hypermarket, at 65ºC, the water equipment was modelled in such a way that the demanded flow would be constant along the 14 hours of opening time per day. Details about the calculations and assumptions can be found in Appendix 4. EnergyPlus model assumes that District Heating is used to warm up this water, which also happens in reality. For simplification, DHW is considered to be used only in the Display Area, since the bakery and pizzeria are located there.

In reality, there are car parking lights, chargers and a snow melter outside the hypermarket's building. Whereas, in the model, the only exterior equipment to be considered is the parking's lights. Those lights were assumed to have a power of 4.35 kW and being on only during the night, according to the real energy consumption's measurements. In order to model this parameter in such a way that the lighting would only occur during the night it was assumed that from the January 1^{st} until the 31^{st} of March and from the 1^{st} of October until the end of the year, the day time would be from 8:30 am to 4 pm. For the other periods of the year, the day time was assumed to be from 6:30 am to 9 pm. Of course, in reality, the variations in day time are much more complex. However, this was considered to be a reasonable approximation and this parameter, as well as the DHW is not expected to have a significant weight on this hypermarket's energy consumption.

4.2 Model Results and Comparison with Measured Values

4.2.1 Daily Loads

After having constructed the model, hourly data was obtained regarding the energy demand of the different systems of the hypermarket, within a year of simulation.

The first parameters to analyse were the refrigeration and space heating and cooling loads of the system (in kW).

To have a reasonable perspective of the hourly loads, a typical day in January and July will be analysed and compared to the field measurements, on a first approach. In figures 4.7-4.19, Q_{MT} stands for the total cooling load of the MT cabinets (refrigeration cases and walk ins). Q_{LT} uses the same rational, but for LT cabinets. *Heating* represents the total space heating of the hypermarket plus domestic hot water, whereas *Cooling* stands for the total space cooling required by the system to meet the temperature set points.

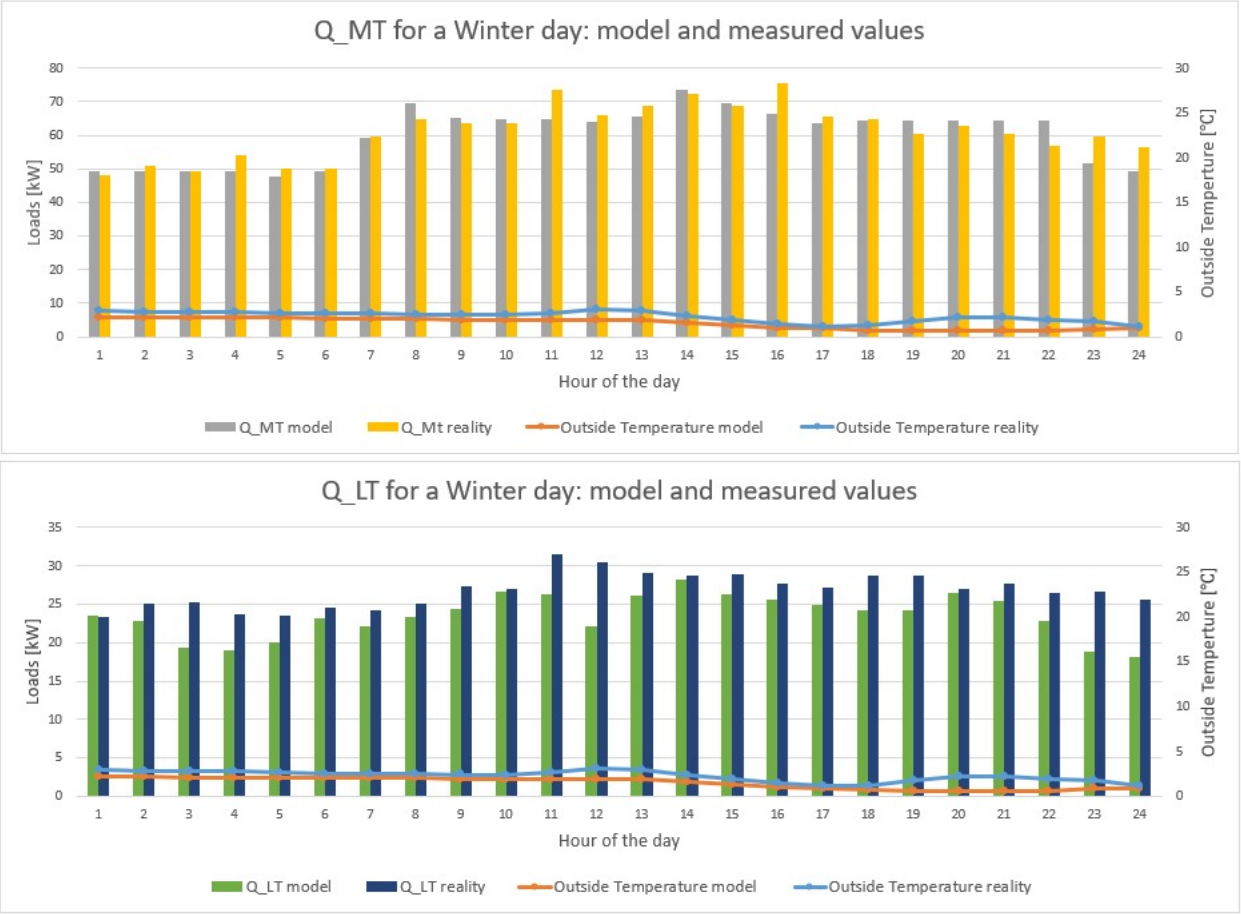


Figure 4.7: Refrigeration loads within a day in January

Figure 4.7 shows the values for Q_{MT} and Q_{LT} found after simulating the model and the values reported by the field measurements of ICA MAXI hypermarket, for 2021, for a typical winter day in Stockholm. Unfortunately, the outdoor temperatures are not exactly the same, which might lead to some "unavoidable" differences between the model and the measurements. Nevertheless, they were considered close enough to make a reliable comparison. Moreover, the relative humidity is not being considered, due to lack of data from the measurements.

According to the model, the Q_{MT} is near 50 kW during the night and mostly around 65 kW during the day, with a peak value of 73 kW at 2 pm. These values seem to have an expected tendency, since they are lower during the night, when there are less internal gains in the building and the case latent credits are reduced, since the cases' doors are not opened by the costumers. Additionally, the peak that occurs at 2 pm might be related with a high presence of internal gains, including costumers that may open the cabinets' doors and the restocking of the refrigeration cases that occurs from 1 to 3 pm.

It is possible to notice that the Q_{MT} values are more constant in the model than on the measurements. During unoccupied hours, the measured Q_{MT} varies from 48 to 56 kW, whereas in the model, Q_{MT} is nearly 50 kW all this time. These loads are always above 60 kW during opening hours, similarly to what is verified in the model. The peak value, although, is slightly higher with 76 kW at 4 pm. Once again, it is a complicated task to estimate for how long the cases' doors are open during the day at it, for sure, affects the cases loads.

The values of Q_{LT} range between 18 at night and 26 kW at peak time, in the model. On this day, the measurements showed a Q_{LT} higher with values ranging from 23 to 31 kW.

These differences between the model and measurements, apart from the slight differences in outdoor temperature, are probably related with consumers and workers' behaviours, namely restocking times and duration and cabinets' doors opening. The uncertainty regarding the internal gains might also be reflected on these differences.

Figure 4.8 illustrates the heating loads for the model and measurements within the same day in January.

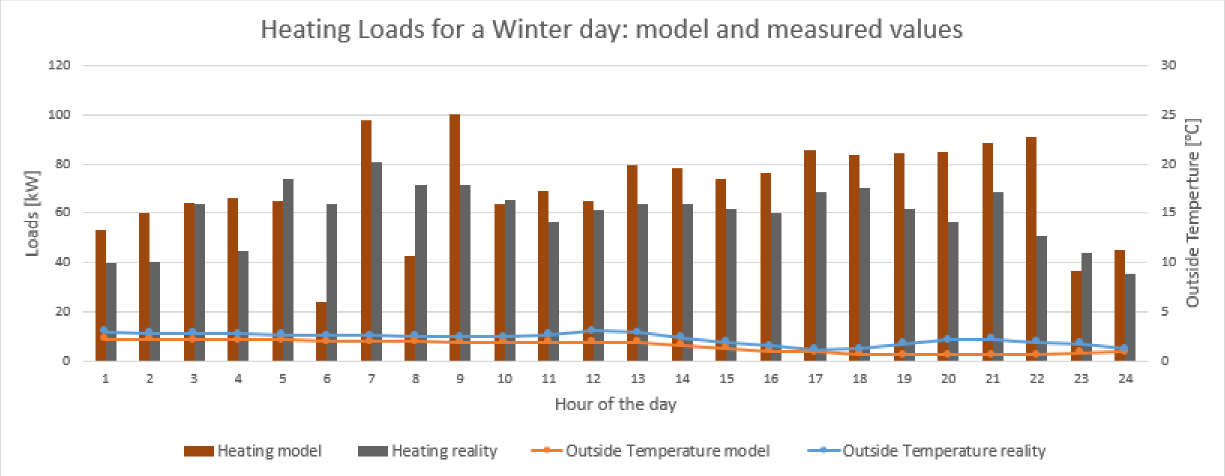


Figure 4.8: Heating loads within a day in January: simulated and measured values

For the model, in a day with an outside temperature ranging from 0.6 to 2.2ºC, the peak heating load was equal to 100 kW at 9 am. The reason why the higher heating demand happens at this time might be related with the fact that, in the model, for January, the temperature set point increases from 18.2 to 19 degrees at 8 am and after 8 am the bakery operation, which represents a considerable internal gain in the system, drops to 50% of its full capacity. Moreover, around 7 or 8 am probably more workers and customers enter the building, which allows the outside air to enter by the doors. It was considered that near and slightly after the opening time the doors from the outside open more frequently, as there are more people arriving. There are also more walk in cases with the door open from 6 to 8 am, which leads to an increase on the heating loads of the Cold Room.

On the model, the minimum value for the heating demand, below 30 kW, at 6 am, occurs once there are no customers, thus there are no interaction between the cabinets and the display and not much entrance door openings and, on the other hand, the bakery is working at full capacity, which represents a considerable internal gain on the system. This effect of the internal gains on the heating loads can also be noticed when from 10 am the heating loads are lower than at 9. Moreover, an oven with a power of 13.4 kW was modelled to operate at maximum capacity from 9 am to 12:30 pm. The oven stops operating at 5 pm, while the outside temperature is slightly decreasing. This might be the reason why the heating loads increase at that time. It is true that at those hours the occupancy is at its maximum level, but it also means more time with the outside's and cabinets' door open, which may lead to increasing heating loads.

The measured loads have a lower amplitude, from near 40 to slightly above 80 KW. Nevertheless, the daily tendencies are, generally, similar. In overall, the heating needs are higher in the model, which seems accurate, taking into account the lower temperatures. Both in the model and reality, there are no cooling loads for this day.

After observing what happens during a day in January, it is time to analyse an entire day in the Summer, both on the model and measured values. Figure 4.9 intends to represent the refrigeration loads for a typical Summer day, according to the EnergyPlus model and real measurements.

In overall, it can be noticed that the Q_{MT} values increased comparing to the Winter's ones. According to the model, during unoccupied hours, these loads are close to 60 kW, whereas they used to be near 50 kW in the Winter. During opening hours, the values are close to 80 kW with a peak value of 93 kW. According to the measurements, for this summer day, the Q_{MT} values are generally higher than on the model. The loads are, on average, approximately 65 kW during the night and the peak value during the day is slightly above 100 kW. The differences between the model and the field measurements are not significant for this parameter and it was expected that in reality these values would be more fluctuating than in the model.

The Q_{LT} values in the model range from 25 to 34 kW. These values for a Summer day are higher than in the Winter, as expected from the beginning. At the same time, the measured values range from 26 to 32 kW, being more constant than in the model. This difference can be related to some uncertainties and assumptions taken when modelling the refrigeration cases and walk in cabinets. However, the results are not significantly far from the measurements.

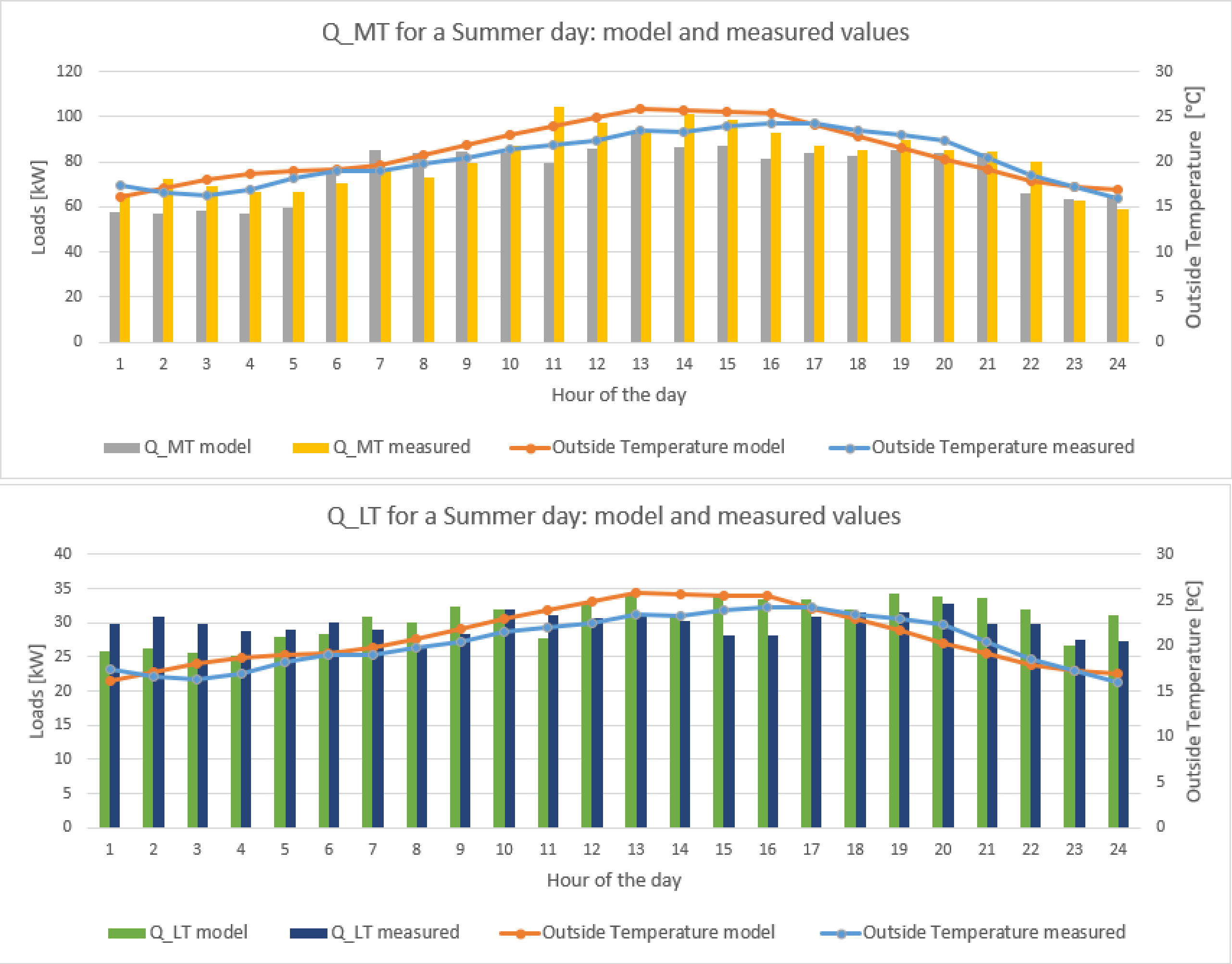


Figure 4.9: Refrigeration loads within a Summer day

Figure 4.10 presents the heating and cooling loads for the same summer day, for both the model and measured on the hypermarket.

Regarding the cooling loads, they are very fluctuating for a Summer day, according to the model. In the night there are no cooling needs, at all, which seems accurate, since the outside temperature is lower than the established cooling set point and the internal gains are much lower than in the opening hours. These loads have a peak value of around 150 kW at 5 pm, which seems to be a high value for an outside temperature below 25℃ . The cooling loads are way more constant in the measurements. Probably the HVAC system is regulated in such a way that it starts supplying cooling earlier, to avoid high peak loads that can lead to problems in the system or the need to install more cooling equipment with higher capacities. In the model, an ideal cooling and heating supply is assumed all the time, in order to meet the temperature set points defined previously, hence a full HVAC system was not designed. This situation can explain such different loads found on figure 4.10. It may be interesting to compare the average daily values for the summer.

The heating loads are presented for the entire summer day, both in the model and measurements. However, the measured values are significantly lower, with a maximum value of 16 kW at 9 pm and a minimum of 2 kW at 4 am. For the model, these loads have a minimum value of 4 kW and occur even during the day, at the same time that there are cooling loads. This situation is somehow difficult to explain, but it might be related to over cooling or different loads in different thermal zones of the building. Possibly, the hypermarket uses some control strategies to decrease these loads in the Summer, for example by recirculating the air inside the building, from different zones.

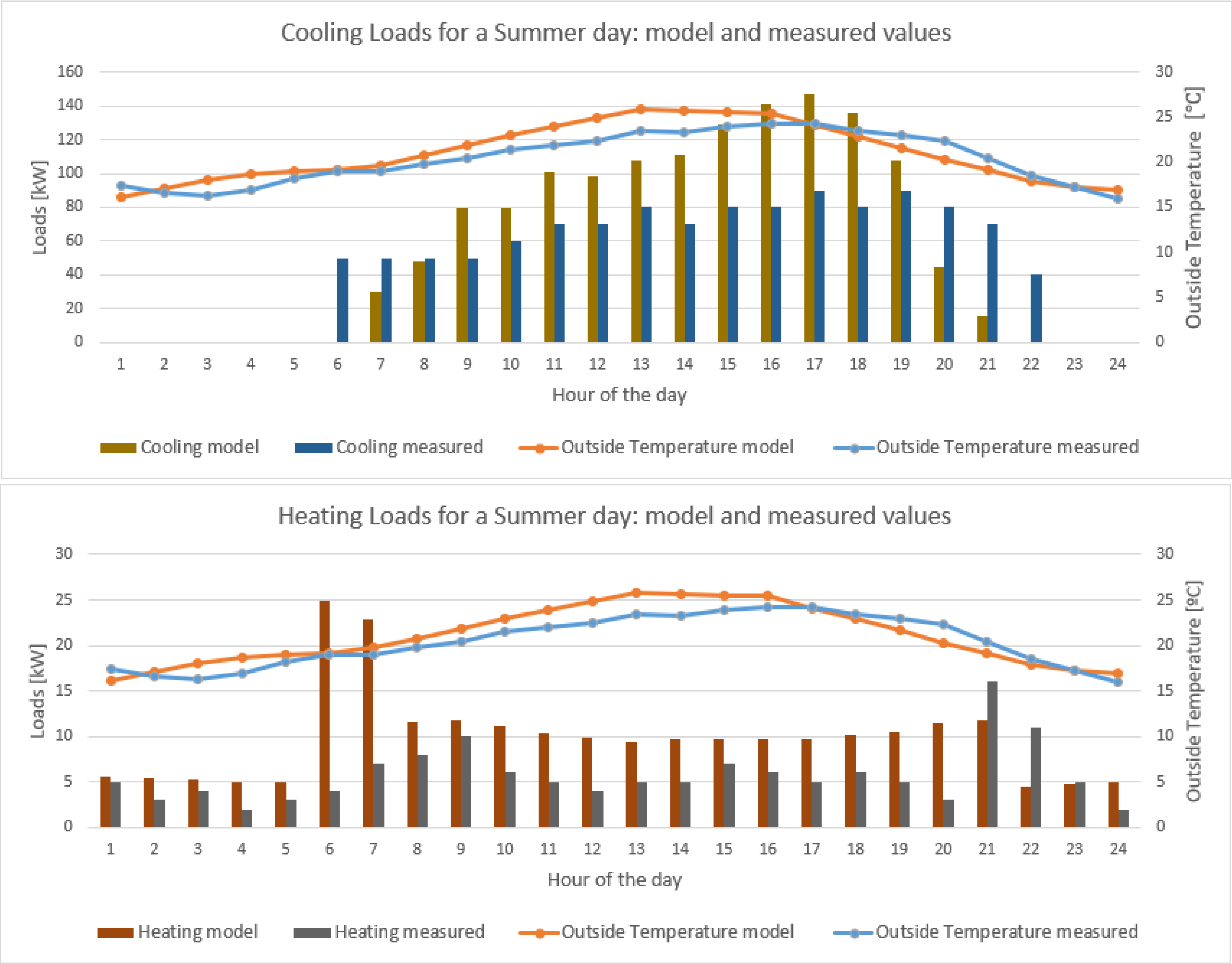


Figure 4.10: Heating and cooling loads within a Summer day: simulated and measured values

4.2.2 Weekly Loads

After having analyzed what happens within a typical day, both in the winter and the summer, at this point some results will be shown within an entire week, both for the model and the measurements, with the aim to analyze some tendencies.

