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Energy Efficiency Assessment, Based on Field Measurements and Computational Simulations

A Swedish Hypermarket's case study

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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 paper, 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

1 Introduction

1.1 Motivation

Energy used in buildings accounts for almost one-third of the global final energy consumption, being responsible for 36% of Greenhouse Gases (GHG) emissions in European countries [1]. On the other side of the coin, buildings have a great potential for energy savings [2]. Therefore, reducing energy use by all building types is essential to achieve Net Zero emissions by 2050. Much attention has been paid to the residential sector, whereas energy consumption in commercial and industrial buildings has been under-investigated due to its diversity, lack of publicly accessible data, and the nature of property ownership [3]. However, the commercial sector accounts for 21% of the total electricity consumption. In which food retail stores are the highest energy-intensive ones (highest energy consumption per sales or total area). Supermarkets consume about 3-4% of the annual electricity production in industrialized countries [4] [5].

In that sense, it is relevant to further study and analyse the energy demand in supermarket buildings, aiming to decrease their energy consumption by implementing energy efficiency measures as much as possible.

According to the International Energy Agency, Sweden is a global leader in decarbonisation and aims to have a net-zero carbon economy by 2045 [6]. That country has been achieving promising results, not only by increasing the share of renewables year by year, but also by reducing the total energy consumption. However, it is important to consider that, although the Swedish electricity mix relies considerably on clean energy sources, in average each kWh still generates the equivalent of 29 g of CO_2 [7] [8] .

1.2 Purpose

This research project aims to validate computational models used to estimate the energy consumption of food retail stores and investigate possible measurements of energy efficiency in a supermarket. In that sense, the energy consumption as it is calculated by the computational tools is compared to field measurements from a specific hypermarket in Stockholm (Sweden). After validating the model, different scenarios will be analysed in terms of final annual energy consumption by changing several parameters in the "real" hypermarket.

1.3 Energy Consumption of a Supermarket

There are several parameters that influence the energy consumption of a supermarket. Those can be seen as subsystems within a large system. Figure 1 shows the different subsystems in a supermarket, such as the Heating, Ventilation and Air Conditioning (HVAC) system, refrigeration system, cabinet system, electrical appliances and occupancy and their respective interactions.

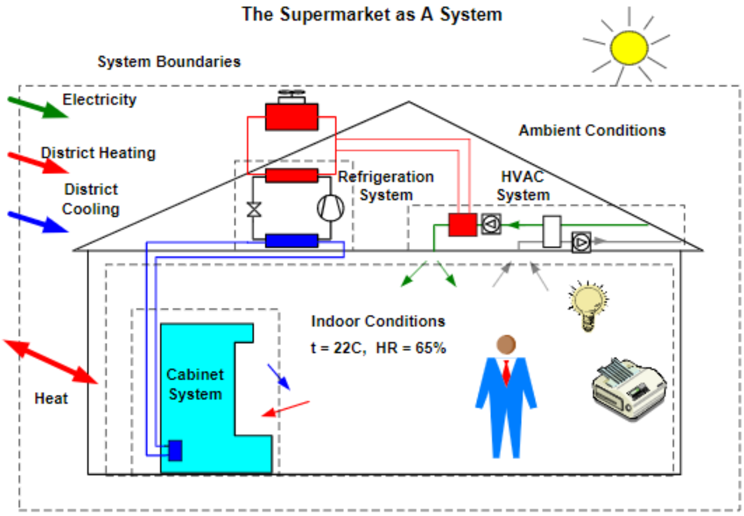

Figure 1: The Supermarket as a System [9]

A survey carried out in 2010 pointed to an average consumption of 400 kWh/m^2 for a Swedish food retail store [4]. Whereas a study from 1998, with 256 supermarkets, found out an average consumption of 421 kWh/m^2 annually and a consumption lower than 330 kWh/m^2 for hypermarkets [9]. This allows concluding that the bigger the food retail store, the lower the energy intensity and over the years, the consumption has been decreased.

1.4 Simulation Tools to Predict the Energy Consumption

Estimating a supermarket's energy demand makes it 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.

