THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Energy in supermarkets

-An overview on the energy flows and refrigeration controls

Tommie Månsson

Department of Civil and Environmental Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2016

Energy in supermarkets
An overview on the energy flows and refrigeration controls
TOMMIE MÅNSSON

Technical report no 2016:7

Department of Civil and Environmental Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
Photo from refrigerated goods area in REWE Wettbergen, Hannover.

Reproservice

Gothenburg, Sweden 2016

Abstract

The electrical energy used by supermarkets represents approximately 3% of Sweden's annual energy use. Of this, the refrigeration system accounts for 50%. To reduce greenhouse gases introduced by energy generation, a larger share of renewable energy sources must be implemented. Energy sources such as solar and wind are predictable but not controllable. Hence, if these sources are implemented, there is a need to make the energy users more flexible e.g. adapt the demand to the production instead of vice versa, as is the case today. Here, supermarkets have great potential to utilise their refrigeration system as an electrical energy sink by transforming electricity to cooling when there is a surplus of energy in the grid.

In this thesis, the energy flows within the supermarket were analysed from a conceptual systems' perspective to find potential leverage points for increasing the power flexibility and energy efficiency. From the systems, it was confirmed that the refrigeration system holds great potential for increasing the power flexibility. The indoor air conditions *(temperature and humidity)*are connected in multiple ways to the supermarkets' energy demand and should, therefore, be included as an important parameter in any energy efficiency measure.

From a numerical CFD model developed in this thesis, the temperature field within a refrigerated display cabinet was visualised and analysed. It was found that the current area for temperature sensor placement in the air return canal might be exposed to warmer air streams, heated by the ambient air in contact with the glass door of the display cabinet. The findings were validated and confirmed in a laboratory. The findings initiated a field study to map and correct the position of the return air temperature sensor in 235 positions. From the measurements of the electrical energy use and temperature in the affected refrigerated display cabinets, a decrease in energy use and temperature variation could be concluded.

The thesis concludes a demand of having a systematic and holistic approach when implementing measures for increasing the energy efficiency and power flexibility of supermarkets.

The thesis also concludes a need for further research on the energy flows within the supermarket to enable the full potential of energy efficiency and power flexibility measures.

Acknowledgements

Firstly, I would like to express my sincere gratitude to both my supervisors, Assistant Professor York Ostermeyer and Professor Angela Sasic Kalagasidis, for their continuous support during my studies and research and for their patience and motivation.

Besides my supervisors, I would like to specially thank Climate-KIC for both the financial support and invaluable training on entrepreneurship in the field of greenhouse gas reducing innovations.

Also, special thanks to REWE and Wurm for sharing invaluable knowledge, data and supporting with equipment for setting up a local laboratory at Chalmers.

Without mentioning any names, I would like to acknowledge and thank my colleagues at Chalmers and fellow PhD students within the Climate-KIC PhD-Label programme for their insightful comments and encouragement along with the hard questions that helped me improve my research from different perspectives.

Last but not the least, I would like to thank my family and friends for supporting, challenging and encouraging me throughout the writing of this thesis.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

In 1988, with the formation of IPCC [32], the idea of anthropogenic climate change entered the scientific community. Among researchers currently in the field, the majority agree that the climate change is fundamentally manmade [10]. In The Stern Review of 2006, the scientific evidence for anthropogenic climate change was described as overwhelming and that it presented a serious global risk that demands an urgent response [38].

The increasing share of renewable energy sources and the phasing out of fossil fuels in combination with a more efficient use of resources are necessary actions to stop or reduce anthropogenic climate change.

1.1 Problem description

Any electrical grid with a large share of renewable energy sources faces problems with fluctuations in the energy supply, and therefore, needs buffering or storage capacities [14]. In this context, the NPO Agency for Renewable Energy (Agentur fr Erneuerbare Energien e. V.) reviewed several governmental and non-governmental studies on future storage demands for the German grid [13]. According to this, the additional demand for electrical storage and buffering will likely reach 18 TWh by 2030 with renewable energy sources producing 50% of electrical power generation in Germany. By 2050, the demand of storage and buffering capacity will reach 30 TWh with renewable energy sources producing 80% of power generation in Germany.

Besides direct storage, the concept of delaying electricity demand, and therefore, tailoring demand to supply is another option to manage the energy balance in the grid. Large-scale energy users should therefore be assessed on their potential to react flexibly in their demand. One such area of energy is the refrigeration of food in supermarkets, which is the main focus of this thesis.