Figure 4.11 shows the Q_{MT} and Q_{LT} for a winter week both according to the model and field measurements. It is possible to observe that within an outside temperature ranging from -8 to 8°C, the refrigeration loads do not vary in the model, since, generally, The values are repeating day by day, with a refrigeration peak value near 105 kW.

On the other hand, with a similar range of outside temperatures, the measured Q_{MT} and Q_{LT} loads vary in according to the outside temperature, while the daily pattern remains the same. It can be seen that in a day with temperatures reaching 6°C, the peak load for the MT and LT is about 115 kW, whereas on a day where the outside temperature went lower than -8ºC, the refrigeration peak load was about 105 kW. It is also interesting to notice that this difference is more strongly felt for the Q_{MT} than for the Q_{LT}.

This difference in tendencies between the simulated and measured results might be related to the difficulty found on modelling the walk in cabinets accurately. The power load of the walk ins vary according to the temperature and times of the day. However, EnergyPlus only allows to input a single constant value for the cooling power of such cabinets. This limitation, as explained before, was tried to be overcome by the restocking schedules. Nonetheless, a true replacement was not possible to achieve.

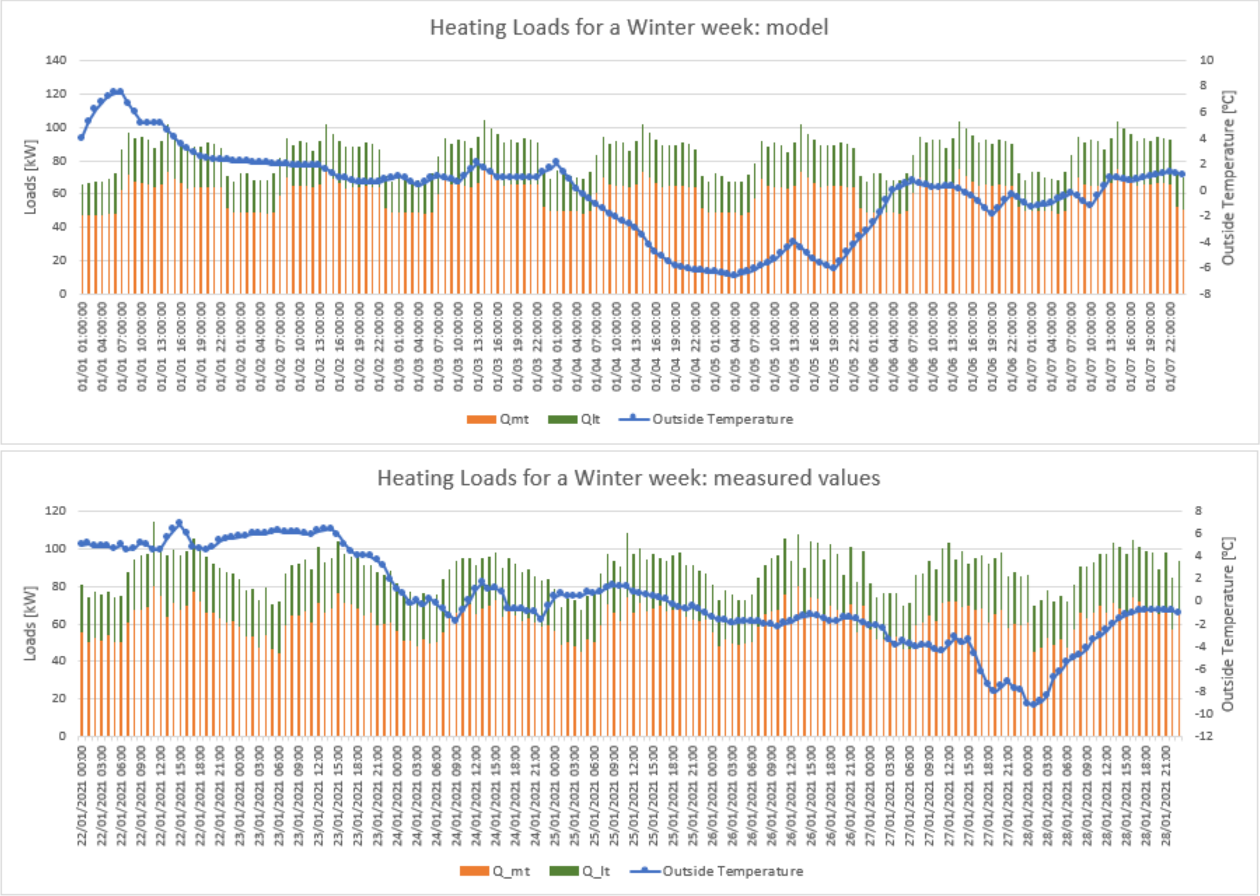


Figure 4.11: Refrigeration Loads within a Winter week

Figure 4.12 allows to observe that, both according to the model and field measurements, the heating loads are strongly dependent on the outside temperature, within a week in the Winter. The peak values are higher in the model, but only for two occasions. In general, these loads are more fluctuating in the model than on the field measurements within the same day. Nevertheless, the weekly variations are similar and the behaviour regarding the variations in the outside temperature do not differ much.

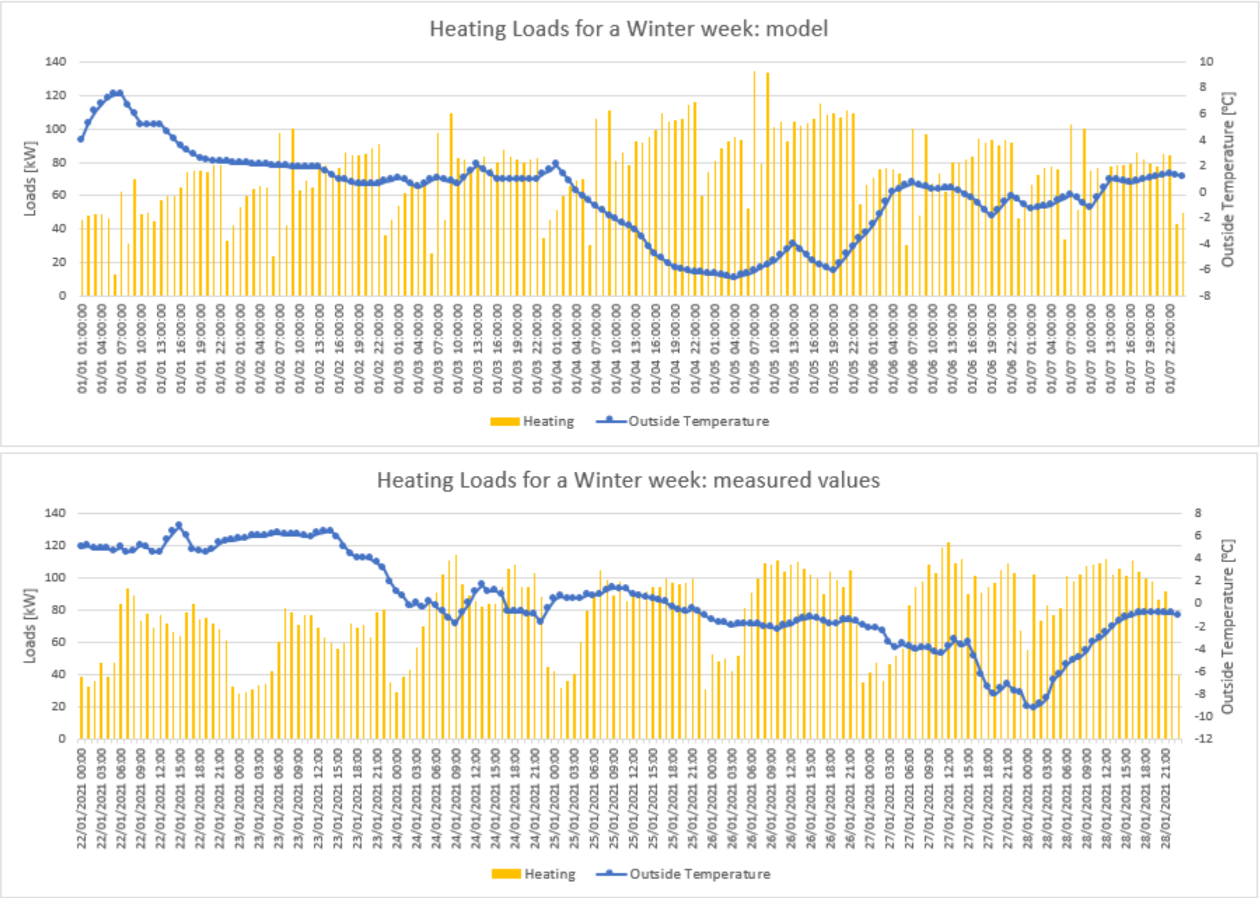


Figure 4.12: Heating loads within a week in the Winter

Similarly to what has been done for the Winter, at this point a Summer week will be under analysis, regarding refrigeration and space heating and cooling loads, both in the EnergyPlus model and field measurements.

On figure 4.13 it is possible to see that in the simulated results, the refrigeration loads do not vary significantly within a temperature ranging from 13 to 25°C. This might have a similar explanation from the one given for the week in the Winter. Nevertheless, and in the same way it was noticed for the loads within a day, the refrigeration loads are higher for a week in the Summer than in the Winter, as expected previously. Once again, for the measured values, the loads are more dependent on the outside temperature, specially the Q_{MT} and the peak values are slightly higher than in the model. Nonetheless, these differences are always lower than 10%.

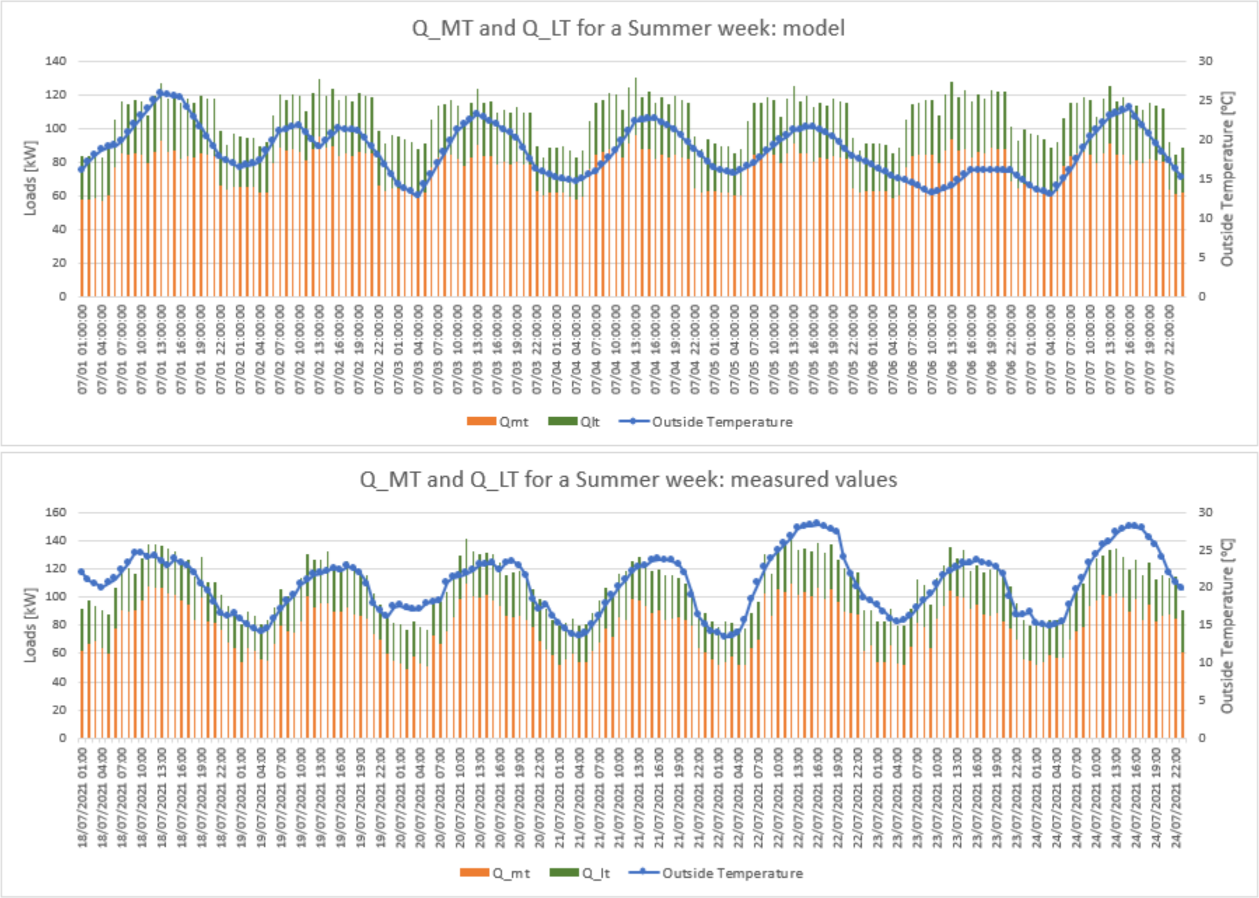


Figure 4.13: Refrigeration loads within a Summer week

Figure 4.14 shows the heating and cooling loads for a Summer week, both in the model and measurements. First of all it is important to notice that the temperatures vary in the two cases, but unfortunately they were the most similar weeks that could be found for the Summer. It is possible to observe that the cooling needs vary in accordance with the outside temperature, in different days of the week. Once again, the loads from the measurements are more constant than in the model. In the model the peak cooling is about 150 kW, whereas in the field measurements it only reaches 110 kW, even though the outside temperature is higher for that time. But, on the other hand, the cooling loads in the measurements remain above 50 kW for longer. It will be interesting to see what happens on a daily average, on the next section.

Regarding the space heating, those loads do not change in different days with different outside temperatures in the model, which is somehow unexpected. However, the maximum heating loads always occur for an outside temperature lower than the heating set point for the Summer (18.5-19.5℃).

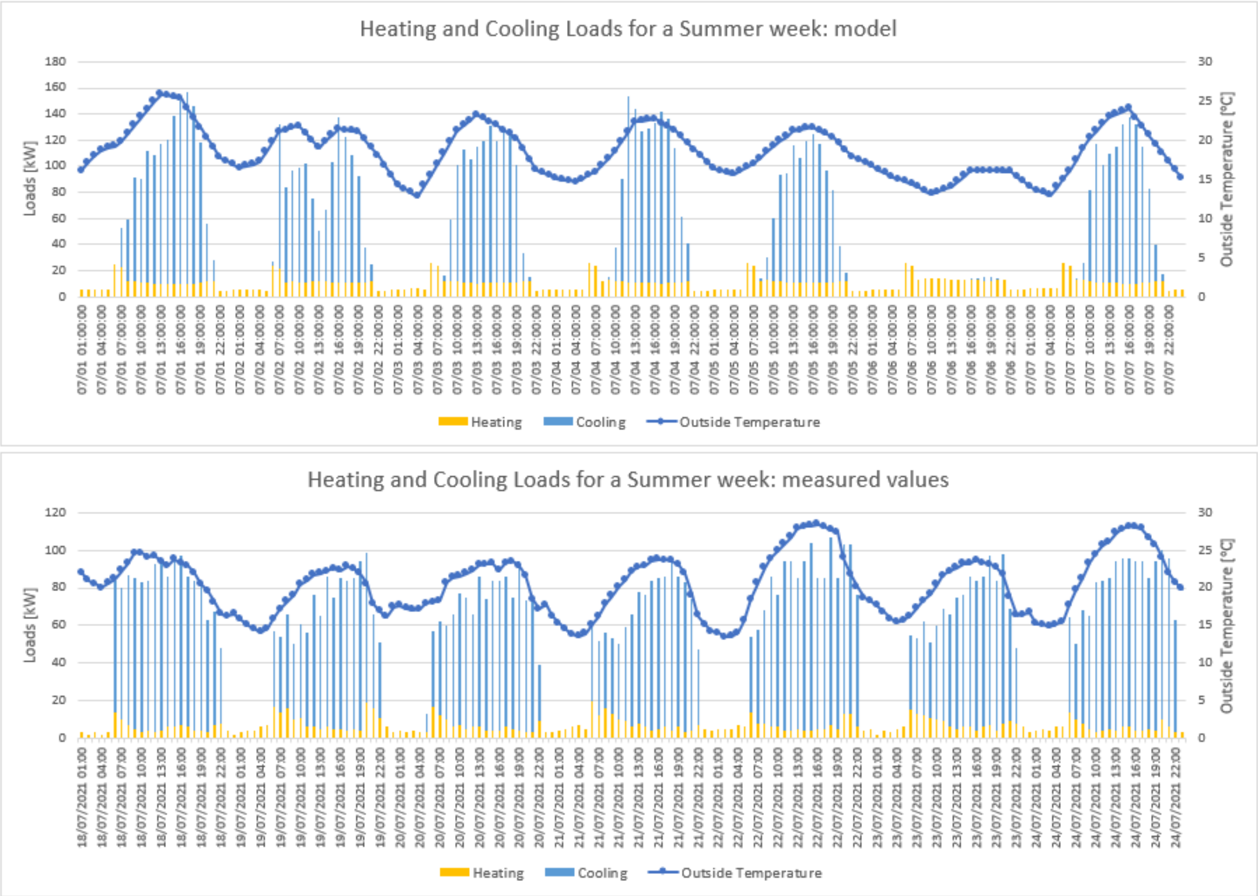


Figure 4.14: Space heating and cooling loads within a summer week

4.2.3 Monthly Loads

In this section, the daily average loads along December and July, both in the model and measured values, will be presented.

Figure 4.15 shows the daily average Q_{MT} and Q_{LT} for December in the model and in measurements.

Q_{MT} values are more constant in the model than in the measurements, as they reflect to be less dependent on the outside temperature. However, the temperatures in the model are also more constant. It is curious to notice that, in the measurements, for an average outside temperature below -10 ℃, on the 6th and 7th of December, the average Q_{MT} is significantly lower than for the remaining days, around 40 and 26 kW, respectively, compared to an average of approximately 57 kW for the whole month. The exact opposite happens for Q_{LT} values, that are increased for these same two days. Apart from these two days, the refrigeration loads have close enough values for the model and measurements. Actually, different behaviours can occur in different days in the hypermarket and the cabinets were not model differently for different days of the week in the model.

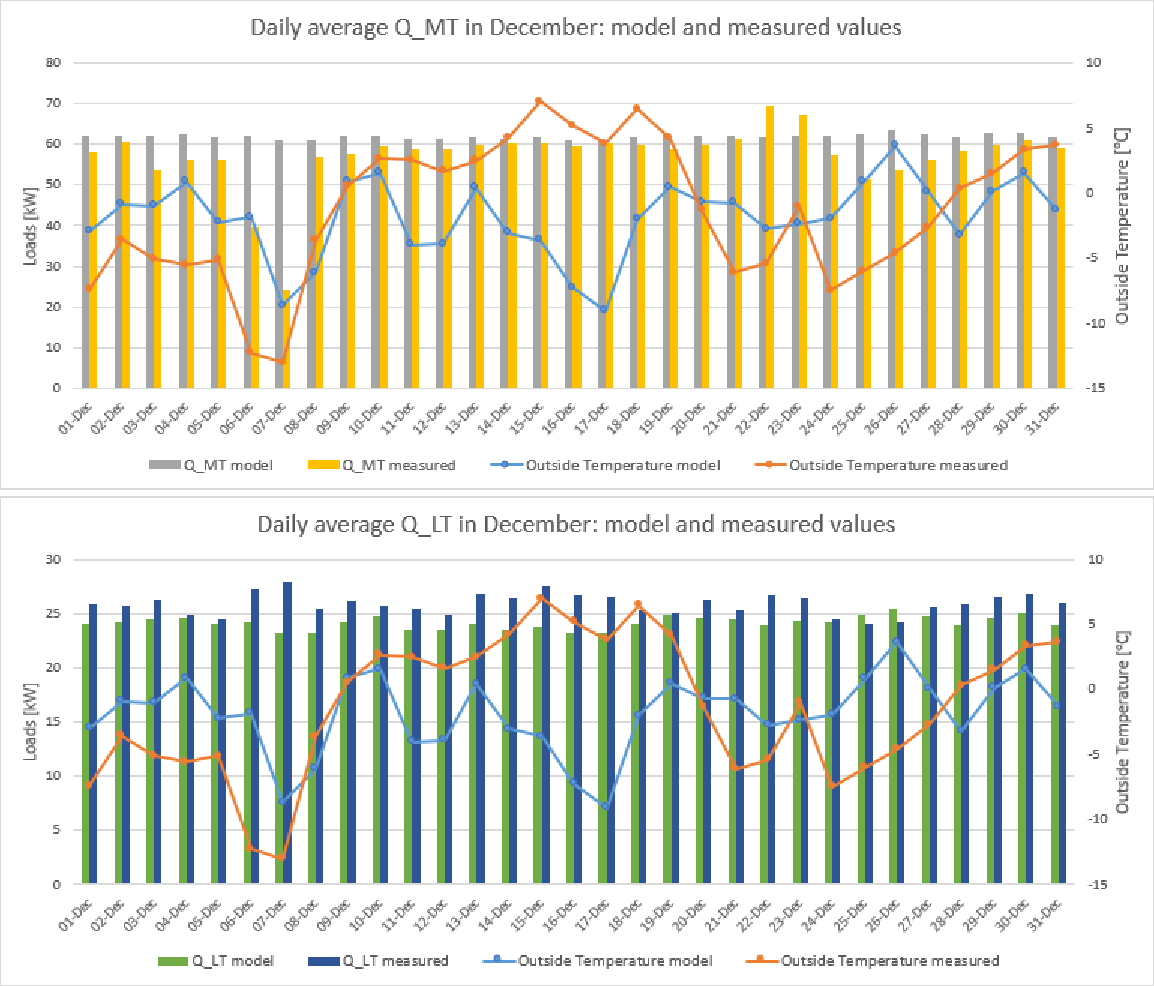


Figure 4.15: Refrigeration loads for December - Model and measured values

Figure 4.16 shows that the space heating is more fluctuating according to the measurements, but also the outside temperatures vary more. In what concerns the space heating in December, the model fairly reflects the changes in the outside temperature. The peak value is significantly higher for the measurements, but the minimum outside temperature is lower and can be identified as extreme low temperature for Stockholm.