In this paper, two different simulation models are constructed to estimate the energy demand of the case study's hypermarket. Amongst several building simulation software available on the market, only a few can be accurately utilized for a supermarket, due to the centralized refrigeration system. In that sense, the two software chosen to model the hypermarket were **EnergyPlus** and **CyberMart**.

EnergyPlus was developed by the US Department of Energy and is a very complex tool that allows modeling any type of building with a high level of detail. Specifically for supermarkets, it enables to model a state-of-the-art CO_2 booster refrigeration system with heat recovery from the refrigeration cabinets to the sales area. Its original interface is not user-friendly, but it can be connected to another interface [10].

CyberMart was developed by Jaime Arias at KTH university near the year 2005 and it is used to model specifically supermarkets [9].

By modeling all the sub-systems of a supermarket, it is possible to obtain the respective hourly energy consumption using both software described above. However, it would be very challenging to model the operation of those systems in EnergyPlus and CyberMart does not allow modeling the CO_2 booster refrigeration system with heat recovery. Consequently, a Python tool previously developed by Sotirios Thanasoulas inputs the thermal demands (space heating, cooling and refrigeration loads from the cabinets) found by EnergyPlus or CyberMart and gives the hourly energy consumption by the refrigeration system. The energy consumed by other electrical appliances and the ventilation system is directly estimated by EnergyPlus and CyberMart.

2 Case Study's Hypermarket

The food retail store used to evaluate the computational models used in this research project is an ICA MAXI, defined as a hypermarket, since its floor area is greater than 2500 m^2. This hypermarket is located in Bålsta, 45 km from the city of Stockholm and it is open from 7 am to 10 pm every day. It has a total conditioned area of 6570 m^2 and is a stand-alone building.

Inside this hypermarket there is a pizzeria restaurant, pharmacy and a post office's collector center, besides the sales area. Outside, there is a visitors' parking place, with lighting, car chargers and snow melters.

Electricity is the only source of energy supply in this hypermarket. A new trans-critical CO_2 refrigeration system was installed in 2020, which allows heat recovery and thus, in this hypermarket, six boreholes are placed in the ground for energy storage. The system is capable of providing refrigeration and freezing for the food products in the store (Medium Temperature (MT) and Low Temperature (LT) loads), air conditioning (AC), heating for space heating and domestic hot water, via heat recovery and from the boreholes.

Most 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.

Table 1 summarizes the display cabinets and cold storage rooms presented in this hypermarket. The display cabinets are located in the sales area and can be accessed by the customers, whereas the cold rooms stay in the storage rooms and only the staff can access it.

Table 1: Refrigeration display cabinets and cold storage rooms

Refrigeration Cabinets	Display Cabinets		Cold Rooms	
	Medium Temperature	Low Temperature	Medium Temperature	Low Temperature
Total Capacity [kW]	65	20	48	15
Operating Temperature [ºC]	2 to 6	-18	2 to 6	-18

3 Modelling the Hypermarket in EnergyPlus

3.1 Simulation Parameters

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 [11].

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 HVAC was model with the requirement of keeping the inside temperature between 19 and 22 ºC in opening hours and between 17.5 and 22 ºC at night, in the beginning of 2021. From June onwards, the inside temperature was modeled to be above 19ºC all day.

The refrigeration cabinets were very challenging to model since a great amount of parameters were input in the model, and much research was required to make estimations about how the cabinet's doors openings, lighting and restocking would affect their cooling loads at each hour of each day. The maximum total capacity of the refrigeration system was model in accordance with table 1.

3.2 Building's Location and Climate

For the model in EnergyPlus, an EnergyPlus Weather File (EPW) was used, referring to Stockholm's location. This weather file contains information such as longitude, latitude, elevation, annual design conditions and monthly average ground temperatures. 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 [12] and no changes were made.

3.3 Building's Components

The building was modeled by setting the coordinates of each wall, window and door and the respective materials. Skanska (the company responsible for the hypermarket's construction) provided some values for thermal transmittance (also known as U-value). The higher the thermal transmittance of the building's envelope, the higher the heat conduction flux through it.