The hypothesis is that by allowing for energy demand forecasting for a refrigeration system and implementation of a cold thermal energy storage, supermarkets would be able to adapt their demand to electrical energy generation. Therefore, they would act as an energy buffer for utility companies allowing them to implement a larger share of the renewable energy sources in electrical energy generation.

1.2 Aims and objectives

This thesis explores possibilities to increase the electrical power flexibility and energy efficiency of supermarkets by implementation of demand side management-oriented control strategies and cold thermal storage. The thesis will present the energy flows within the supermarket by conceptual systems showing the interconnections and dependence of the sub-systems existing within the supermarket. The thesis will map the energy flows at a high level of detail in scales down to the component level of technical equipment.

The thesis aims to provide directions for future research in cold thermal energy storage in supermarkets. In addition, the thesis will serve as a feasibility study for a continuation of the PhD project entitled: "Supermarkets as thermal buffers for renewable electricity grids".

1.3 Limitations

This thesis focuses on where and what the possible measures for increasing the energy efficiency and implementing cold thermal energy storage for increased electrical power flexibility are. The molecular properties of the material and components as well as technological limitations of system intercompatibility for measures are not considered. The system boundary for this thesis was set to the supermarket site. The impact on the grid level will be used for argumentation and discussions only.

1.4 Method

A literature review of the development of energy concepts and energy simulations was conducted to define the relevant research questions as well as appropriate research methods. The literature study in combination with interviews and field studies serve as the basis for the background and introduction to supermarkets. The outcome is also presented in system diagrams that qualitatively describe the sub-system interconnections and dependency within the supermarket.

A more detailed analysis of the refrigeration system within the supermarket was based on a literature review on energy calculation methodologies for estimating the heat extraction rate from refrigerated display cabinets. A computational fluid dynamics model was created and the temperature field was analysed in depth and validated by laboratory experiments.

The findings of inhomogeneity in the temperature field in the area of the air return temperature sensors of the refrigerated display cabinet triggered a field survey in existing supermarkets with the aim of investigating the real position of temperature sensors and consequences of this. This investigation was performed as a field study in two steps. The first field study was conducted to obtain a statistical background of the actual position of temperature sensors in refrigerated display cabinets. With the first field study proving that the temperature sensors most commonly are placed in areas where temperature inhomogeneity exists, the second field study was conducted. This field study was performed by an external technician who registered the position of the temperature sensor and re-positioned it to a location where the temperature is homogeneous. Metadata and photo documentation was also provided and the temperature readings from the re-positioned sensor and the discharge air sensor were collected for one month before and after the re-positioning.

The model, systems and field studies within this thesis were made with a holistic and systematic approach in mind for later integration to a building or grid scale energy model.

1.5 Disposition of thesis

In Chapter 2 - An introduction to supermarkets, the concept of supermarkets is introduced from a historical perspective and described from a technological perspective. The different systems and areas in a supermarket are introduced together with an overview of the energy flows within the building and some of the currently most common energy efficiency measures in supermarkets.

In Chapter 3 - Refrigeration in supermarkets, the refrigeration system is described more in detail focusing on giving an overview of the systems complexity and interconnections.

In Chapter 4 - Energy mapping of a refrigerated display cabinet, the focus is narrowed to the refrigerated display cabinets of the supermarkets and how they interact with the indoor environment. The interaction is investigated by CFD-aided models, looking into the heterogeneous temperature field in the refrigerated display cabinets.

In Chapter 5 - Field study of actual temperature sensor placement in refrigerated display cabinets, the impact of the findings of heterogeneous temperature distribution in the air return channel is investigated further.

The final Chapter 6 - Conclusion summarises the findings of the thesis and concludes the next steps towards and implementation of energy buffering systems in supermarkets.

Chapter 2

An introduction to supermarkets

The modern supermarket has its roots in the 14^{th} century's dry good dealer, called the grocer or purveyor. As staple food became available in cans and other preserving packaging evolved into grocery retail stores, a wider range of staple foodstuffs, meat, dairy products, eggs etc. were sold. [23]. This concept has gradually changed to be the modern grocery retail stores, which is most commonly divided into categories defined by the store size, as shown in Table 2.1. The supermarkets, as we see them today, emerged from a concept where food was low priced, self-service oriented, more impulse buy related, larger sales area, larger volumes of foodstuffs and free parking. In addition, the entrance of cars, cash register and large refrigeration systems was a large part in the development towards today's supermarkets.