It is possible to observe some cooling loads for certain days, according to the ICA MAXI measurements, with a maximum of 7.5 average kW, for a day in which the average outside temperature was around 0°C, perhaps due to some kind of control issues. Cooling loads were not found on the model's results, as expected for a winter month.

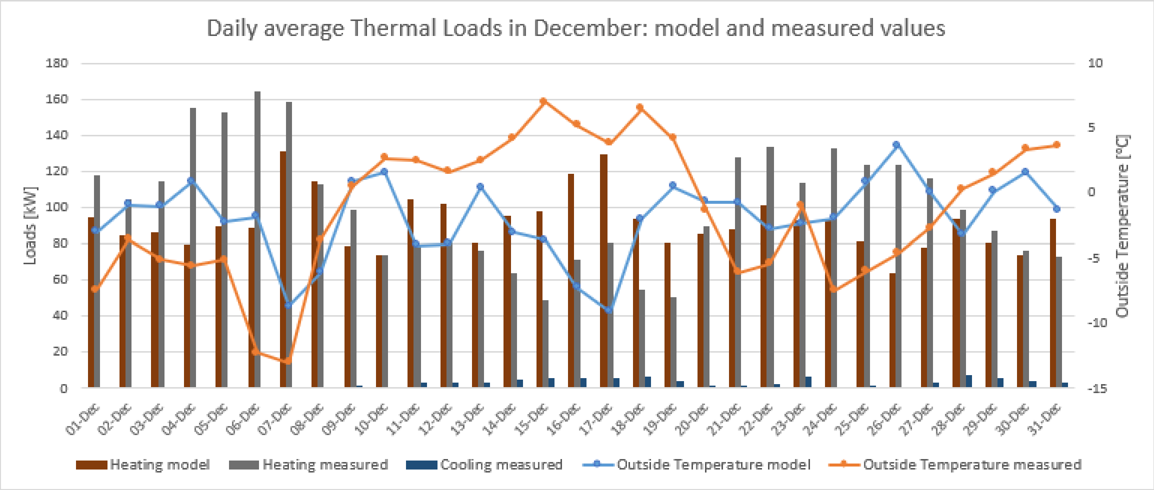


Figure 4.16: Thermal Loads for December: Model and measurements

To further analyse the results during the Summer, the month of July was studied in both the model and measured values for the refrigeration and space heating and cooling loads. Figure 4.17 shows the refrigeration loads.

First of all, it is important to notice that, although the same month is being presented, for the same location, the temperatures are considerably different. It explains the reason why the refrigeration loads are, generally, higher in the measurements. However, it can be noticed that when the average daily outside temperature is below 20°C , the daily average Q$_{MT}$ is below 80 kW, as happens in the model. Moreover, it can be noticed that the closer the outside temperature, the closer the daily average Q$_{MT}$ for model and measurements.

Regarding the daily average Q$_{LT}$, the values from the model and measurements are close, with a difference lower than 10% every day in July. Therefore, the model is reliable on predicting the refrigeration loads.

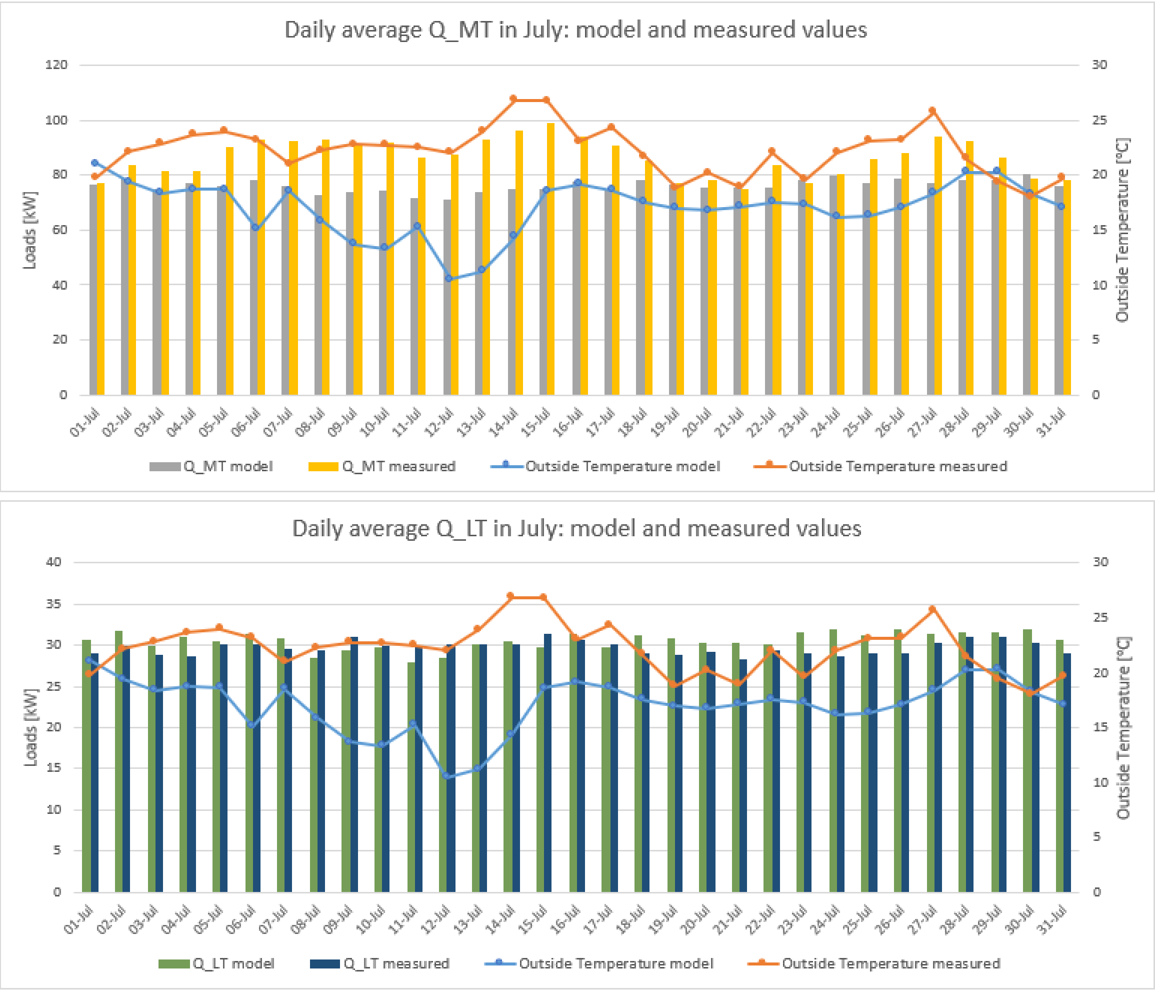


Figure 4.17: Daily Average refrigeration loads for July: Model and measured values

Figures 4.18 shows the thermal loads according to the model and measurements in the hypermarket.

The great differences on cooling loads between the model and reality might be related to the differences in daily outside temperatures. In the range of outside temperatures of the model, it is understandable that the cooling has a very fluctuating behaviour, since those temperatures are near the temperature set points defined for each zone.

Similarly to what was verified within a summer week, the heating loads are significantly higher in the model. It might be related to the significant lower outside temperature, usually below the heating set point established for 19 degrees in the Summer. In practical operation of the hypermarket, this is not a significant problem, since these loads are far from the heating peak loads along the year.

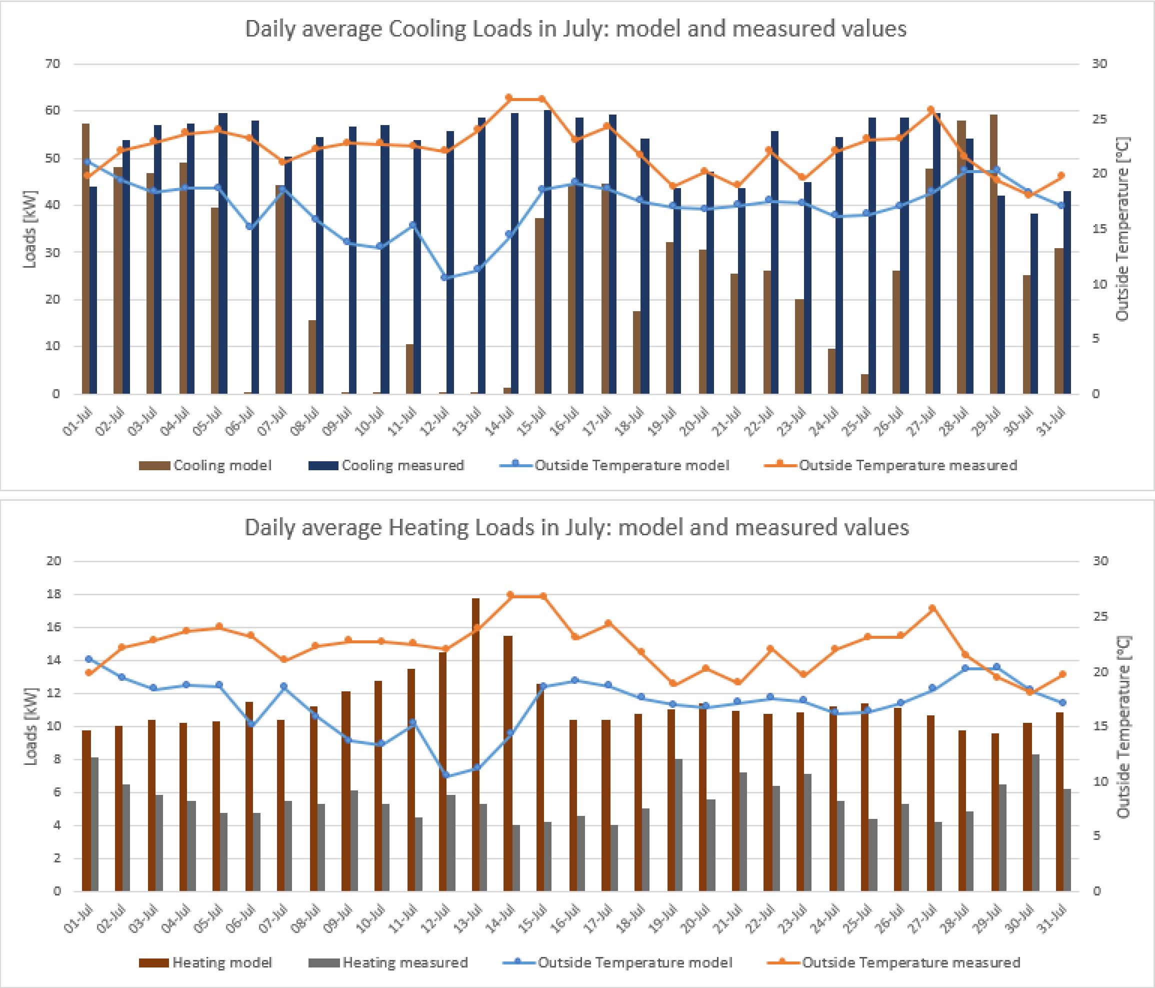


Figure 4.18: July daily average thermal loads

4.2.4 Annual Loads

Finally, the average loads of each month of the year will be analysed. Figure 4.19 represents the refrigeration and thermal loads regarding the model's simulations and measured values, as well as the average outside temperatures . It is possible to see that, for example in January, the average outside temperature was significantly higher in the measurements than in the model. This might be the reason why the average heating load is higher in the model, whereas the average refrigeration loads are slightly higher in reality.

On the model's outputs, the average Q_{MT} are higher for the months with higher temperatures, as excepted from the beginning. As seen in hourly, daily and weekly results before, the Q_{MT} values have more amplitude in the measurements than in the model. The measured values point for average Q_{MT} lower for April than for the three first months of the year, which was unexpected, since the temperature is higher in April.

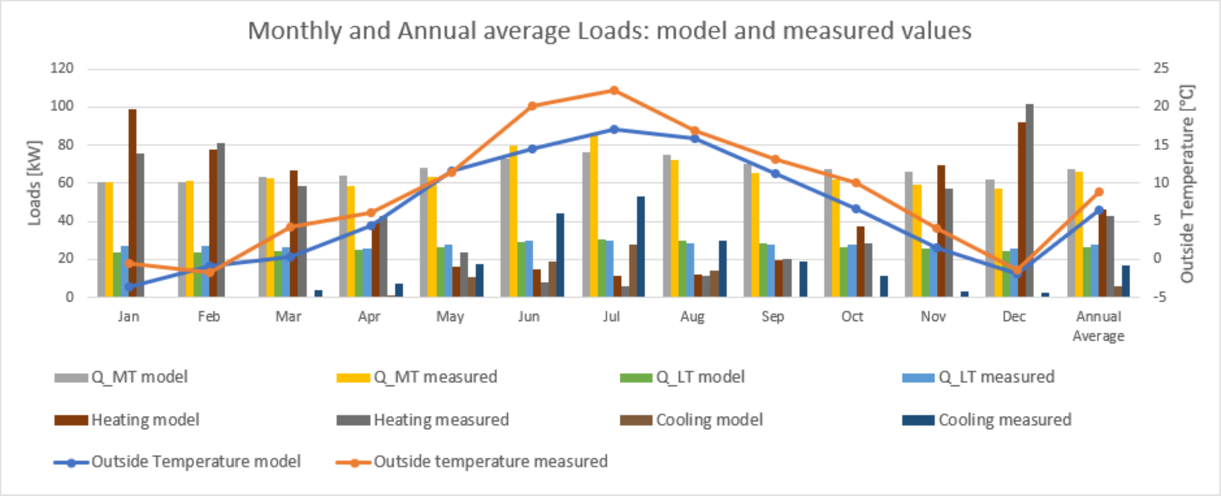


Figure 4.19: Monthly and Annual Loads: Comparison

The Q_{LT} values are very constant, both on the model and measurements and similar between them. These loads are clearly less dependent on the outside temperatures than the Q_{MT}. This is coherent with the results of other previously analysed studies, mentioned on the literature review.

The average heating loads have, naturally, an opposite tendency from what is verified for the Q_{MT}, since, along the months of the year, the higher the outside temperature, the lower the heating load. Most of the times, the outside temperatures are not the same on the model and reality, which makes it difficult to establish a direct comparison on the heating loads. However, for the months of May and December, when the average outside temperature is really close, the heating loads are higher in the measurements than in the model (about 46% and 11% higher for May and December respectively). This differences might be related with different control strategies, different outside relative humidity or different outside temperatures amplitudes along the month, since extremes can have a high influence on the thermal demands and, for example, for the month of December, the real temperatures are more extreme than on the model, even though the final average is similar.

In what concerns the cooling loads, the measured results are always higher than in the model. It is true that usually the outside temperatures for 2021 are higher, but even in May and December the cooling loads are significantly higher in the measurements (more than the double for May). It might be related with the control strategy applied by the hypermarket, probably in order to avoid the high loads verified in the model within a day, the cooling supply in reality is more constant, which demands more cooling supply. It can also be noticed by verifying the inside temperatures during the Summer, since the inside temperature according to the model is almost always at the maximum allowed level of 21°C, whereas the measured inside temperatures go around 20°C.

Table 4.4 summarizes the differences on the average annual loads between the field measurements and the model's results.

Table 4.4: Comparison between EnergyPlus' Model and measured annual average loads

Annual Average Loads	Outside Temperature [°C]	Q_{MT} [kW]	Q_{LT} [kW]	Heating [kW]	Cooling [kW]
Measurements	8.1	65.9	27.5	42.8	16.8
EnergyPlus' Model	6.5	67.3	26.5	46.2	6.1
Relative Difference	-24.6 %	+2.1%	-3.8%	+7.4%	-175.4%

On average, during the whole year, the outside temperature is 25% lower in the model, the Q_{MT} is 2% higher and the annual average Q_{LT} is 4%. Regarding the thermal loads, the heating is 7% higher in the model, whereas the average cooling load is -1.8 times lower in the model.

4.2.5 Final Energy Consumption

Based on the cabinets, cold rooms and space heating and cooling loads found on EnergyPlus, for the hypermarket, the final energy consumption was estimated with another simulation tool. That tool, developed in Python by Sotirios Thanasoulas, takes as inputs the building loads, estimated by EnergyPlus, in this case, and, by defining the refrigeration system of the hypermarket, gives as outputs its hourly energy consumption. As explained previously, this hypermarket's refrigeration system is a CO_2 trans-critical booster system that, with the right control, provides all the space heating and cooling required by the building.

In that sense, the energy consumption of the refrigeration system can be divided into 6 categories, as showed in figure 4.20: **MT** that stands for the cooling supplied to the MT display cabinets and cold rooms; **LT** is the cooling supplied to the LT cabinets and cold rooms; **Heating** stands for the energy consumed to face the space heating and hot water requirements; **Cooling** represents the energy used to cool down the building, **Gas cooler** stands for the energy used to cool down the refrigerant, in this case, the CO_2, after each refrigeration cycle. Finally **Ancillary** refers to the energy consumed by the fans, lights, defrosts and anti-sweaters from the cabinets and cold rooms. Regarding the field measurements, such detailed information was not provided. Therefore, figure 4.21 comprises the total electricity consumption for the refrigeration system for each month of the year.

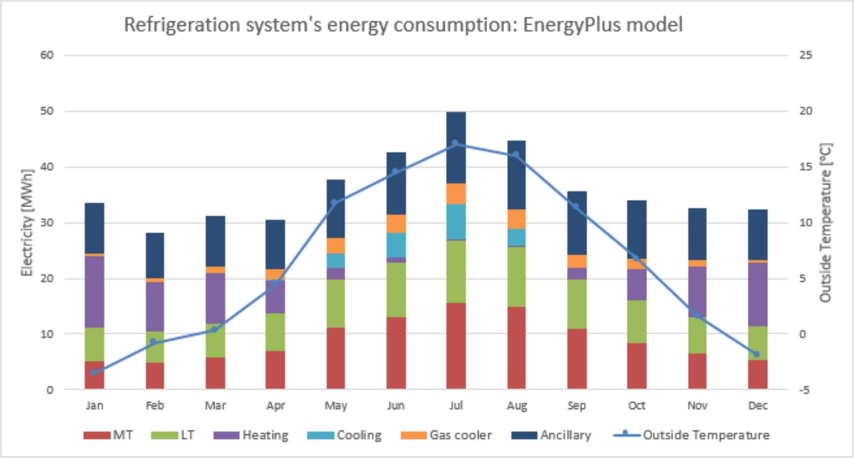


Figure 4.20: Monthly refrigeration system's energy consumption from EnergyPlus model

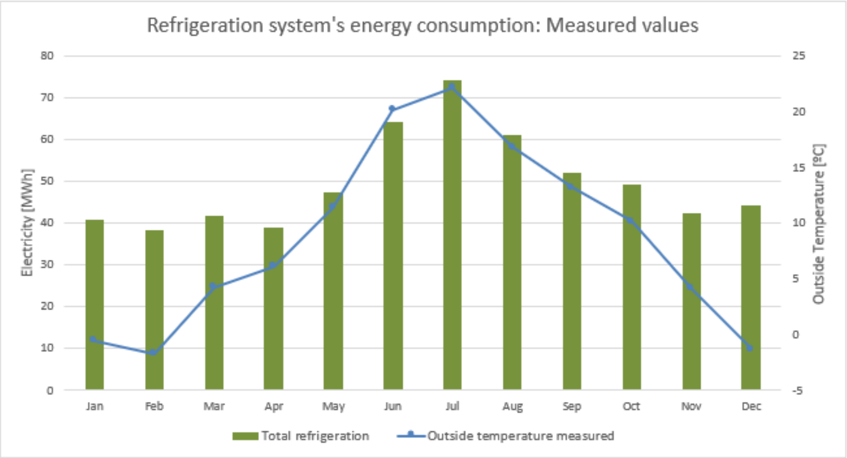


Figure 4.21: Monthly refrigeration system's energy consumption from field measurements

Figure 4.20 illustrates a higher electricity consumption for the MT, LT, Cooling and Gas cooler during the summer and the opposite for the Heating. The energy consumed by the ancillary component is mostly constant along the year. Alike what happened in the measurements for 2021, the model predicts the highest consumption for July, which is the warmest month. A similar tendency along the year can be verified. However, figure 4.21 shows that the total energy consumed by the refrigeration system was higher according to the field measurements, specially in the Summer. As seen before, the cooling loads were considerably higher in the measurements than in the model's predictions and, as the space cooling is totally provided by the refrigeration system, it can explain the higher consumption in the Summer.