The modeled external walls have an U-value of 0.19 W/m^2K, ceiling and ground of 0.11 W/m^2K, windows of 1.7 W/m^2K and doors of 1.3 W/m^2K. Skanska also estimated a value of 0.3l/m^2 of the outside walls for the infiltration rate.

Although this hypermarket has many different zones, it would be extremely time-consuming for EnergyPlus to process all these different zones and, since many zones have similar number occupants and HVAC system control strategies, they were grouped into six different zones, as represented in table 2.

Table 2: 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** contains the selling products and it also includes the pharmacy and pizzeria. The **Offices**' zone includes all the offices in the building and resting rooms for the staff. The **Back Room** includes the storage and preparation rooms, whereas the **Cold Room** zone contains the actual 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.

3.4 Internal Gains

Table 3 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 [13] or assumed by similar cases found in the literature. Based on EnergyPlus 9.6 reference documentation [14], this model estimates that each person contributes 120 W of additional heat. Lighting was estimated from data provided by the hypermarket and also using typical values for offices [15].

Table 3: 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.

EnergyPlus allows modeling a schedule for each single internal gain category. For example, the occupancy was modeled to be maximum from 5 to 8 pm. Schedules were estimated for all the electrical appliances, as well as for the outside doors' openings.

4 Modelling the Hypermarket in CyberMart

CyberMart is a software used for modeling food retail stores exclusively and was constructed to provide a fast estimation of the energy consumption. All the assumptions described for EnergyPlus' model were used in CyberMart, but with a lower level of details. CyberMart only allows modeling one thermal zone and a unique floor. Moreover, no schedules for electrical appliances or doors' opening are possible to model. The model only distinguishes between close and open hours. Therefore, an average value of 74 kW was used for the total electrical appliances load for opening hours, taking into account the intensity of the electrical appliances described in table 3 and the estimated hours of use. Regarding occupancy, CyberMart allows modeling a schedule for the occupants' density, alike EnergyPlus.

Modeling the refrigeration cabinets was much simpler than in EnergyPlus, since CyberMart comprises an extended list of cabinets that contains all the necessary parameters to estimate their power consumption at different hours of the day, considering the surrounding conditions.

CyberMart also has a library with different files for the climate conditions of many locations. Once again, Stockholm's location was chosen.

5 Results

5.1 Thermal Loads

As seen in figure 2, EnergyPlus' model is closer to the measurements considering the energy demanded to keep the display and walk-in cabinets at 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 software's databases. It can be noticed that the heating demands are higher in EnergyPlus, which is consistent with the lower outside temperatures. However, there is a considerable difference in the cooling demands between the EnergyPlus and the field measurements. The hypermarket's energy manager pointed out some inconsistencies with space cooling supply with negative outdoor temperatures. This can be related to the bakery, which is a closed space with no connection to the outside. This effect was strongly felt in December when there is a higher demand for pastry and customers in the store. Moreover, the EPW file estimates an outdoor temperature 25% lower than the one measured in 2021. This gap in the cooling demand 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. This can be related to the geometry of the building, that is more compact in CyberMart than in reality and the lack of schedule for the outside doors' openings.

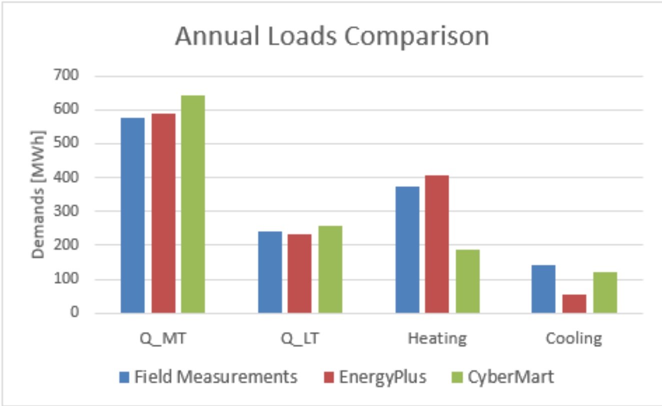

Figure 2: Field Measurements, EnergyPlus and CyberMart's Loads comparison

5.2 Final Energy Consumption

Figure 3 shows the energy consumed by the different sub-systems and the total of the hypermarket, according to the field measurements and EnergyPlus and CyberMart's model associated with the Python tool.