Table 2.1: Different types of grocery retail stores named by size according to [21]

Type	Sales area $[m^2]$
Convenience store	<280
Supermarket	$280 - 1400$
Superstore	$1400 - 5750$
Hypermarket	>5750

In the continuation of this thesis, the word "Supermarket" will be used for grocery retail stores of all sizes including convenience stores, supermarkets, superstores and hypermarkets.

In Sweden, there is a current trend towards increasing floor areas of newly built supermarkets from $302m^2$ in 1976 to $2253m^2$ in 2006, as shown in Figure 2.1. Although the store size increased, the number of newly built stores during the same time has decreased from 182 to 67, as shown in Figure 2.2. The reason for the trends could be the increased urbanisation, where a higher density of population requires larger shops in the cities.

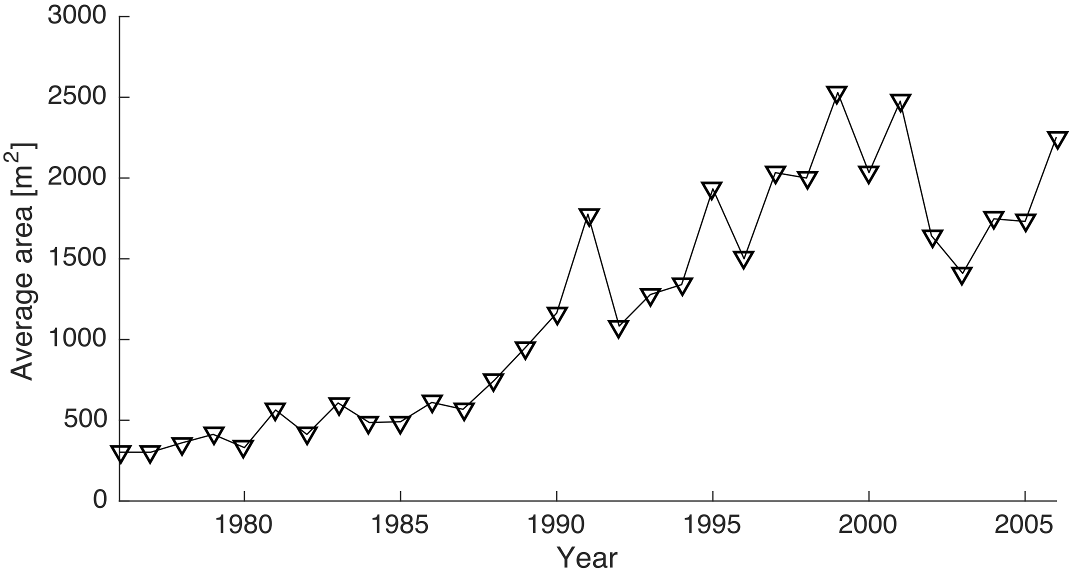

Figure 2.1: Annual average sales area of new grocery retail stores in Sweden between 1975−2005. Plot created by Tommie Månsson based on the data from "Number of newly built stores" and "Total newly built sales area" presented in SCB Livsmedelsförsäljningsstatistik 2006, HA24 SM 0701