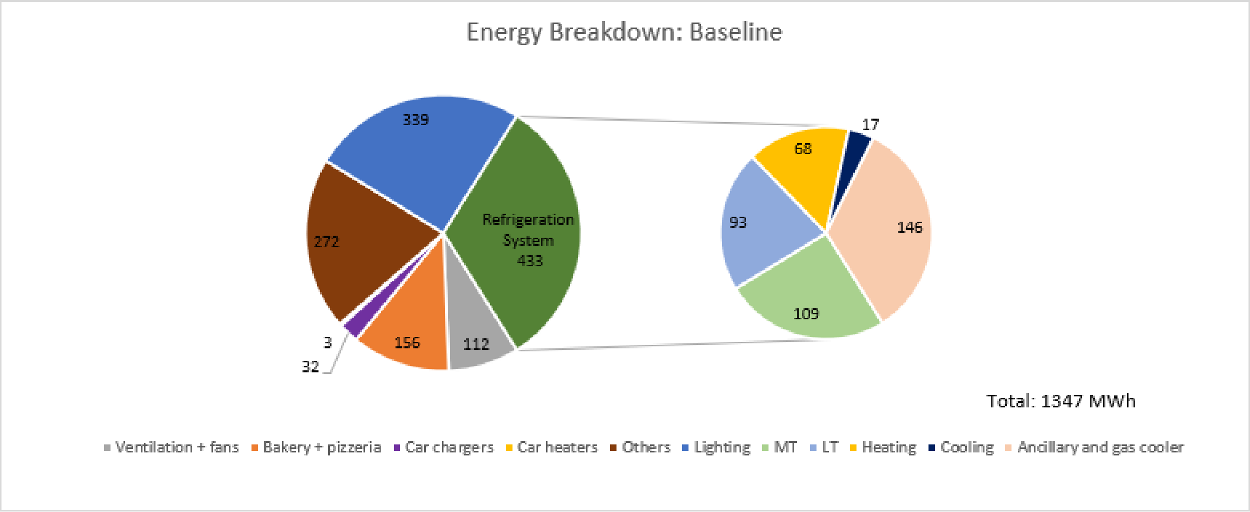


Figure 4.22: Energy Breakdown, EnergyPlus' model

Figure 4.22 shows the hypermarket's annual energy consumption by its different components, according to the EnergyPlus model. The model predicts a total energy consumption of 1347 MWh, which corresponds to 205 kWh/m^2 of conditioned floor area and an equivalent CO$_2$ emissions of 39 tons per year.

The biggest share of consumption is due to the refrigeration system, which, as explained previously, also supplies space cooling and heating and domestic hot water. Lighting also represents a considerable share: 25% of the total energy consumption. The ventilation and fans energy consumption is also an important part of the hypermarket's system. The value of 112 MWh was estimated by taking into account the mechanical ventilation requirements to ensure indoor environmental quality, estimated by EnergyPlus' model. The ventilation was assumed to consume 2.5 Watts/liter/second of the outdoor air flow entering the building and the energy consumed by the fans, which are responsible for the inside air circulation, was estimated equal 20% of the ventilation's consumption [38] .

Regarding the remaining electrical appliances, the bakery and the pizzeria's oven are responsible for 12% of the energy consumption and, according to the model, have a strong impact on the building's thermal loads. Car chargers and heaters were assumed to have the same consumption as verified in the measurements from 2021 and do not represent a significant share of the energy breakdown. The *others* component include several appliances, such as computers used at the offices and for e-commerce, cashiers, storage room's appliances, microwaves and fridges to be used by the staff, control machines, security cameras, etc. More details about these appliances' energy consumption can be found on the appendices.

4.3 Results' Analysis

The previous sections of the report showed some mismatches between the model and real measurements. Table 4.5 summarizes the differences on the building's loads, found on EnergyPlus and on the real measurements.

Table 4.5: Total annual MT, LT, space heating and cooling demands

Annual Demands [MWh]	Medium Temperature cabinets and cold rooms	Low Temperature cabinets and cold rooms	Heating	Cooling
Field Measurements	577	241	375	142
EnergyPlus' Model	589	232	405	54

The space cooling demand was significantly higher in the measurements, with a total of 141.8 MWh against a 53.6 MWh demand estimated by the model. Consequently, a more detailed analysis was carried out regarding this parameter. Through figure 4.23 it is possible to see that the outside temperature considered by the EnergyPlus weather file is considerably lower than the 2021's measurements, which surely affects the cooling demand of the hypermarket.

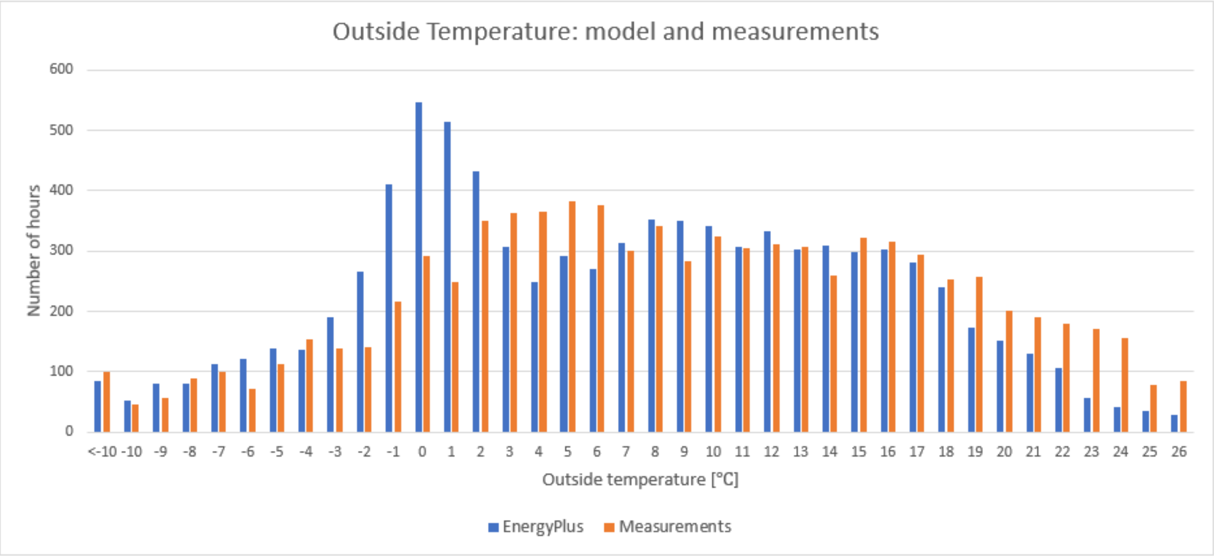


Figure 4.23: Outside temperatures estimated by EnergyPlus weather file and the real ones in 2021

Through figure 4.24 it is possible to observe that, although according to the model the AC is only required when the outside temperature is above 17℃, in 2021 there were occasions, with outdoor temperatures below zero degrees, where AC was demanded. This figure also reinforces the fact that in reality the AC demand is more constant, with a maximum required capacity of 100 kW, while on the model no limitation regarding this maximum was imposed and a load of 180 kW could be found. It can also be noticed that, according to the measurements, the same AC load can be found for different outside temperatures. This suggests that there are several other factors that influence the AC load apart from the outside temperature. Those factors should be the internal gains vary in different hours and days.

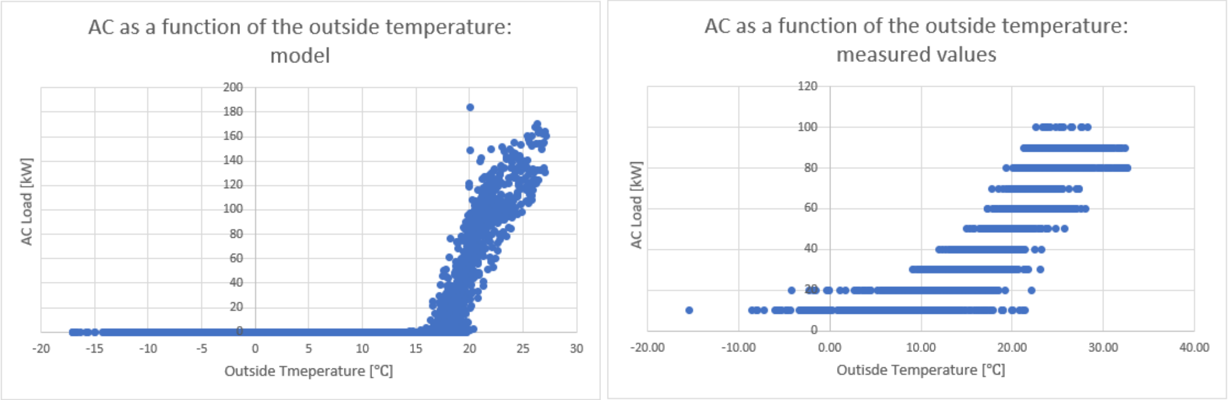


Figure 4.24: Cooling demands as a function of the outside temperature

It does not seem natural to find space cooling demand with such low outdoor temperatures. Some reasons behind those occurrences might be related with the functioning of the bakery, inside the hypermarket. In reality, the bakery is a closed place, whereas on the model it was assumed to be part of the display area, with no separation. Consequently, the internal loads created by the bakery and pizzeria equipment were dissipated to a much larger area, with a door to the outside, whereas in reality, those internal gains are very concentrated in a limited place, with no connection to the outdoor. Moreover, the hypermarket's HVAC system works in such a way that the inside air is recirculated. Different rooms may have different equipment to provide space heating or cooling, according to their specific needs. Therefore, although the bakery might have air extraction for the outdoor, it may have a requirement of cooling when having high indoor temperatures.

This process might help explaining the cooling demands for low outdoor temperatures and, additionally, not so high demands for the higher outside temperatures, once the heat generated by the bakery and pizzeria equipment is located in a particular place, instead of being dispersed to all the sales rooms. However, it may happen that some kind of control issue has occurred in the system, since a 10 kW cooling supply was verified for negative outdoor temperatures.

Based on a trend line created for the cooling demand of the model, as a function of the outside temperature and by assuming the temperatures of 2021, instead of the ones taken from the EnergyPlus weather file, the cooling demand would have a predicted value of 139 MWh, instead of 54 MWh. Details about this computation can be found in appendix 5.

Refrigeration system's energy consumption

According to the field measurements for 2021, the refrigeration system consumed 596 MWh of electricity. Whereas, according to the EnergyPlus and Python models, the electricity consumption by this system was predicted to be equal to 433 MWh, which corresponds to a performance gap of -27%.

At this point, it is important to recall that the refrigeration system on this hypermarket is responsible, not only to keep the chilled and frozen products on the desired temperatures, but also to provide space cooling, heating and domestic hot water to the store. In that sense, one of the reasons behind this considerably high performance gap is the difference in the outside temperatures between the EnergyPlus weather file and the real values verified for 2021. As seen before, these higher values for the outside temperatures in reality were responsible for an increase of 88 MWh of AC demand.

On the other hand, in the python model it was assumed that all the space heating and domestic hot water needs would be supplied by the refrigeration system. However, due to non optimal control strategies, electric heaters were used in the hypermarket to supply extra heating, with a total of 23 MWh of electricity consumption. By considering an average COP of 4 for the space heating supply by the refrigeration system, approximately, 6 MWh more of electricity would have been consumed by the system.

It is important to take into account that the outside temperature affects not only the space heating and cooling demand, but also the refrigeration's cooling demands, as well as the energy consumption for the gas cooler. In that sense, the graph from figure 4.25 intend to illustrate how each of these components is affected by the outside temperature on the EnergyPlus and Python model. It is possible to see that the power required for space heating purposes decreases as the outside temperature increases. The opposite occurs for the remaining four components, with a strong slope for the cooling with higher outside temperatures.

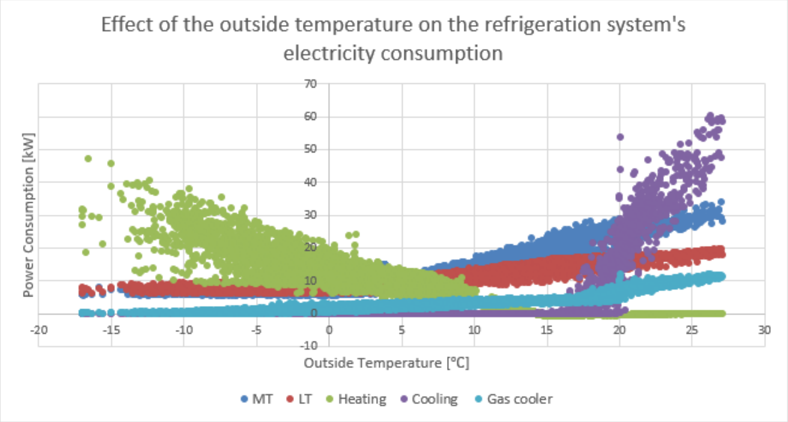


Figure 4.25: Influence of the outside temperature on the refrigeration system's electricity consumption by component

The graph shown on figure 4.26 groups all these 5 components together and a trend line was design, correlating the refrigeration system's total power consumption, excluding the ancillary, with the outside temperature. Based on its trend line, and using the data from figure 4.23 for the outside temperature verified for 2021, the model would assume a total electricity consumption of 358 MWh, instead of the verified 310 MWh for all the refrigeration system's components, except from the ancillary. Details about this estimation can be found on the appendix.

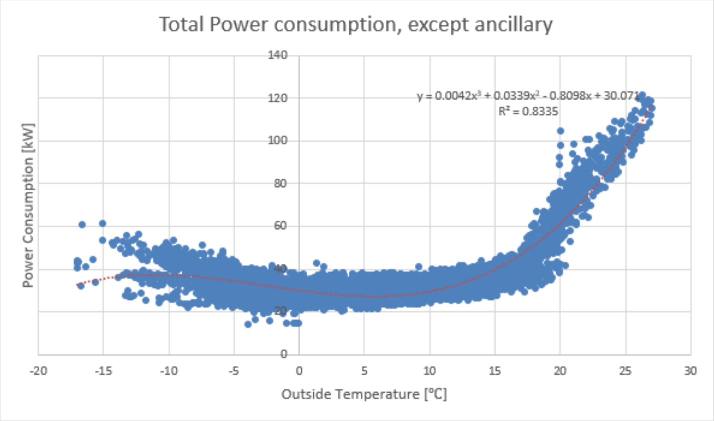


Figure 4.26: Influence of the outside temperature on the compressors' electricity consumption

In what concerns the electricity used by the cabinets' and cold rooms' ancillary components (fans, lights, defrost, anti-sweaters), the real consumption was about 60 MWh higher than it was assumed by the manufacturer.

Therefore, if the outside temperatures were the same and the ancillary and space heating components had worked optimally, the refrigeration system's energy consumption would have been equal to 481 MWh according to the model and about 546 MWh in reality (596+6-60). It would still represent a mismatch of almost 12% between the model and reality.

Total energy consumption

Figure 4.27 shows the total annual energy breakdown both according to the real measurements performed in 2021 and the EnergyPlus and Python models. It can be noticed that the total measured energy consumption was considerably higher on the real measurements, with a difference of 387 MWh.

As mentioned before, there is a significant difference regarding the refrigeration system, which had a 163 MWh higher consumption, compared to the model prediction. The differences found by the outside temperature's influence and the mismatch on the ancillary energy consumption enable to explain 98 MWh of this difference.

If the refrigeration system had worked optimally in 2021, the heating demands would have been entirely covered by the refrigeration system, which operates with a higher COP. Therefore, the 23 MWh of electricity consumed by the electric heaters, would have been minimized.

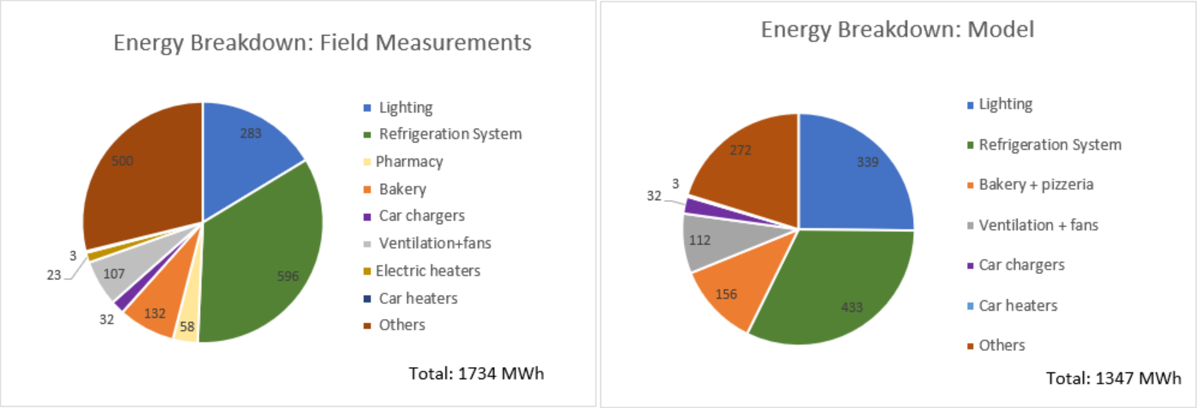


Figure 4.27: Energy Breakdown: Real measurements vs EnergyPlus model

It may look like the energy consumed by lighting is higher according to the model. It happens once the lighting represented by the real measurements' chart only refers to the sales area and the outside parking. The lights from other rooms, such as pharmacy, offices, storage areas, staff rooms are contemplated on the *Others* section.

This last section also includes the electricity used by the pizzeria's oven, cashiers, e-commerce computers, security cameras and the electrical appliances of all the other rooms in the building. No detailed information was provided by the hypermarket regarding these many appliances, which constitute a large share of the total energy consumption (about 28%). Therefore, a considerable amount of assumptions was made when modelling the store on EnergyPlus. The *Other* section on the right's chart includes cashiers, e-commerce computers, storage and pharmacy's equipment, offices appliances, microwaves, dishwashers and fridges for staff's areas, lift, revolving door, etc. Detailed information about the assumptions taken for each component can be found on the appendix.

In the end, apart from the mismatches regarding the refrigeration system and electric heaters, there is still a 266 MWh gap of electricity consumption between the model and field measurements, which corresponds to about 15% of the total measured energy consumption.

Chapter 5

CyberMart Model

The previous chapter illustrated the complexity of EnergyPlus software. Modelling ICA MAXI hypermarket on EnergyPlus required a large amount of information collection, knowledge about the hypermarket's systems and interactions between them and also some research, to be able to model several parameters.

CyberMart was proven to be a less detailed software and easier for any engineer to use. In this chapter, the same hypermarket will be modelled, but using CyberMart tool. In the end, the results from CyberMart and EnergyPlus' models will be compared.

5.1 Construction of the model in CyberMart

After having the model in EnergyPlus, the hypermarket was modelled in CyberMart software, which means that the same assumptions were taken. Moreover, the heat balance and refrigeration loads equations presented for EnergyPlus still apply on this new model.

The amount of input parameters required by this software was much smaller and easier to complete. "The intended users of the program are designers and engineers from different companies involved in the implementation of new systems and energy efficient measures in supermarkets." [1]

The first parameter to select was the weather file, in this case for Stockholm city. The program takes into account the hourly air temperature, relative humidity, wind speed and diffuse radiation on a horizontal surface, height of sun, solar azimuth and cloud cover fraction to run the simulation [1]. The respective window on CyberMart software can be seen in figure 4 in appendix 7.

CyberMart only allows to input a thermal zone in an unique floor. In that sense, a 4.5 meters' height building was modelled, with a floor area of 6570 m^2, in which the sales area is equal to 4860 m^2, as can be seen in figure 5 in appendix 7. The choice of the height was made so that the real volume of the hypermarket would be kept, even though CyberMart does not allow to model the two floors.

The Ventilation inputs (figure 6) were adapt to represent the same information as in EnergyPlus' model. The ventilation flow operates in the same way for all year long and constant during the day. The infiltration is considered to be equal to 0.3 air changes per hour constantly and a value of 5 was modelled near the entrance door.