CyberMart's model predicts a higher consumption for the refrigeration system than EnergyPlus, which is coherent with the loads presented in figure 2.

The lighting's energy consumption differs on the field measurements, since only the lighting for the sales area and parking is considered, whereas the lighting for the other rooms is accounted in the "electrical appliances" section. The energy consumed by the ventilation sub-system is very similar for the three cases.

There is a considerable uncertainty regarding the "Electrical appliances" presented in this hypermarket. While detailed data was given for the cabinets and cold rooms, lighting and oven, not much detail was provided for the other electrical appliances used in the hypermarket. The initial assumptions were lower than the measured consumption for 2021.

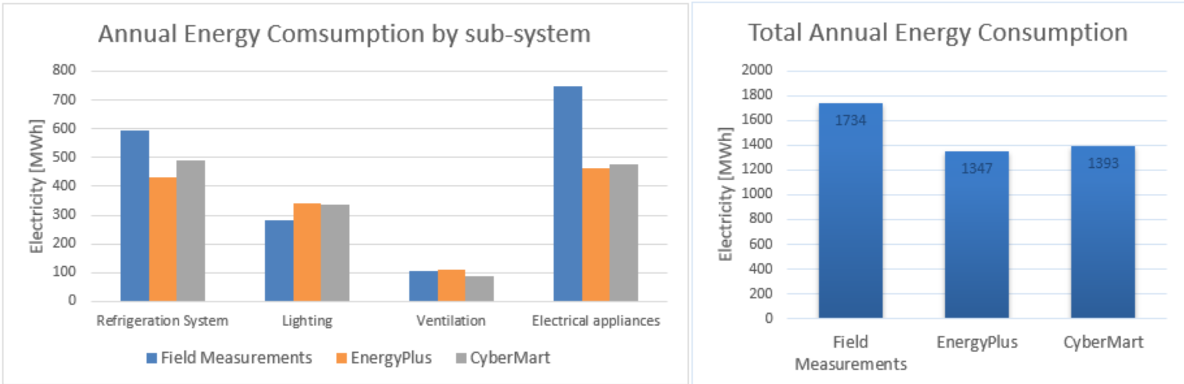

Figure 3: Energy consumption by sub-system according to the field measurements, EnergyPlus and CyberMart's models

Both models predicted a lower energy consumption for the hypermarket compared to the measurements. This was, somehow, expected since non-optimal management actions usually occur in reality, whereas the models assume that every sub-system works optimally.

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 are more accurate.

6 Conclusions

In spite of the enormous effort to provide accurate hourly measurements of the energy consumed by this hypermarket in 2021, detailed information regarding energy usage by several components was missing. Additionally, some irregularities were verified on the energy consumed by the lights, fans, defrosts and anti-sweaters in the refrigeration display cabinets. Although all the space heating was supposed to be fulfilled by the heat recovery from the refrigeration system, electric heaters were used. In the end, the origin of 28% of the electricity consumed in 2021 could not be identified.

EnergyPlus software was very challenging to use, since it is not user-friendly and requires a great understanding of the previously described sub-systems. CyberMart, on the other hand, was developed for any engineer to model a food retail store. After all, EnergyPlus ended up estimating more accurate loads. However, CyberMart was slightly closer to the measurements concerning the final annual energy consumption.

According to the field measurements, the hypermarket consumed 264 kWh/m^2 in 2021. This value is in accordance with the values reported in studies [4] [9].

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**: responsible for a 48 MWh difference; **non-optimal control strategies**, which led to an increase of 120 MWh; **lack of information regarding the electrical appliances**, responsible for 219 MWh gap between the measured values and the model.

This enables to conclude that rising temperatures affect a supermarket's 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 to identify more feasible energy efficiency measurements using these simulation tools.

Despite being way less detailed than the EnergyPlus one, CyberMart's model led to a slightly better prediction of the final annual energy consumption. This software showed a good potential to help understanding the hot spots of energy consumption of a supermarket, in a fast and easier way.

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