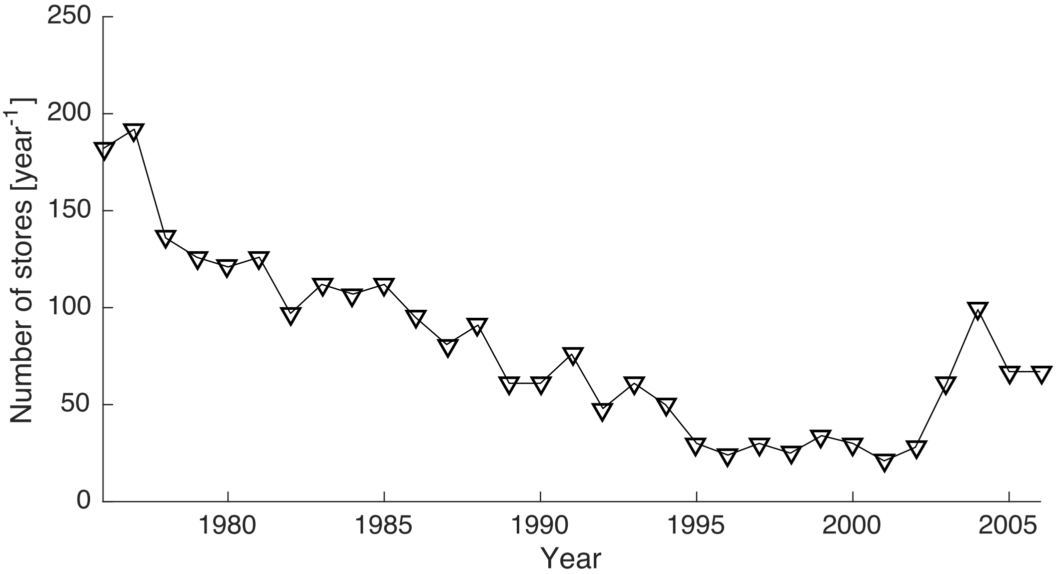

Figure 2.2: Number of newly built stores annually in Sweden between 1975 − 2010. Source: SCB Livsmedelsförsäljningsstatistik 2006, HA24 SM 0701

The higher density of supermarkets within cities can also be seen in Figure 2.3, where statistics shows that 33.6% of the population had access to a supermarket within a radius of $300m$ in the overall country, compared to 39.3% in cities.

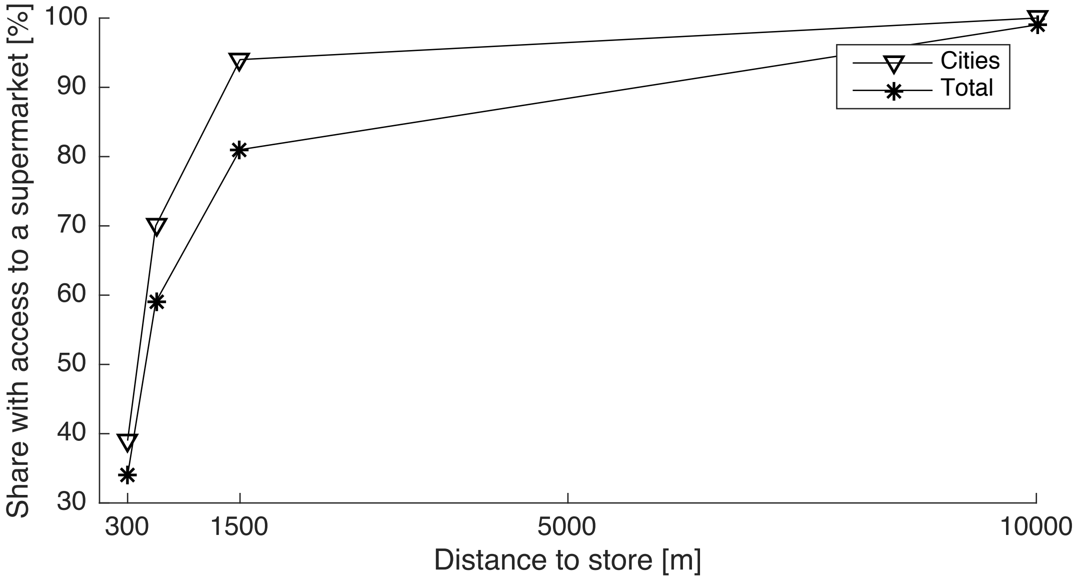

Figure 2.3: Share of the population with access to a supermarket within a certain range. Plot based on data from "Andel av befolkning med tillgång till livsmedelsbutik" from SCB. Source: $http : //www.scb.se/sv\_/Hitta - statistik/Statistik - efter - amne/Miljo/Markanvandning/Transportinfrastrukturens - markanvandning/Aktuell - pong/115628/Tillganglighet - till - livsmedelsbutik/Andel - av - befolkning - med - tillgang - till - livsmedelsbutik/$ - Accessed: 20160707

In 2014, there were a total of 6168 registered grocery retail stores in Sweden [33], with annual sales of 232 billion Swedish krona [SEK] [11]. These stores represent approximately 3% of the annual energy demand in Sweden [2], and the same figure applies for UK[39]. For Sweden, 3% is equivalent to 1.8TWh/year[26], which divided by the annual sales, derives an energy demand of about 7.76 MWh/million SEK.