CyberMart does not have the option to model schedules for occupancy or electrical appliances that work as a heat source inside the building. As such, average values from tables 1 and 4.2 were adapted to fill the information presented in figure 7.

The opening hours were modelled with the same information provided by ICA MAXI and also used in EnergyPlus, as can be found in figure 8.

Regarding the control temperature setpoints, CyberMart allows to input a single value for the temperature for open and close hours, both for the Winter and for the Summer, instead of an interval as happens in EnergyPlus software. In that sense, a value of 20ºC was chosen for all the time, as shown in figure 9. The maximum cooling and heating capacities were set at 400 kW, not to present a constraint in the system.

Even though CyberMart offers several options for modelling the refrigeration system, the option to model a trans-critical CO_2 booster system does not exist. Hence, a direct system was chosen, since it was found to be the most simple one to obtain the MT and LT loads of the cabinets and cold rooms. In what concerns the display cabinets, CyberMart offers a data set with many cabinets available to model, with data provided by the respective manufacturers. Whereas, the storage cold rooms require the user to input the dimensions and inside temperature. Subsequently, as illustrated in figure 11 from appendix 7, the MT and LT refrigeration capacities are calculated by the system. Needless to say that this modelling is considerably simpler than on EnergyPlus software.

5.2 Final Loads

In the end, similarly to what was done with EnergyPlus, the purpose was to find the Q_{MT}, Q_{LT}, heating and cooling loads of the system and, subsequently, input them on the Python's simulation tool, to better represent the new CO_2 trans-critical system with heat recovery of ICA MAXI.

Figure 5.1 shows the monthly and annual average loads, both according to the CyberMart's model and field measurements of 2021. Table 5.1 contains the annual average loads and the relative difference between the model and the field measurements, to help seeing these results clearly.

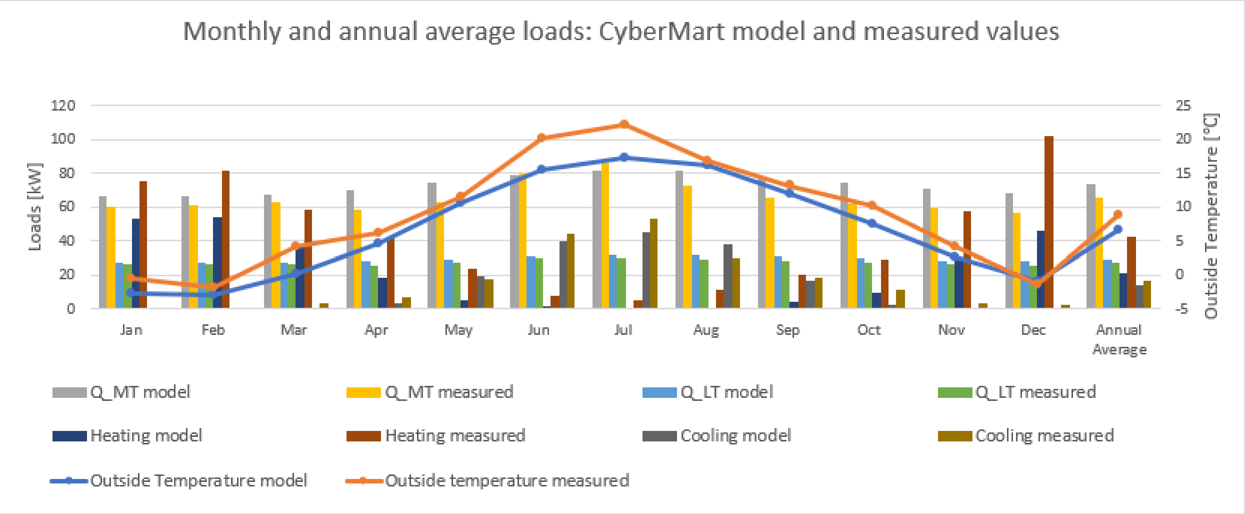


Figure 5.1: Monthly and Annual Loads: CyberMart's model and measured values

Table 5.1: Comparison between CyberMart's Model and measured annual average loads

Annual Average Loads	Outside Temperature [°C]	Q_{MT} [kW]	Q_{LT} [kW]	Heating [kW]	Cooling [kW]
Measurements	8.1	65.9	27.5	42.8	16.8
CyberMart' Model	6.7	73.4	29.4	21.6	13.9
Relative Difference	-20.9 %	+10.2%	+6.5%	-98.1%	-20.9%

An expected tendency can be seen for the refrigeration and thermal loads in the model. Alike what happened with EnergyPlus, the outside temperatures along the year are significantly lower than what was reflected by the filed measurements. Both the Q_{MT} and Q_{LT} are higher in the model than according to the measurements, with a difference of 10% and 7% respectively, which seems reasonable.

On the other hand, the heating and cooling loads differ considerably and are both lower in the model. This behaviour was expected regarding the cooling, taking into account the differences on the outside temperatures, but not on the heating loads, which are 98% lower in the model.

This gap can be related with the circumstance of the building in CyberMart just having a single thermal zone and the building envelope is probably more compact, (with a lower external wall surface) than on the real hypermarket. It might also happen than in reality the doors open more frequently, which increases the space heating needs in the system. Moreover, appliances as snow melters, car chargers and heaters and lighting on the parking were modelled as being inside the building, which does not corresponds to the reality, but CyberMart does not allow to model them outside, as in EnergyPlus. This creates extra internal loads in the system, which, due to the heat balance principle, used by CyberMart, decrease the heating demand of the building.

5.3 Final Energy Consumption

By following the same procedure used in EnergyPlus' model, the loads found in CyberMart were input in the same Python model, that describes the hypermarket's CO_2 trans-critical refrigeration system. Subsequently, the annual electricity consumed by the hypermarket's different systems was found.

Figure 5.2 describes the monthly energy consumed by each parameter on the refrigeration system. As expected, there is a higher consumption for the summer, where all the components, apart from the space heating and ancillary system, consume more electricity. By comparing figures 5.2 and 4.21, it is possible to see that, even though the tendency described by the model is similar to the one in the measurements, the total energy consumed by the refrigeration system is higher according to the measurements, in every month of the year, similarly to what was verified for the EnergyPlus' model.

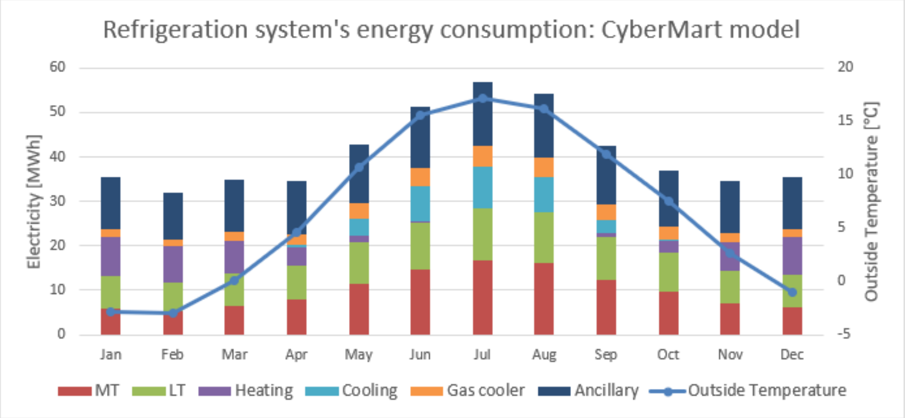


Figure 5.2: Refrigeration system's energy consumption from CyberMart's model

Figure 5.3 represents the energy breakdown of the hypermarket, considering CyberMart's model. The total energy consumption is 339 MWh (19.6%) lower than what was reflected by the field measurements. The refrigeration system is responsible for a 104 MWh gap, which might be related with the different loads found for the space heating and cooling and the non-optimal control management of the refrigeration system, in reality.

Alike what happened in EnergyPlus, many electrical appliances were not model, due to lack of available data. In this modeled "Electrical appliances" also includes the bakery and pizzeria equipment. The electricity consumed by the ventilation and air circulation (fans) is 17% lower than according to the field measurements. This gap might be related not only with the schedule of the Air Handling Unit, but also with the efficiency of fans and air volume flow.

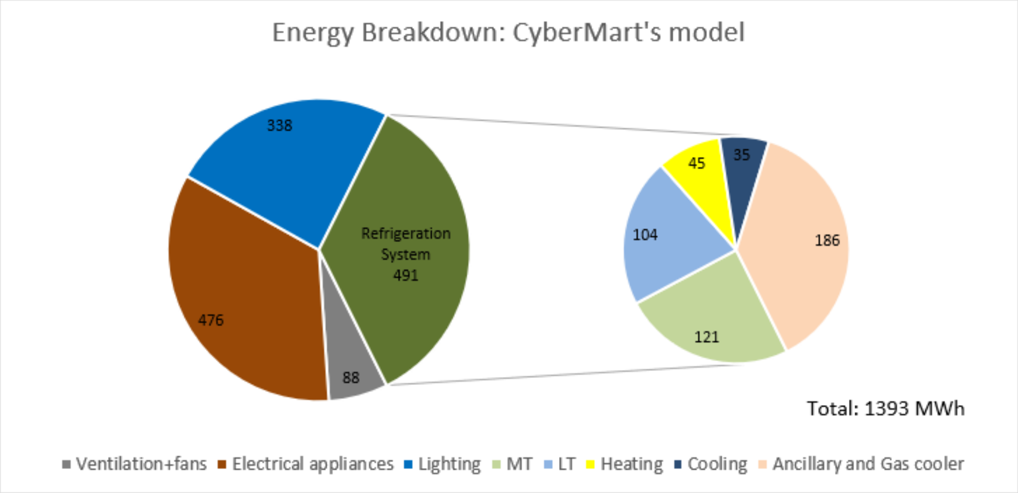


Figure 5.3: Energy Breakdown, CyberMart's model

5.4 Models' Comparison

After having analysed the hypermarket's energy measurements from 2021 and the results from EnergyPlus and CyberMart models connected to the Python tool, it is possible to proceed to a comparison between the three cases.

First of all, it is important to notice that the measured outside temperatures were considerably higher than the ones presented on both the softwares' libraries. EnergyPlus and CyberMart's weather files use an average of 30 years to predict the weather conditions and several factors, such as relative humidity, solar irradiation, wind speed, cloudiness, apart from the outside temperature, are taken into account in the performed simulations.

The outside temperature according to the field measurements had an average value of 8.8ºC, whereas EnergyPlus considered an average of 6.5ºC, very close to the values seen on CyberMart's weather file, with an average value of 6.7ºC.

This means that, on average, the measured temperatures are 33% higher than the values assumed by both the models, which reflects a considerable different that might influence the results showed as follows.

Figure 5.4 shows the display cabinets and cold rooms' cooling loads, both for MT and LT, as well as the space heating and cooling loads for ICA MAXI hypermarket, according to the field measurements, EnergyPlus and CyberMart's models.

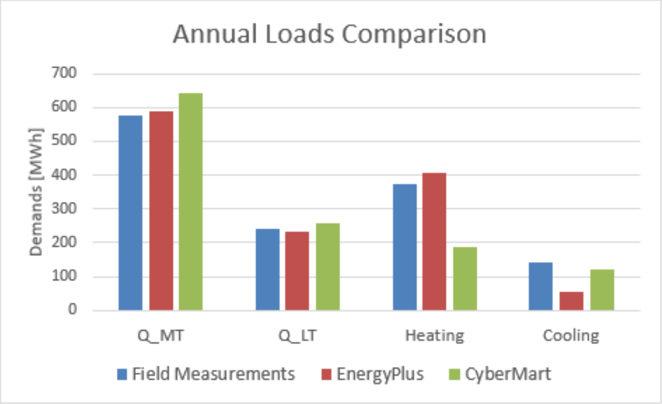


Figure 5.4: Field Measurements, EnergyPlus and CyberMart's Loads comparison

EnergyPlus' model is closer to the measurements in what concerns the energy demanded to keep the display and walk-in cabinets on the desired temperatures (Q_{MT} and Q_{LT}). Regarding the space heating and cooling demands, EnergyPlus shows to be more accurate, taking into account the differences in the outside temperatures experienced on the measurements and on the softwares' data bases. It can be noticed that the heating demands are higher in EnergyPlus, which is accurate with the lower outside temperatures. There is, although, a considerable difference in the cooling demands between the EnergyPlus and the field measurements, (some possible reasons were explored on the previous chapter). This gap is lower on CyberMart's model. On the other hand, CyberMart's model seems less accurate for the Heating demands, since it predicts a lower value than the one measured in 2021, even though it considers lower outside temperatures.

Figure 5.5 allows to compare the energy consumed by the different sub-systems and total of the hypermarket, according to the field measurements and EnergyPlus and CyberMart's model associated with the Python's tool.

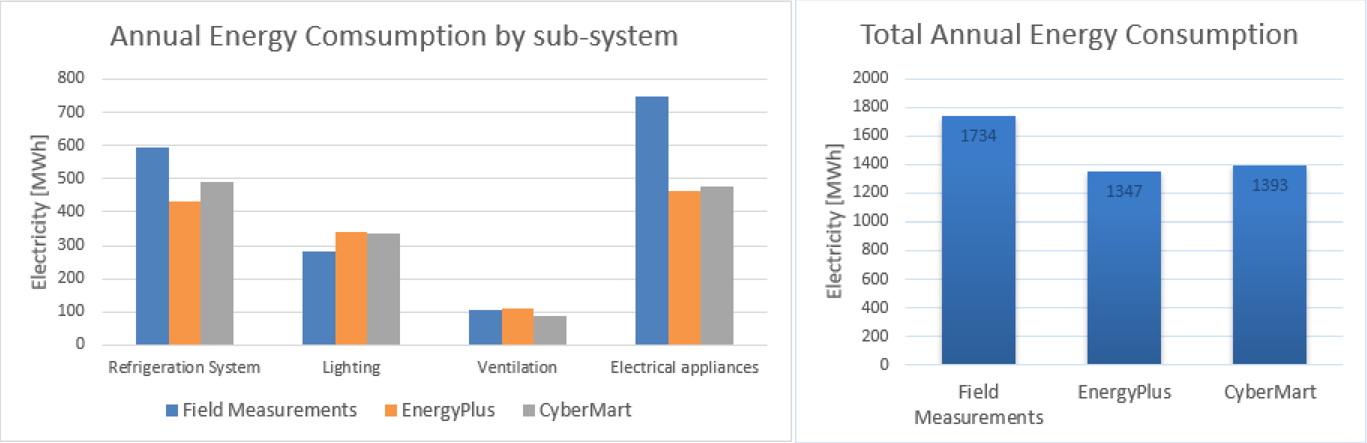


Figure 5.5: Energy consumption by sub-system according to the field measurements, EnergyPlus and CyberMart's models

CyberMart's model predicts a higher consumption for the refrigeration system than EnergyPlus, which is coherent with the loads presented in figure 5.4. In addition, the ancillary components consume more energy according to CyberMart than according to EnergyPlus, 151 and 122 MWh, respectively, against 173 MWh verified on the field measurements. On the one hand, CyberMart is closer to the measurements, but, on the other hand, the given value by the manufacturer for this parameter was around 115 MWh annually.

Regarding the lighting, same values were verified for both the models, as the exact same inputs were assumed, based on the Skanska's report from 2019 [34]. The lighting's energy consumption differs on the field measurements, once only the lighting for the sales area and parking is considered, whereas the lighting for the other rooms (pharmacy, bakery, offices, storage rooms...) are counted in "electrical appliances" section.

The energy consumed by the ventilation sub-system is very similar for the three cases. It can be seen that it is slightly lower according to the CyberMart's model. Notice that the "ventilation" sub-system consumes energy both for bringing the outdoor's air into the building, but also for recirculating the air inside the building.

As mentioned previously, there is a considerable uncertainty regarding the "Electrical appliances" presented in the hypermarket. While detailed data was given for the cabinets and cold rooms, lighting and oven, not much detail was given for the other electrical appliances used in the hypermarket. The initial assumptions, (described in the appendices) ended up by being low, compared to the measured consumption for 2021. Once the same assumptions were used on the two models, the energy consumption for these appliances is very similar for EnergyPlus and CyberMart. The slight difference is due to the schedules used in EnergyPlus for each modelled equipment, whereas CyberMart uses a hourly average value for all the appliances.

Both the models predicted a lower energy consumption for the hypermarket, compared to the real measurements. This was, somehow, expected since non-optimal management actions are expected to occur in reality, whereas the models assume that every sub-system works optimally. In this hypermarket, several irregularities in the control strategy were identified.

EnergyPlus' model predicts a 22% lower annual consumption, whereas CyberMart's value is 20% lower than the measured total annual consumption. In the end, CyberMart's model revealed a closer value from the field measurements, even though EnergyPlus' loads seemed to be more accurate.

Chapter 6

Different Scenarios in EnergyPlus

EnergyPlus model revealed to be the most accurate to predict the hypermarket's demands. It allows to input very detailed information and has shown to have a good potential on modelling the energy consumption in supermarkets. In that sense, different scenarios were created in EnergyPlus, by varying some parameters on the baseline model. This aims to better understand the model's behaviour and to identify energy efficiency measures that could be implemented in the hypermarket.

6.1 Scenarios' characteristics

Scenario 2: Constant Temperature Setpoints

The baseline scenario was constructed in such a way that the reality measured in ICA MAXI would be replicated, as much as possible. In that sense, the temperature setpoints in the model were modelled with the aim to reflect the indoor temperatures measured along 2021. At the beginning of the year, the indoor temperature could be as low as 17.3ºC, whereas from May onwards the indoor temperature would be most of the times at least 19.5ºC. Moreover, the maximum temperature would rarely be higher than 21ºC.

Scenario 2 was modelled in such a way that the indoor temperature would be always between 20 and 22ºC, as a common practice in several supermarkets' studies.

Scenario 3: Constant Temperature Setpoints, Lisbon weather

In scenario 3, all the parameters from scenario 2 are kept, except for the location. The hypermarket was simulated to be placed in Lisbon, where the climate is considerably different than in Stockholm. Probably, in reality, a hypermarket place in Lisbon would have a significantly different building's envelope, with lower insulation.

Nonetheless, this scenario's construction aims to analyse how the model reacts with different outdoor conditions and if the hypermarket's CO_2 booster refrigeration system with heat recovery would be efficient in a warmer country.

Scenario 4: Different Temperature setpoints for winter and summer

In scenario 4 the temperature setpoints were set differently in the Summer and the Winter. In that sense, from May to September, the indoor temperature was set to be between 20 and 24ºC, whereas for the rest of the year it must be between 18 and 22ºC. This choice was motivated by the idea of maximizing customers' comfort while achieving some heating or cooling savings in the system. During the Winter, customers are more likely to enter the hypermarket with a jacket, therefore it would be reasonable for the indoor temperature to be lower than during the summer.

Moreover, in this scenario, the allowed temperature interval is higher than on scenarios 2 and 3. All the other parameters are equal to the baseline and scenario 2.

Scenario 5: No cooling or heating at closing hours

Scenario 5 is equal to scenario 2, except for the fact that during the unoccupied hours there is no control on the inside temperature of the hypermarket. When there are no customers inside the store, there is no need to ensure thermal comfort. Moreover, considering the hypermarket's location, it is very unlikely to have such high temperatures inside that could interfere negatively on the selling products' quality.

This allows the heating and cooling supplies to work less hours per day, leading, hopefully, to energy savings. However, a higher power load is excepted to be required for the first hours of the hypermarket's operation.

Scenarios 6 and 7: Different infiltration rates

The parameter that varies in the model, with scenarios 6 and 7 is the infiltration rate through the building's envelope. Scenario 6 considers an infiltration rate of 0.1 l/m^{2}exterior surface, whereas scenario 7 uses a rate of 0.5 l/m^{2}exterior surface. Both scenarios use the same control strategy of scenario 2, in what concerns the indoor temperature. As a reminder, the baseline was modelled with an infiltration rate of 0.3 l/m^{2}exterior surface.

These scenarios were constructed in order to perform a parametric analysis over the infiltration rate parameter and understand how such variable can influence the energy consumption of the hypermarket, according to the EnergyPlus' model. However, decrease the infiltration rate by 0.1 l/m^{2}exterior surface, as scenario 6 represents is, somehow, unrealistic.

Table 6.1: Summary of the different scenarios in EnergyPlus

Scenario	Temperature Setpoints	Inflitration Rate	Location
Baseline	17.5-21ºC depending on the time of the day and year	0.3 l/m^2 exterior surface	Stockholm
Scenario 2	20-22ºC always	0.3 l/m^2 exterior surface	Stockholm
Scenario 3	20-22ºC always	0.3 l/m^2 exterior surface	Lisbon
Scenario 4	20-24ºC from May to September 18-22ºC for the rest of the year	0.3 l/m^2 exterior surface	Stockholm
Scenario 5	20-22ºC from 7 am to 10 pm	0.3 l/m^2 exterior surface	Stockholm
Scenario 6	20-22ºC always	0.1 l/m^2 exterior surface	Stockholm
Scenario 7	20-22ºC always	0.5 l/m^2 exterior surface	Stockholm

6.2 Results of the different scenarios

Through figure 6.1 it is possible to see that the MT and the LT cabinets and cold rooms would consume more electricity if the exact same hypermarket would be placed in Lisbon, instead of Stockholm. The heating, cooling and gas cooler consumptions seem to have an expected and natural variation along the year, considering the differences on the average outside temperatures. The electricity consumption due to ancillary components do not change considerably with the outside temperature. In overall, it is possible to observe that the model reacts accurately to different climate conditions.