Going from national down to the store level, energy demand can be divided into sub categories of heating and hot water, food refrigeration, air-conditioning, lights, auxiliary and other. In two studies conducted in Sweden in 1990 and 2009, an increased energy demand per square meter could be seen. The results are shown in Figure 2.4. With refrigerated food being one of the fastest growing markets [16], the increase could be explained by the increased amount of products demanding refrigeration in supermarkets.

In Figure 2.5 and Figure 2.6, the electrical power demand by a 1300m^2 German supermarket

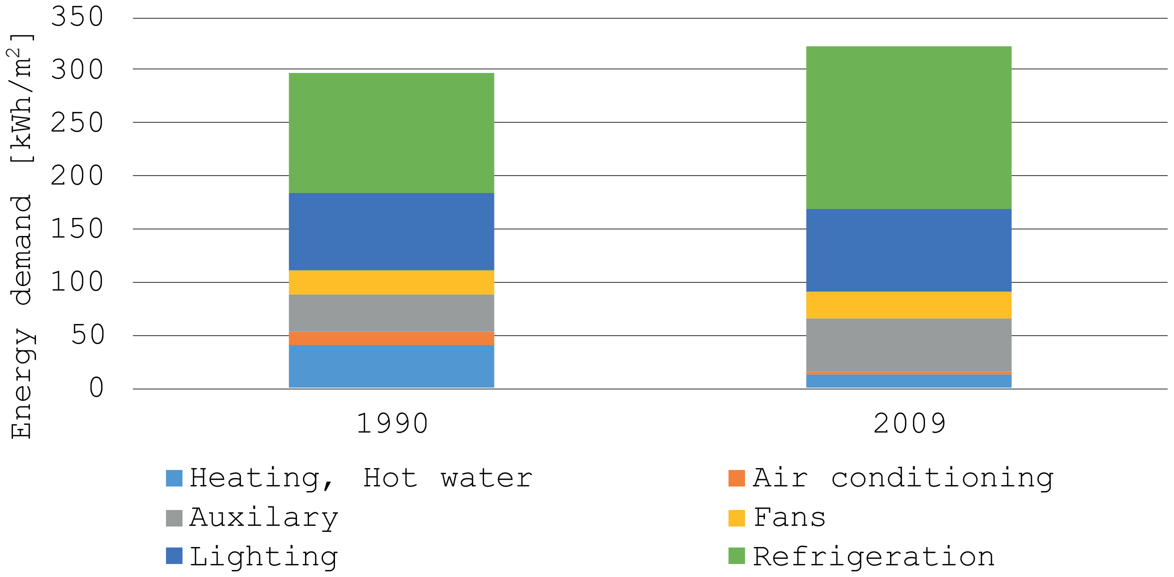

Figure 2.4: Stacked bar chart showing a comparison between energy use in stores in 1990 and 2009. [36] [37]

in Hannover is shown. The supermarket is of a Passivehouse standard, and it is equipped with recirculating ventilation, occupancy and demand-controlled lighting and a highly insulated envelope. The seasonal effects can be seen in the annual overview where the daily peak power demand for refrigeration increases while the overall power demand decreases during summer. In addition, the daily variations can be seen as the total power demand varies between 28 to 94 kW.

The weekly overview shown in Figure 2.6 shows the electrical power demand of week 10, 2015, starting with Monday the 14^{th} of March. It shows that the electrical power demand is transient, meaning that the share of electrical power demand for refrigeration varies with time. During opening hours, it represents $\sim 35\%$, whereas during closed hours it represents $\sim 75\%$. However, from the energy balance presented in Figure 2.4, it could be seen that refrigeration represents almost 50% of the annual energy demand. This transient behaviour should be taken into consideration when designing energy-efficient supermarkets.

More detailed characteristics of the energy demand in supermarkets will be explained in Section 2.2 on page 16.

Figure 2.7 show that an increasing sales area tends to decrease the energy demand per square

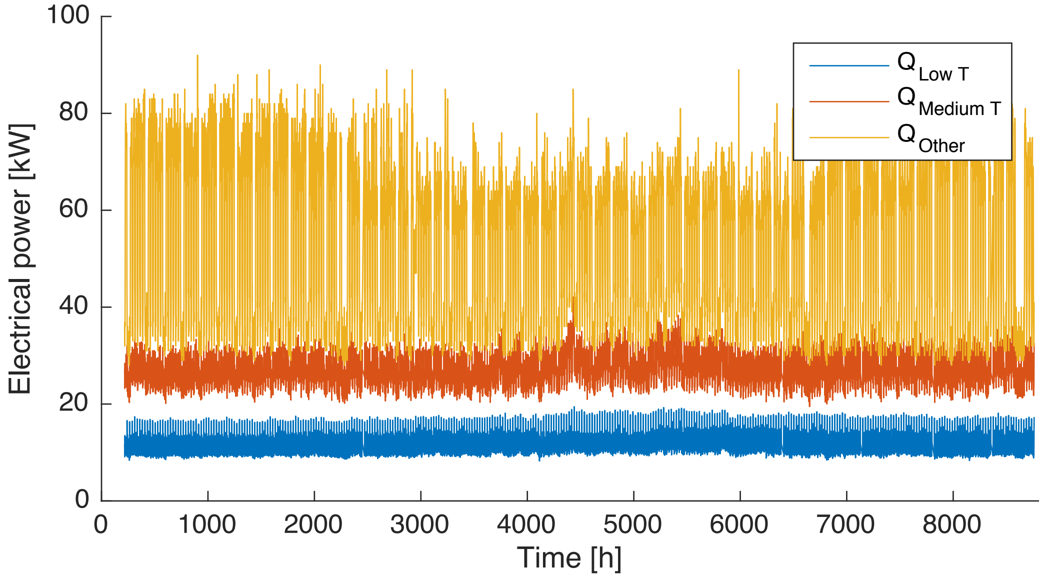

Figure 2.5: Stacked line plot of the annual electrical power demand by a 1300 m^2 supermarket in Hannover, where Q_{Low} and Q_{Medium} represent the energy use for low- and medium-temperature refrigeration, respectively, and Q_{Other} represents all other electrical energy use such as lights, HVAC etc.

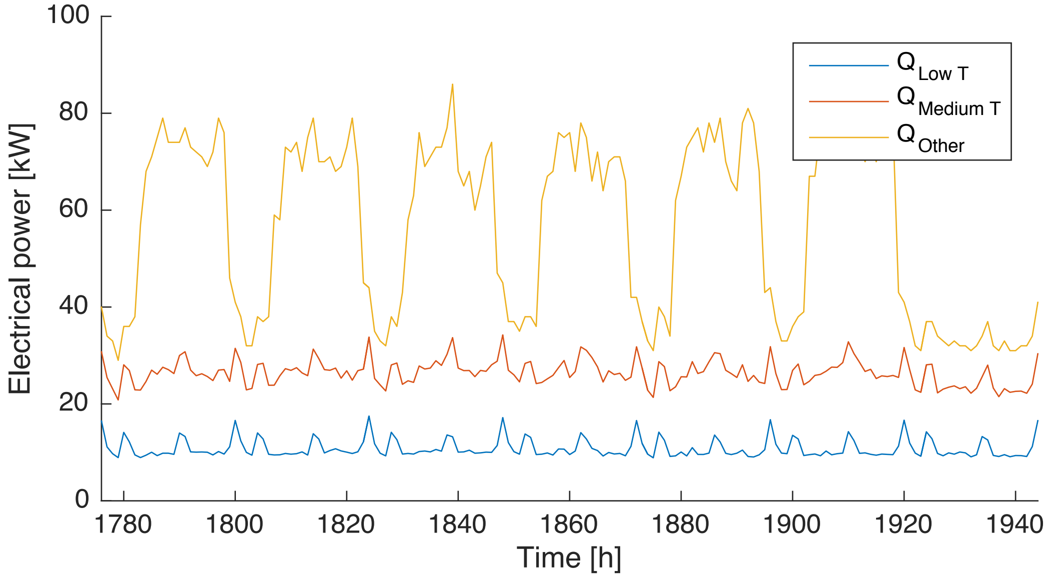

Figure 2.6: Stacked line plot of the weekly electrical power demand by a 1300 m^2 supermarket in Hannover. Where Q_{Low} and Q_{Medium} represent the energy use for low- and medium-temperature refrigeration, respectively, and Q_{Other} represents all other electrical energy use such as lights, HVAC etc.

meter in Swedish stores [36]. Similar trends can also be observed on the UK market in [39] [35]. This is because larger markets have a lower ratio of meters of refrigerated display cabinets to floor area.