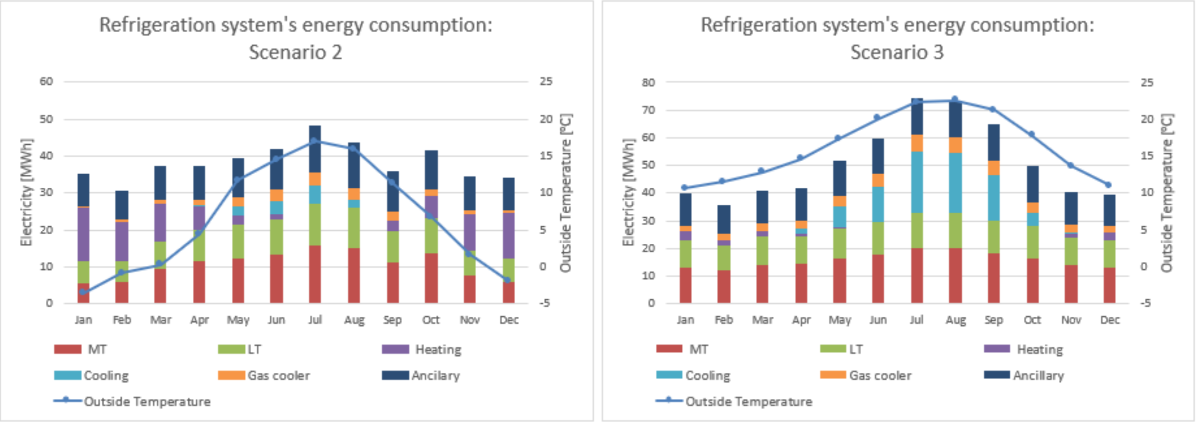


Figure 6.1: Refrigeration system's monthly electricity consumption: scenarios 2 and 3

Compared to the baseline model, scenario 2 considered, generally, higher temperature setpoints. That resulted on a 5 MWh increase on the Refrigeration system's energy consumption, as can be seen by comparing figures 4.22 and 6.2. As expected, the energy consumed with space heating and hot water is higher in scenario 2 than on the baseline and the opposite happens for the space cooling. Nonetheless, this change on the temperatures setpoints resulted on a very low difference on the final annual energy consumption.

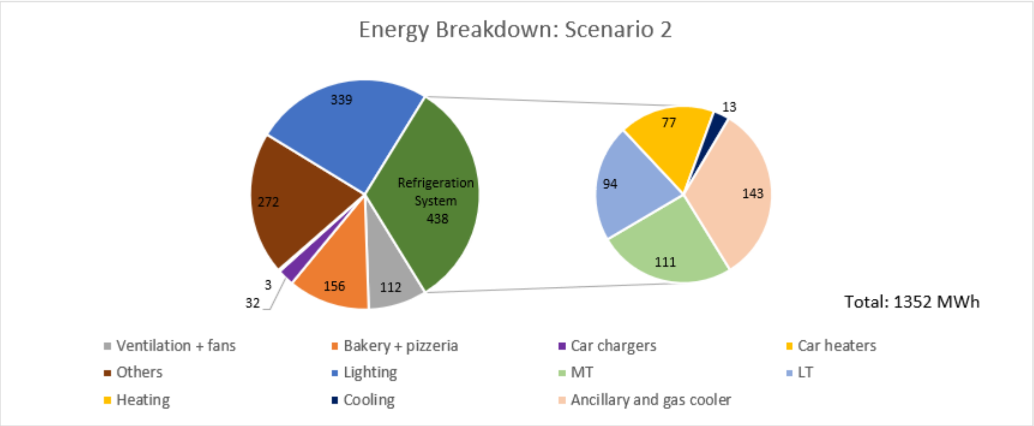


Figure 6.2: Energy Breakdown of scenario 2

With figure 6.3 it is possible to identify clearly the influence of the outdoor conditions on the refrigeration system's energy consumption. Not only the energy consumption by the space heating and cooling, but also from the MT and LT cabinets and cold rooms and the gas cooler, changed significantly.

Car heaters and snow melters were not considered in the model for Lisbon's location, which slightly affects other components on the energy breakdown of the system.

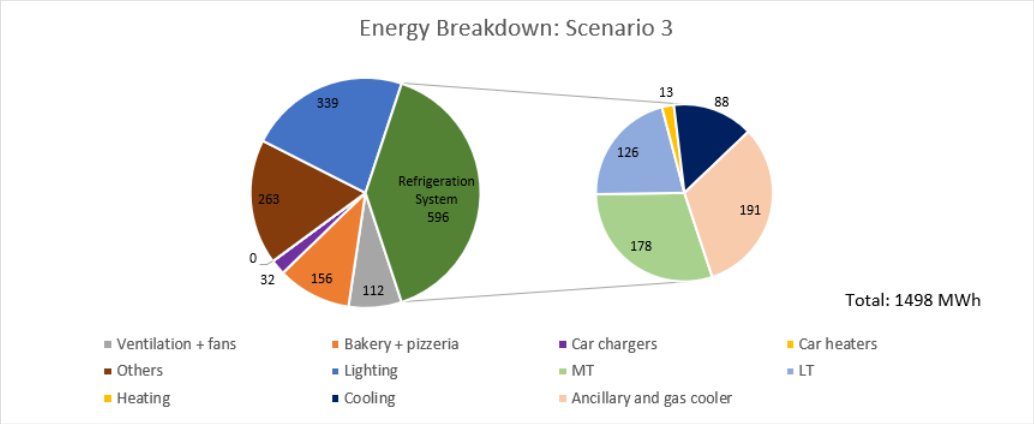


Figure 6.3: Energy Breakdown of scenario 3

Figures 6.4-6.6 show that both the approaches of changing the temperature setpoints according to the customer's thermal comfort needs, in a more effective way, can actually lead to a reduction on the final energy consumption of the hypermarket. It is curious to notice that scenarios 4 and 5 have a very similar energy consumption's behaviour. However, scenario 5 may require a heating supply above 150 kW during the first opening hours, due to a sometimes drastic variation on the temperature setpoints. This high peaks can lead to an increase on the electricity cost, if an additional cost for peak demands is charged. Meanwhile, in scenario 2, with constant temperature setpoints within the same day, the maximum heating requirement would be equal to 48 kW. Therefore, scenario 5 would, on the one hand, allow to energy savings, and, on the other hand, require a 3 times larger heating installation on the hypermarket.

Scenario 4 would not cause a similar issue, but instead alleviate the heating and cooling systems' stress, since a lower maximum capacity would be required in both the cases. This is natural, taking into account that the minimum inside temperature would be 18ºC in the Winter and 24ºC in the Summer.

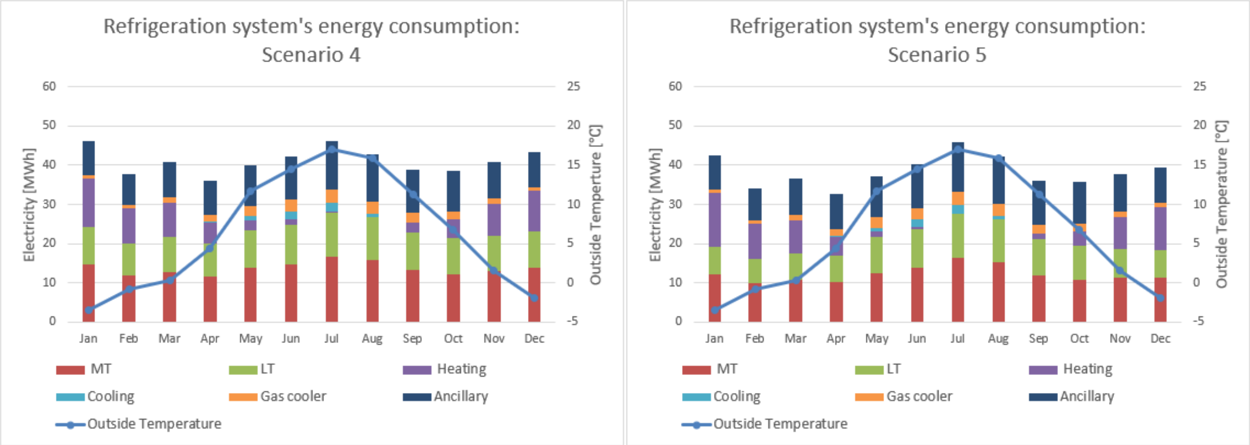


Figure 6.4: Refrigeration system's monthly electricity consumption: scenarios 4 and 5

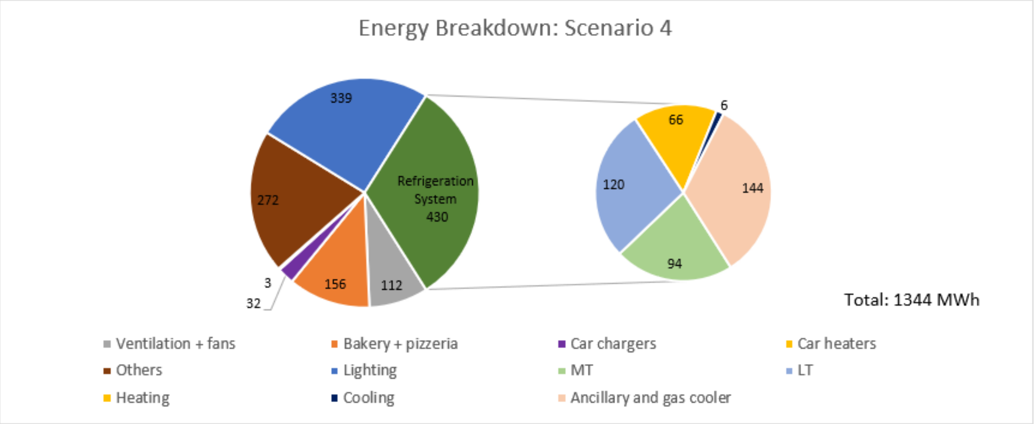


Figure 6.5: Energy Breakdown of scenario 4

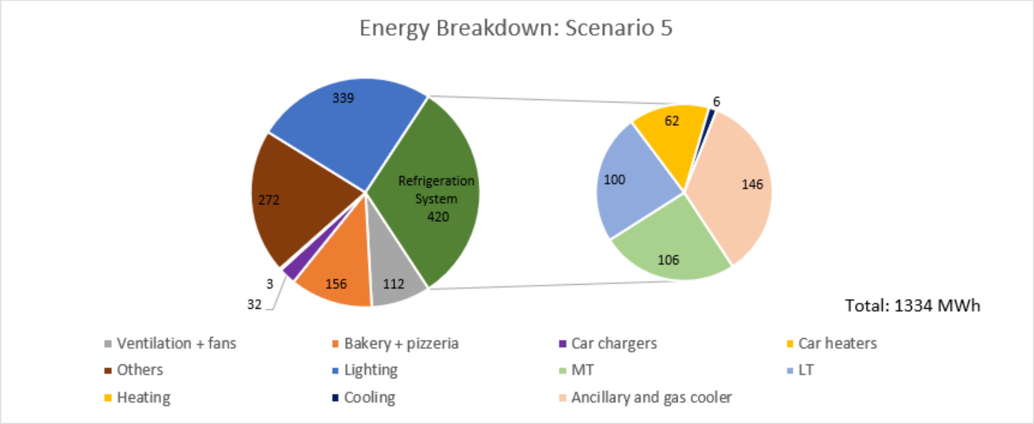


Figure 6.6: Energy Breakdown of scenario 5

Scenarios 6 and 7 were created to simulate how the system would react to different infiltration rates of outdoor air inside the building. The main difference between both the scenarios and scenario 2 is the energy consumed to supply heating. While scenario 6 leads to a 22 MWh energy saving, scenario 7 would result on an 32 MWh of energy consumed due to space heating purposes. It is, at the same time, curious to notice that changing the infiltration rate on the range of 0.1-0.5 l/m^{2}exterior surface would barely affect the space cooling requirements. This explains the reason why these scenarios' profiles are so different for the Winter and similar in the Summer months.

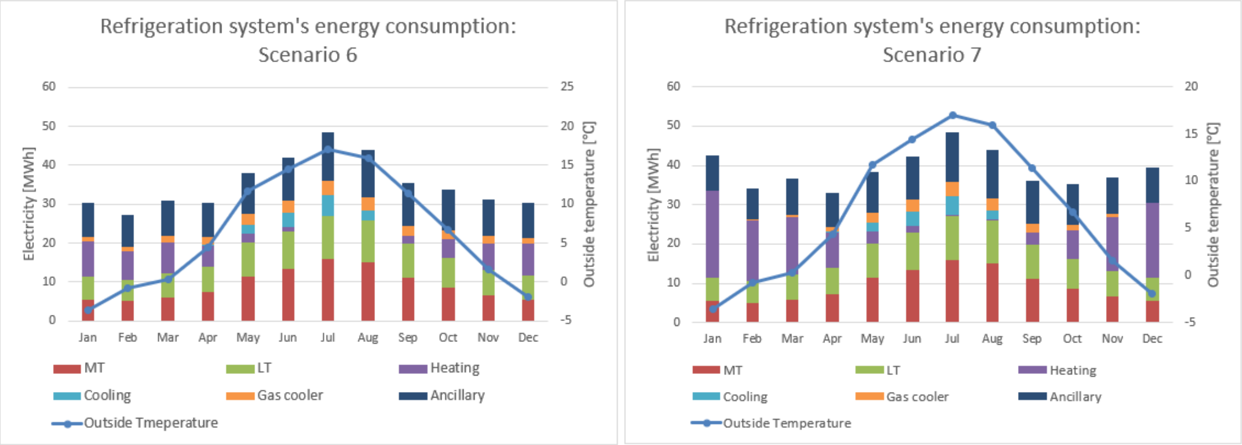


Figure 6.7: Refrigeration system's monthly electricity consumption: scenarios 6 and 7

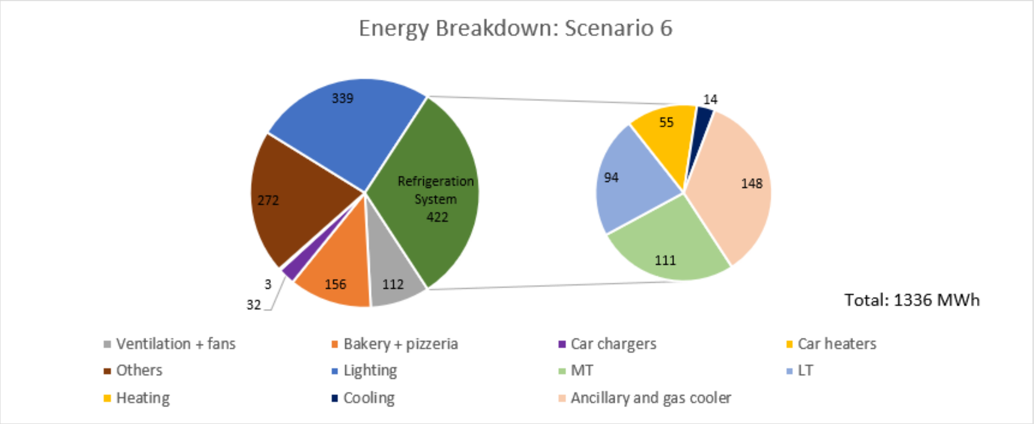


Figure 6.8: Energy Breakdown of scenario 6

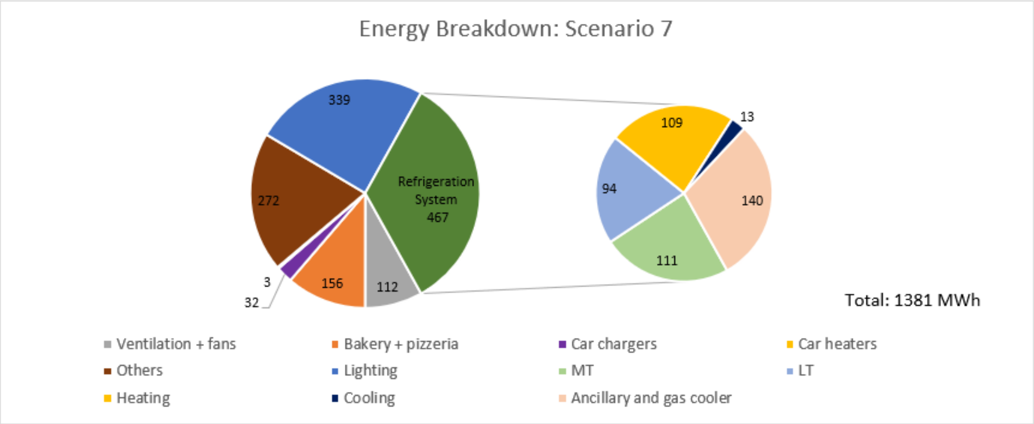


Figure 6.9: Energy Breakdown of scenario 7

Table 6.2 summarizes the total annual energy consumption of each scenario and compares their difference with scenario 2. Special attention is given to the refrigeration system, considering that the presented scenarios vary specially on this system's energy consumption.

Table 6.2: Annual Energy Consumption of the different scenarios

Scenario	**Refrigeration System [MWh]**	**Difference from Scenario 2 [%]**	**Total [MWh]**	**Difference from Scenario 2 [%]**
Baseline	433	-1.1	1347	-0.4
Scenario 2	438	-	1352	-
Scenario 3	596	+36	1498	+10.8
Scenario 4	430	-1.8	1344	-0.6
Scenario 5	420	-4.1	1334	-1.3
Scenario 6	422	-3.7	1336	-1.2
Scenario 7	467	+6.6	1381	+2.1

Scenario 3 is the worst case scenario, which suggests that the CO_2 booster system with heat recovery used in this hypermarket, would not be optimal in a warmer place, like Lisbon. This finding goes in the same direction of several studies found in the literature.

Scenario 5, on the other hand, is the one which lead to the less energy consumption on the hypermarket's annual operation. This allows to conclude that having a better adjustment of the indoor temperatures, according to the hypermarket's real needs, results on annual energy savings. However, scenario 5 would require high heating and cooling installed capacities, since there would be a great power demand at 7 am.

Although the total energy savings would be less, scenario 4 would not lead to this issue of more power needed in the early morning.

Even though not great energy savings would be achieved with the proposed adjustments, these scenarios and comparisons with the field measurements performed in 2021 show how efficient this hypermarket can be by using its refrigeration trans-critical CO_2 booster system on an optimal way.

Chapter 7

Conclusions

7.1 Field Measurements

The main goal of this master thesis was to compare the energy consumption of a hypermarket from field measurements performed in 2021 with the predictions from building's simulation softwares. And, consequently, to access the accuracy of the models constructed on each software and understand their relevance in such studies.

This hypermarket integrates a state of the art refrigeration trans-critical CO_2 booster system, which has been identified to be very efficient for cold climate countries, by several research projects. Moreover, KTH's Energy Department has been acquiring knowledge and collecting information about the hypermarket's sub-systems, through partnerships with ICA company.

In spite of the enormous effort to provide accurate hourly measurements in what concerns the energy consumed by this hypermarket in 2021, detailed information regarding the energy usage by several components was missing. Additionally, some irregularities were verified concerning the energy consumed by the lights, fans, defrosts and anti-sweaters in the refrigeration display cabinets and, although all the space heating and hot water supply was supposed to be ensured by the heat recovery from the refrigeration system, electric heaters were used in 2021.

In the end, the origin of 28% of the electricity consumed in 2021 was unable to be identified. This represents a large share of the energy breakdown of the system and by lacking this information, it becomes very difficult to find reasons to justify the consumption and model the system on the simulation tools. However, several studies in the literature found the same issue, which means that more efforts shall be taken by the supermarkets' energy managers, in order to better understand the different sub-systems and possibly minimize their energy consumption.

7.2 Selected softwares and their utility

Out of the several building's simulation softwares available to access the energy consumption in buildings, EnergyPlus and CyberMart were the selected ones to model this hypermarket, due to their availability, transparency and accuracy.

7.2.1 EnergyPlus

EnergyPlus software ended up by being the most used tool of this research project. KTH's Energy Department has been using CyberMart, in other studies regarding the energy consumption in supermarkets. However, no supermarkets' studies had ever been performed there with EnergyPlus and as this software has been shown to be useful and accurate to perform such studies, a great effort was put on this master thesis to better understand the software and being able to model such a hypermarket with all its subsystems there.

One review has described EnergyPlus as "without any doubt a very complex and sophisticated tool for building energy modelling. It is a tool that can be only recommended for expert users or for modellers willing to explore more advanced modelling tools" (Low carbon Cymru, 2011) [24]. Modelling ICA MAXI hypermarket in EnergyPlus was, indeed, revealed to be very challenging. Many parameters had to be input on the model and for some occasions, knowledge on the supermarket's systems was lacking, to model them accurately on EnergyPlus. Therefore, modelling this hypermarket on EnergyPlus required months of researching, many trials and a considerable support from my supervisor, Sotirios Thanasoulas. It also required taking many assumptions regarding a hypermarket's typical electrical appliances and the respective power consumption and used hours.

As described previously, EnergyPlus was used to predict the building's loads and, subquentely, a Python tool developed by Sotirios Thanasoulas was used to predict the hourly energy consumed by the refrigeration system. This tool has been developed on Thanasoulas' PhD at KTH and, due to his proximity and knowledge about this ICA MAXI's refrigeration system, is probably more reliable than the trans-critical CO_2 booster system' designing options offered by EnergyPlus. However, there are plenty of options in EnergyPlus to design such systems.

In the end, modelling the hypermarket on EnergyPlus revealed some irregularities that are happening on the real hypermarket. It also enabled to show the potential energy savings, by using an optimal control of the refrigeration system, associated to the HVAC system. The COPs predicted by the software for the refrigeration cabinets' cooling supply were way higher than the ones verified on the measurements.

The scenarios created showed that changing the indoor temperatures' control strategy might lead to energy savings and it consists of a measure that can be taken without any monetary investment. However, it was not proven to provide a significant saving. This finding suggests that the major efforts to be taken in order to increase the energy efficiency of the hypermarket shall rely on operating the existing sub-systems more efficiently.

7.2.2 CyberMart

CyberMart software was created by Jaime Arias during his PhD at KTH's Energy Department and was exclusively developed to access supermarket's energy consumption. Contrarily to what was experienced while using EnergyPlus, CyberMart was easy to understand and to work with. It was, actually, designed for any engineer to be able to work with and have a quick overview of a supermarket's system, described by each of the sub-systems. It has a user-friendly interface, showing useful graphs for different parameters.

After constructing the model in EnergyPlus and having taken the assumptions regarding several parameters, one day was enough to model the hypermarket in CyberMart. The disadvantages were being unable to test as many parameters as in EnergyPlus and the lack of possibility to design a trans-critical CO_2 booster system, which represents the state of the art of refrigeration systems of supermarkets in cold climate's countries.

7.3 Final Results' Analysis

According to the field measurements, the hypermarket consumed 264 kWh/m^2 in 2021. This value is in accordance with the values reported on the studies that can be found on the literature review chapter's. It is below the main values found for other studies mentioned there, but those studies were mainly for smaller supermarkets and, as also mentioned on the literature, there is a tendency to decrease the specific energy consumption with the increase of the supermarket's total area.

EnergyPlus' model predicted an annual consumption of 205 kWh/m^2, which is significantly lower than the measured one. Three main causes were concluded to be responsible for this performance gap: **difference in outdoor temperature**; **non-optimal control strategies**; **lack of information regarding the electrical appliances** used in the hypermarket. The first reason was assumed to be responsible for a difference of 48 MWh on the annual energy consumption (section 4.4). The second reasons lead to an increase of about 120 MWh, due to the high consumption on the refrigeration cabinets, non concerning the compressor consumption, the use of electric heaters and the lower COP achieved by the refrigeration system. The third reason was assumed to be responsible for a 219 MWh gap between the measured values and the model.

This analysis allows to conclude that rising temperatures can actually affect the buildings' energy consumption. Efforts should be made to drive the refrigeration systems' operations to their optimal levels, since it was revealed to lead to considerable energy savings. In addition, more detailed measurements shall be performed, aiming to identify more feasible energy efficiency measurements, using this kind of simulation tools.

CyberMart's model, in spite of being way less detailed than the EnergyPlus' one, led to a final annual energy consumption prediction between the value found on EnergyPlus and by the field measurements. This software showed a good potential to help understanding the hot spots of energy consumption of a supermarket, in a fast and easier way.

Taking into account that for an industry that consumes less than 2000 MWh of electricity per year in Sweden, the price of electricity is 6.15 euro cent per kWh [39] . In that sense, the annual electricity expense of ICA MAXI in 2021 was approximately equal to 1,120,000 swedish krona [40]. By managing the refrigeration system with heat recovery optimally, a saving of around 77.6 thousands of swedish krona annually can be achieved.

7.4 Limitations

As explained previously, many assumptions had to be taken while modelling the hypermarket on the simulation tools. Unfortunately, and contrarily to what was expected while starting this project, it was not possible to perform a field visit to the hypermarket in a useful time. This visit would have the aim to better understand the hypermarket's sub-systems and respective functioning and also identify some irregularities.

7.5 Future Work

Regarding supermarkets' energy consumption's research, this project allowed to identify several steps that may be taken in the future. EnergyPlus software was widely explored, in the IDF file, which might be useful for future researches at KTH's Energy Department. Unfortunately, it was not possible to successfully work with user-friendly interfaces to be associated to EnergyPlus, during the modelling development of the current project. However, an interface software, OpenStudio, can be connected to EnergyPlus and help designing the several sub-systems of a supermarket and better visualizing the results. Contrarily to other software that must be paid or do not allow to model a full refrigeration system, OpenStudio does not rise up such issues.

In that sense, this alternative of using OpenStudio as the user-friendly interface associated to EnergyPlus might save a large amount of hours modelling a supermarket in EnergyPlus, while keeping the same level of details. And, therefore, allowing more studies to be performed, by exploring different supermarkets and acquire knowledge about good practices that can potentially be implemented to larger scales.

Regarding CyberMart, it would be interesting to be able to model a trans-critical CO_2 refrigeration system and probably more than one thermal zone and the option to model external electrical appliances. It might allow to obtain more accurate results, while keeping the simplicity of the software.

It would also be interesting to re-define the weather files, in order to further study the potential of climate change to influence the energy consumption in supermarkets. Adjustments on the equipment's capacities may be required to respond to the future needs.

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Appendix

[1] Plug-in Cabinets' Power Consumption

According to the survey [41], the average energy consumption of a MT plug-in cabinet is equal to 6000 kWh/m^3 year, whereas for a LT plug-in cabinet, this value reaches 8000 kWh/m^3 year.

It was assumed that each MT plug-in cabinet has 300 liters of capacity and each LT plug-in cabinet has 200 liters.

As mentioned before, there are 12 MT and 6 LT plug-in cabinets in the hypermarket. Thus, the total annual energy consumption for the MT plug in cabinets is equal to:

$$12 \times 6000 \times 0.3 = 21600 \text{ kWh}$$

And the total annual energy consumption for the LT cabinets is equal to:

$$6 \times 8000 \times 0.2 = 9600 \text{ kWh}$$

The total average power consumption for the plug-in cabinets was estimated to be equal to: (total energy consumption, divided by the total number of hours in a year.)

$$\tfrac{21600+9600}{8760} = 3.6 \text{ kW}$$

Due to a large degree of uncertainty connected to this estimation, in the model, a value of 4 kW was input.

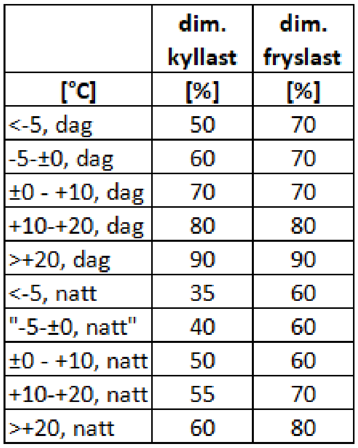
[2] Electrical equipment's electricity consumption

Table 1: Input values for the electric equipment energy consumption

Equipment	**Thermal Zone**	**Power [KW]**	**Functioning hours per day (approx)**
Bakery	DisplayArea	55.5	6.5
Oven		13.4	5
Plug-in cabinets		4	24
Revolving door		7.3	15
Lift		1	15
Cashiers		5	15
Mantainance		3	9
Pharmacy		5.1	15
e-commerce PCs		2.35	15
Security cameras		3	24
Office printers, computers	Offices	1	8
Microwaves		0.28	15
Dishwashers		0.36	15
Domestic fridge		0.125	24
Backroom machines	BackRoom	4	15
Control equipment	MachineryRoom	8.3	15
Car chargers	Outside	5.85	15
Car heaters		0.62	15
Snow Melters		1.64	15

Cameras: [42]
Microwaves: [43]
Control systems: [5]
Computers: [44]

[3] Restocking Schedule

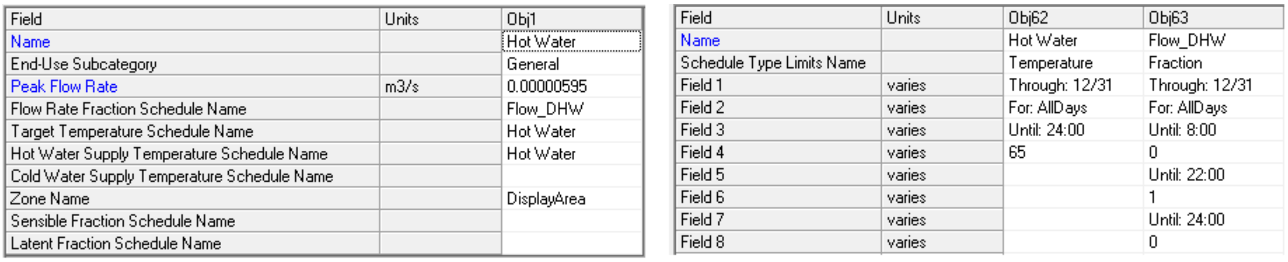


	dim. kyllast	dim. fryslast
[°C]	[%]	[%]
<-5, dag	50	70
-5-±0, dag	60	70
±0 - +10, dag	70	70
+10-+20, dag	80	80
>+20, dag	90	90
<-5, natt	35	60
"-5-±0, natt"	40	60
±0 - +10, natt	50	60
+10-+20, natt	55	70
>+20, natt	60	80

Figure 1: Inputs for Restocking Schedule

[4] Inputs for the Domestic Hot Water

Initially, it was assumed that the hot water consumption would be around 300 liters per day, at a temperature equal to 65ºC. Due to lack of information regarding this parameter, a constant flow was assumed, during opening hours, as represented on figure 2, with a fraction schedule of 1 from 8 am to 10 pm and 0 otherwise. The peak flow input in the model, also shown on figure 2, was calculated as 300 liters divided by 14 hours, which is equal to, approximately, 0.00000595 m^3/s.



Field	Units	Obj1
Name		Hot Water
End-Use Subcategory		General
Peak Flow Rate	m3/s	0.00000595
Flow Rate Fraction Schedule Name		Flow_DHW
Target Temperature Schedule Name		Hot Water
Hot Water Supply Temperature Schedule Name		Hot Water
Cold Water Supply Temperature Schedule Name		
Zone Name		DisplayArea
Sensible Fraction Schedule Name		
Latent Fraction Schedule Name		

Field	Units	Obj62	Obj63
Name		Hot Water	Flow_DHW
Schedule Type Limits Name		Temperature	Fraction
Field 1	varies	Through: 12/31	Through: 12/31
Field 2	varies	For: AllDays	For: AllDays
Field 3	varies	Until: 24:00	Until: 8:00
Field 4	varies	65	0
Field 5	varies		Until: 22:00
Field 6	varies		1
Field 7	varies		Until: 24:00
Field 8	varies		0

Figure 2: Inputs for DWH

[5] Estimation of the AC demand for the model with the measured temperatures in 2021

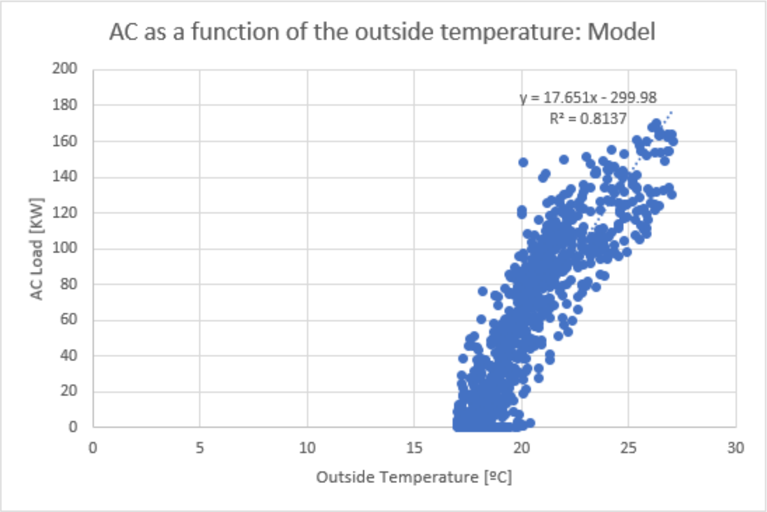


Figure 3: AC as a function of the outside temperature

The linear regression presented in figure 3 and the number of hours of a certain outside temperature presented in figure 4.23 enable to estimate the cooling needs for a situation in which the outdoor temperatures of the model would be equal to the ones measured for 2021.

According to the model, the cooling is only demanded for outdoor temperatures above 17ºC, that is why the linear regression only represents those cases. Let us call the equation $y = 17.651x - 299.98$ as f. Then, the total cooling needs estimated by the model with the current outside temperatures of the used weather file would be given by:

$$AC_{demand} = \sum_{x=17}^{32} xi.ni.f \tag{.0.1}$$

Where xi is the outside temperature (between 17 and 32ºC) and ni is the number of hours at the year in which temperature xi has occurred, according to the used weather file.

According to the above expression, the AC demand predicted by the model would have been 61.4 MWh, which is above the actually prediction of 53.6 MWh. In fact the square R of this linear regression is considerably below 1, which means that function f does not represent the reality very precisely, but is still a reasonable approximation. A factor of 0.87 (53.6 divided by 61.4) was used to correct the value of the AC demand predicted by this linear regression as a function of the annual outside temperature.

Hence, the expression presented above, corrected by the factor of 0.87, was used to predict the AC demand resulted from the model if the hourly outside temperature bins registered for 2021 would have been used in the weather file. A value of 139 MWh was obtained.

[6] Estimation of the AC power consumption for the EnergyPlus model with the measured temperatures from 2021

The cubic regression presented in figure 4.26 and the number of hours of a certain outside temperature presented in figure 4.23 enable to estimate the cooling needs for a situation in which the outdoor temperatures of the model would be equal to the ones measured for 2021.

Let us call the equation $y = 0.0042x^3 + 0.0339x^2 - 0.8098x + 30.071$ as f. Then, the total energy consumed by the refrigeration system (except ancillary system), according to the model with the current outside temperatures of the used weather file would be given by:

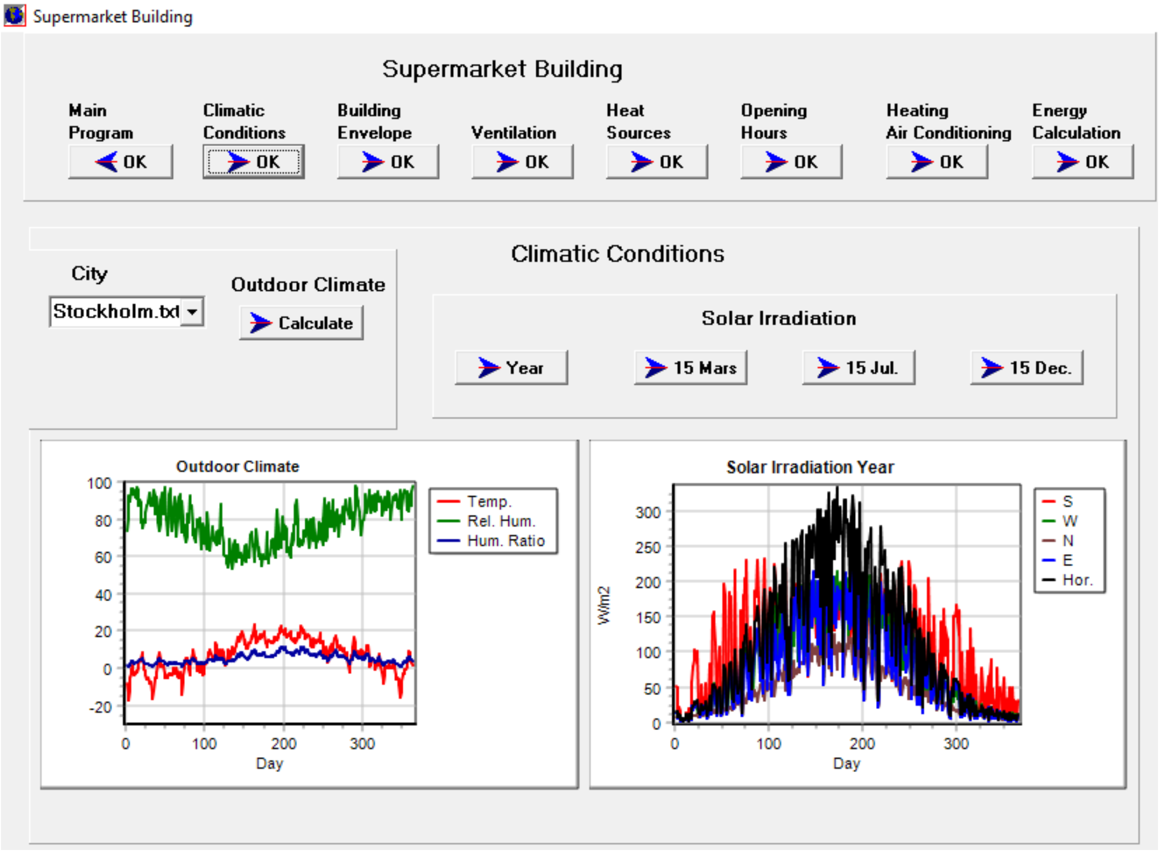
$$EnergyConsumption = \sum_{x=-15}^{32} xi.ni.f \tag{.0.2}$$

Where xi is the outside temperature (between -15 and 32$^{\text{o}}$C) and ni is the number of hours at the year in which temperature xi has occurred, according to the used weather file.

According to the above expression, the the total energy consumption predicted by the model would have been 314 MWh, which is above the actually prediction of 310 MWh. In fact the square R of this linear regression is considerably below 1, which means that function f does not represent the reality very precisely, but is still a reasonable approximation. A factor of 0.988 (310 divided by 314) was used to correct the value of the total energy consumption predicted by this cubic regression as a function of the annual outside temperature.

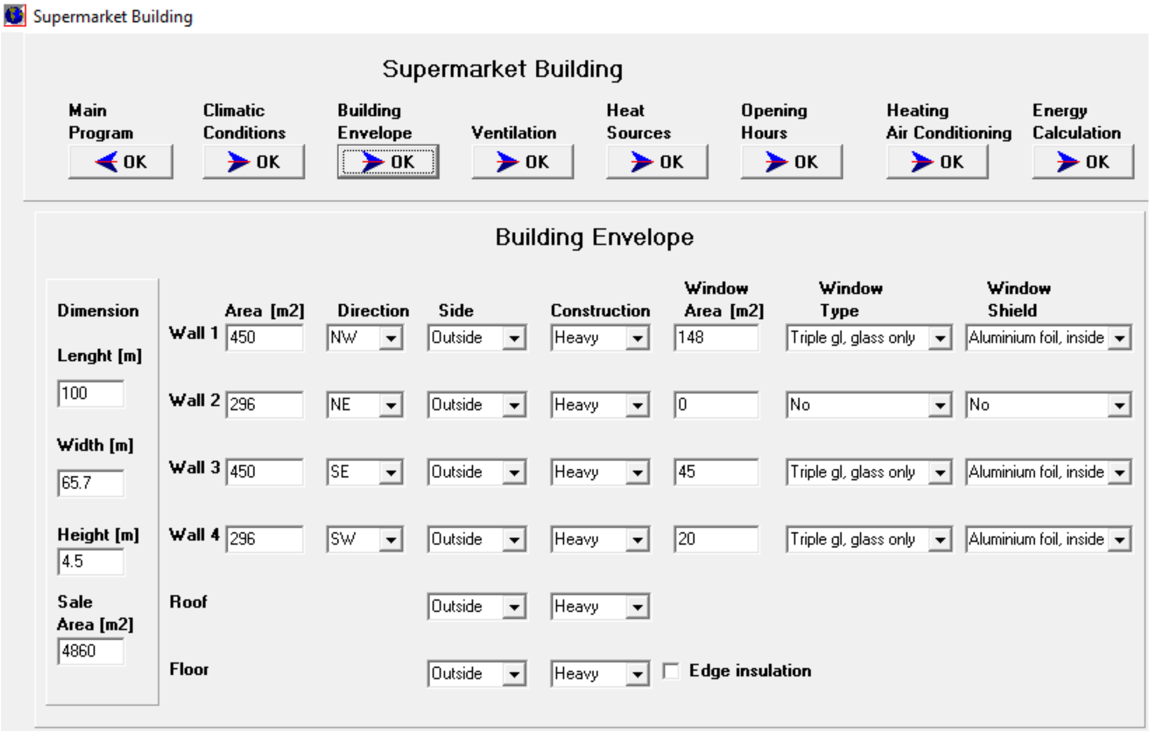
Hence, the expression presented above, corrected by the factor of 0.988, was used to predict the energy consumed by the compressor, resulted from the model if the hourly outside temperature bins registered for 2021 would have been used in the weather file. A value of 358 MWh was obtained.

[7] Modelling in CyberMart



City: Stockholm.txt

Figure 4: Climate conditions: CyberMart's model



Building Envelope

Dimension

Lenght [m] 100

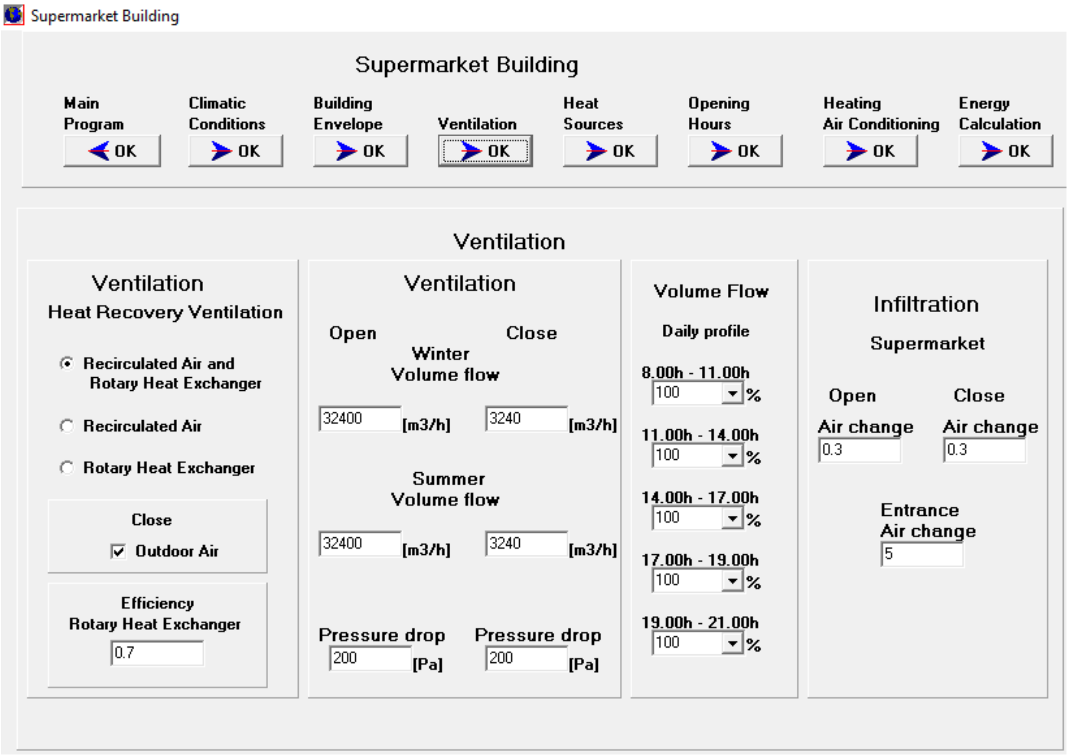
Width [m] 65.7

Height [m] 4.5

Sale Area [m2] 4860

	Area [m2]	Direction	Side	Construction	Window Area [m2]	Window Type	Window Shield
Wall 1	450	NW	Outside	Heavy	148	Triple gl, glass only	Aluminium foil, inside
Wall 2	296	NE	Outside	Heavy	0	No	No
Wall 3	450	SE	Outside	Heavy	45	Triple gl, glass only	Aluminium foil, inside
Wall 4	296	SW	Outside	Heavy	20	Triple gl, glass only	Aluminium foil, inside
Roof			Outside	Heavy			
Floor			Outside	Heavy	☐ Edge insulation		

Figure 5: Building's envelope construction in CyberMart



Ventilation

Ventilation

Heat Recovery Ventilation

● Recirculated Air and Rotary Heat Exchanger

○ Recirculated Air

○ Rotary Heat Exchanger

Close

☑ Outdoor Air

Efficiency Rotary Heat Exchanger 0.7

Ventilation

	Open	Close
Winter Volume flow	32400 [m3/h]	3240 [m3/h]
Summer Volume flow	32400 [m3/h]	3240 [m3/h]
Pressure drop	200 [Pa]	200 [Pa]

Volume Flow

Daily profile

8.00h - 11.00h 100 %

11.00h - 14.00h 100 %

14.00h - 17.00h 100 %

17.00h - 19.00h 100 %

19.00h - 21.00h 100 %

Infiltration

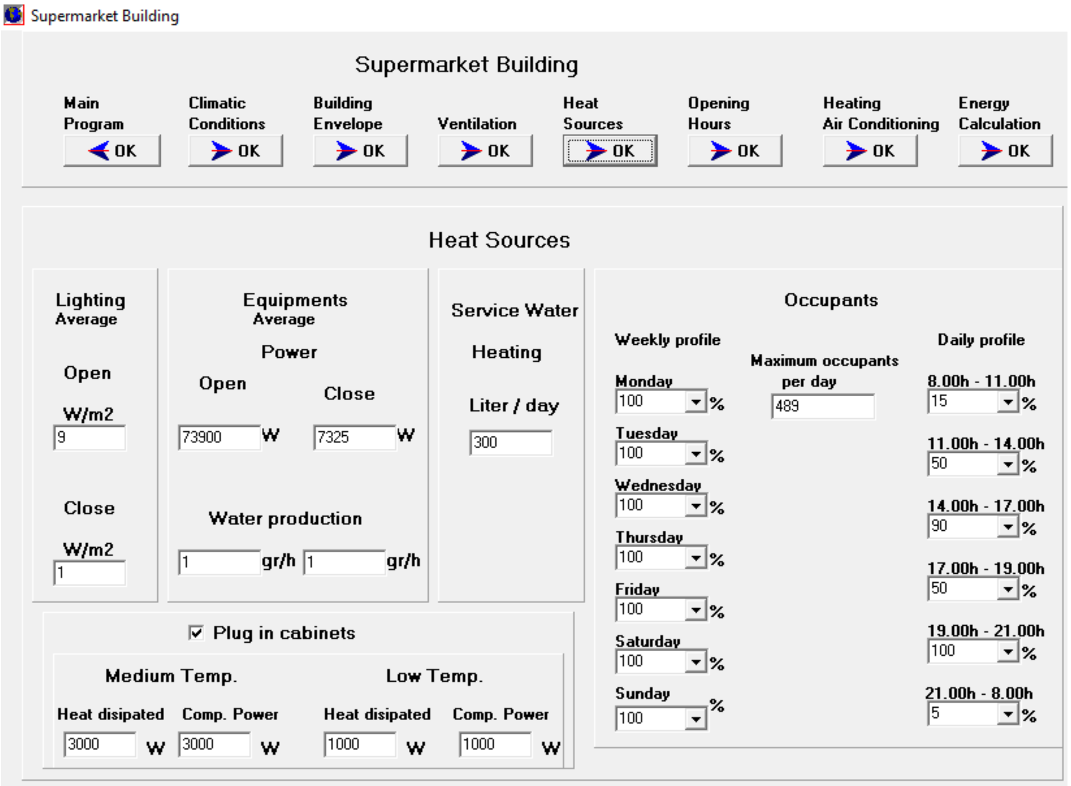
Supermarket

Open Air change 0.3

Close Air change 0.3

Entrance Air change 5

Figure 6: Ventilation system: CyberMart's model



Heat Sources

Lighting Average
Open W/m2: 9
Close W/m2: 1

Equipments Average Power
Open: 73900 W
Close: 7325 W
Water production: 1 gr/h, 1 gr/h

Service Water Heating
Liter / day: 300

☑ Plug in cabinets

Medium Temp.
Heat disipated: 3000 W
Comp. Power: 3000 W

Low Temp.
Heat disipated: 1000 W
Comp. Power: 1000 W

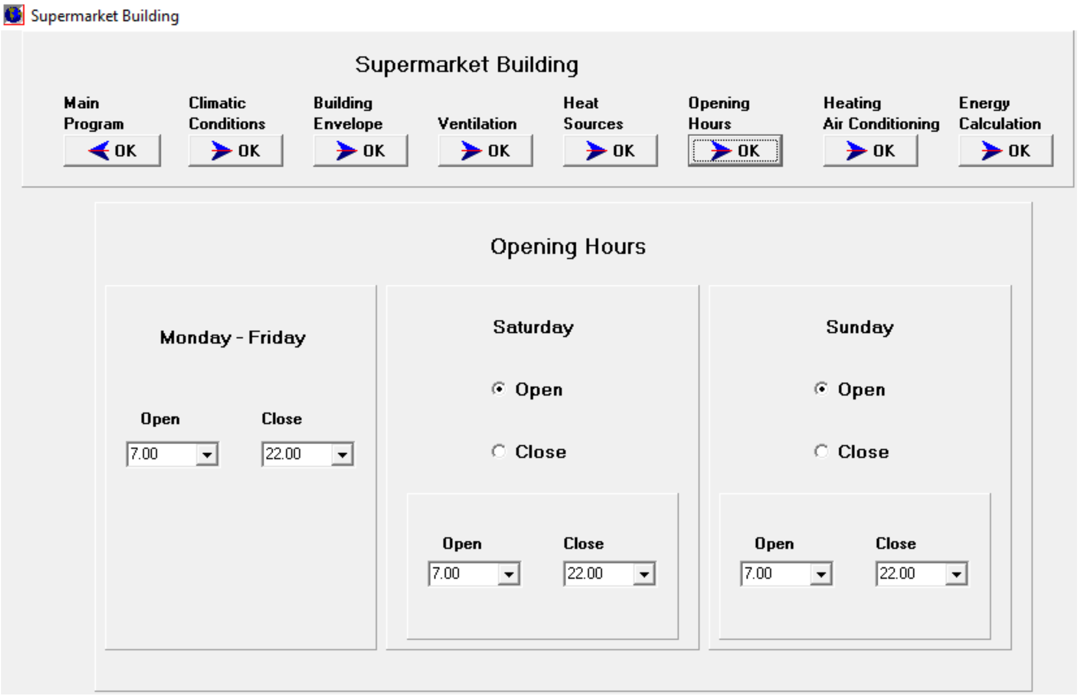
Occupants

Weekly profile
Monday: 100 %
Tuesday: 100 %
Wednesday: 100 %
Thursday: 100 %
Friday: 100 %
Saturday: 100 %
Sunday: 100 %

Maximum occupants per day: 489

Daily profile
8.00h - 11.00h: 15 %
11.00h - 14.00h: 50 %
14.00h - 17.00h: 90 %
17.00h - 19.00h: 50 %
19.00h - 21.00h: 100 %
21.00h - 8.00h: 5 %

Figure 7: Internal Gains: CyberMart's model



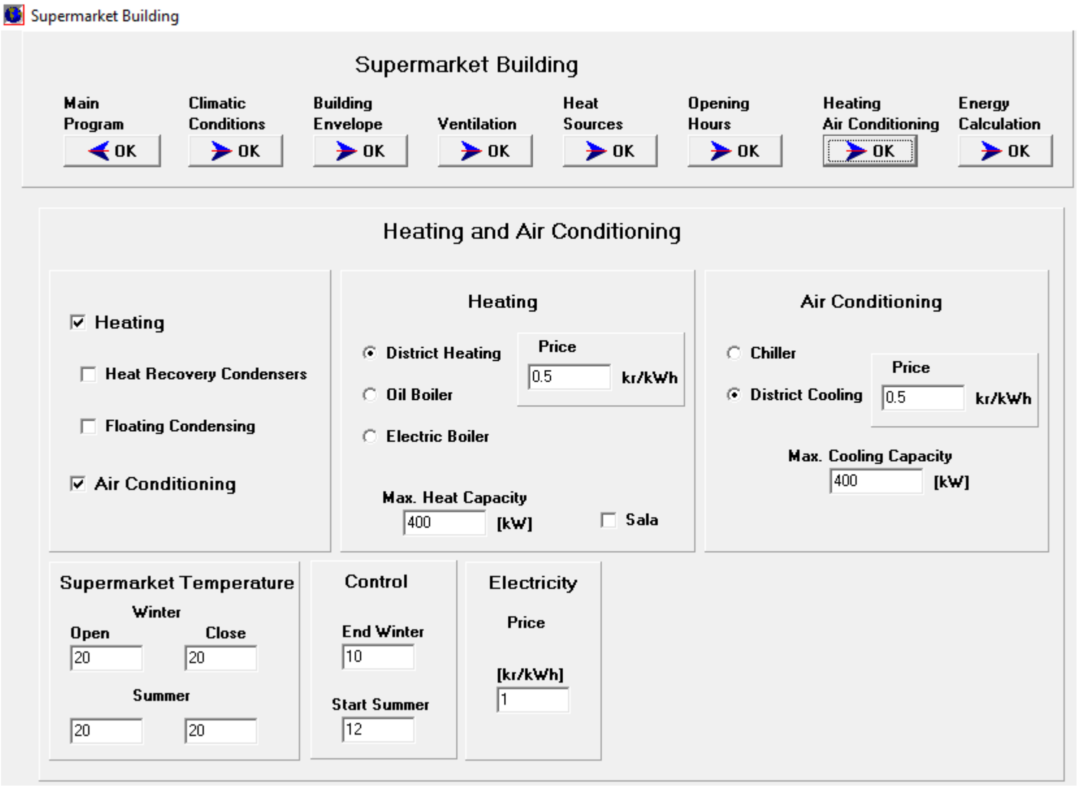
Opening Hours

Monday - Friday
Open: 7.00
Close: 22.00

Saturday
● Open
○ Close
Open: 7.00
Close: 22.00

Sunday
● Open
○ Close
Open: 7.00
Close: 22.00

Figure 8: Opening hours: CyberMart's model



Supermarket Building

Heating and Air Conditioning

☑ Heating

☐ Heat Recovery Condensers

☐ Floating Condensing

☑ Air Conditioning

Heating

● District Heating

○ Oil Boiler

○ Electric Boiler

Price: 0.5 kr/kWh

Max. Heat Capacity: 400 [kW]

☐ Sala

Air Conditioning

○ Chiller

● District Cooling

Price: 0.5 kr/kWh

Max. Cooling Capacity: 400 [kW]

Supermarket Temperature

	Open	Close
Winter	20	20
Summer	20	20

Control

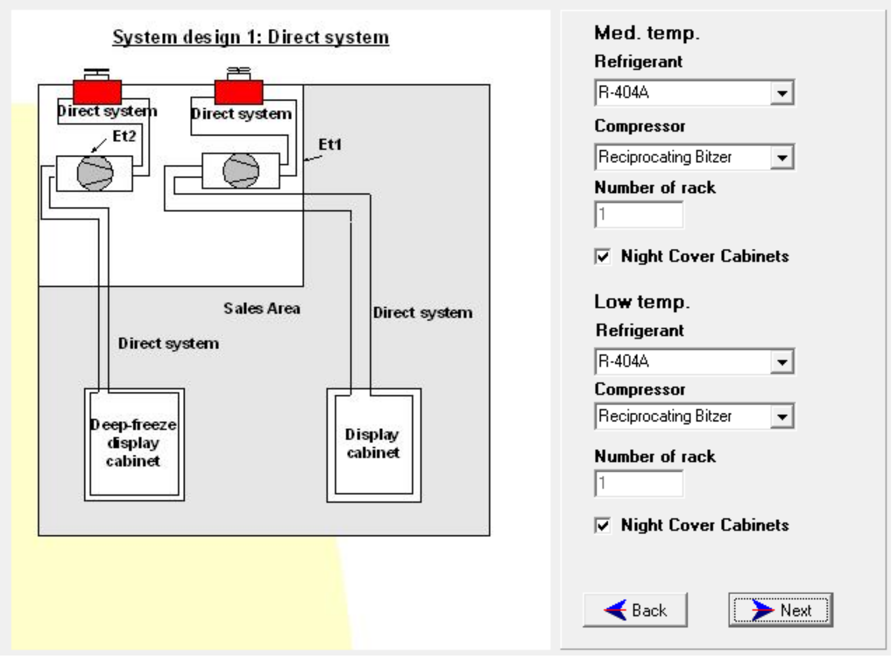
End Winter: 10

Start Summer: 12

Electricity

Price [kr/kWh]: 1

Figure 9: Heating and cooling sources: CyberMart's model



Med. temp.

Refrigerant: R-404A

Compressor: Reciprocating Bitzer

Number of rack: 1

☑ Night Cover Cabinets

Low temp.

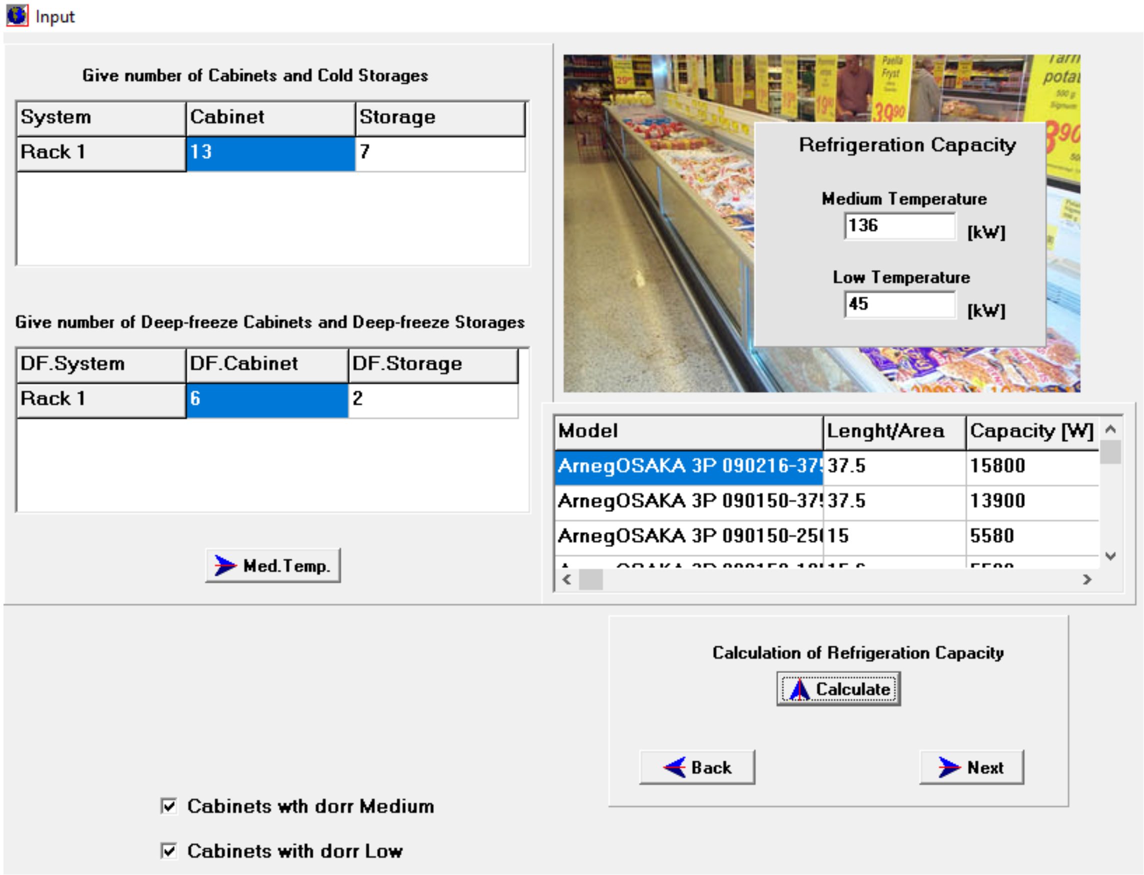
Refrigerant: R-404A

Compressor: Reciprocating Bitzer

Number of rack: 1

☑ Night Cover Cabinets

Figure 10: Refrigeration system's illustration: CyberMart's model



Give number of Cabinets and Cold Storages

System	Cabinet	Storage
Rack 1	13	7

Give number of Deep-freeze Cabinets and Deep-freeze Storages

DF.System	DF.Cabinet	DF.Storage
Rack 1	6	2

Refrigeration Capacity

Medium Temperature 136 [kW]

Low Temperature 45 [kW]

Model	Lenght/Area	Capacity [W]
ArnegOSAKA 3P 090216-37	37.5	15800
ArnegOSAKA 3P 090150-37	37.5	13900
ArnegOSAKA 3P 090150-25	15	5580

Calculation of Refrigeration Capacity

☑ Cabinets wth dorr Medium

☑ Cabinets with dorr Low

Figure 11: Refrigeration's display cabinets and walk-ins: CyberMart's model