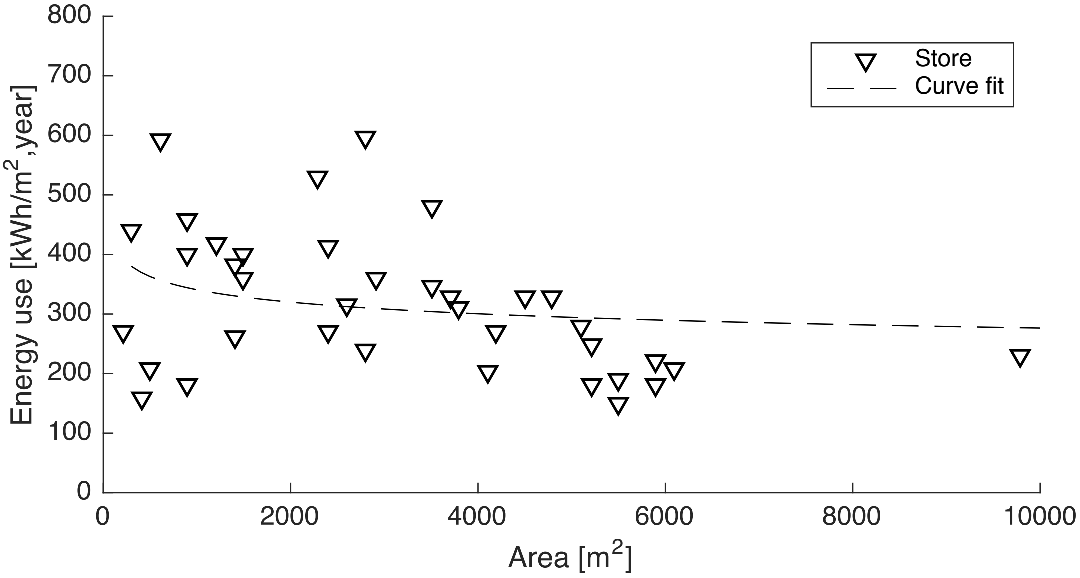

Figure 2.7: Scattered plot of the energy demand to area. Showing the correlation between an increasing area to decreasing energy demand per square meter. Based on data from *Energimyndigheten STIL 2 page 50 Figure 18*

In the climate scenario of 2040 in northern England, the electrical energy demand of supermarkets are expected to increase by 2.1% [9]. [9] also concludes by linear regression analysis of supermarkets energy demand that the outdoor moisture content has a larger impact than the temperature. This is however contradicting the findings by [2], who stated that according to parametric sensitivity analysis performed in CyberMart[1] the outdoor temperature, refrigeration load from cabinets, compressor efficiency and the opening time of supermarket are the main affecting parameters. In [7], the author concludes that the heat extraction rate to maintain the temperature level in a RDC is linearly dependent to the enthalpy of the indoor air. This would then cause about half of the energy demand of the stores to be linearly dependent on the indoor air enthalpy. This has been studied in [8], who concluded that a reduction by 5% RH indoors would decrease the refrigeration load by 9.25% and hence, the overall energy demand by 4.84%.

However, none of the above factors were mentioned to have a significant correlation with the electrical energy demand according to [35]. By stepwise multiple linear regression of the energy demand of supermarkets in UK, [35] states that by knowing only the Sales floor area,

---

[1] Software for indoor climate and energy simulations in supermarkets

Volume of sales, Food to Non-food ratio of sales area and year of construction, the annual energy demand can be calculated confidently.

The disagreements in the above mentioned studies show the complexity of the energy systems within a supermarket and also the vast possibilities to set system boundaries, functional units and angle of view differently. Therefore, this thesis will introduce and describe the supermarket and its sub systems in detail before discussing the potential location and effect of energy efficiency measures and thermal storage.

The energy flow map of a supermarket presented in 2.2 and the sub-systems described will serve as a basis for the discussions.

2.1 Content - What does the supermarket contain

To align the view of the reader and author of this thesis, this section will introduce what in this thesis will be referred to as a "supermarket". The market is an arbitrary market in which content represents what can be seen as a typical 1300 m^2 market. In Figure 2.8, a plan drawing of the supermarket is presented.

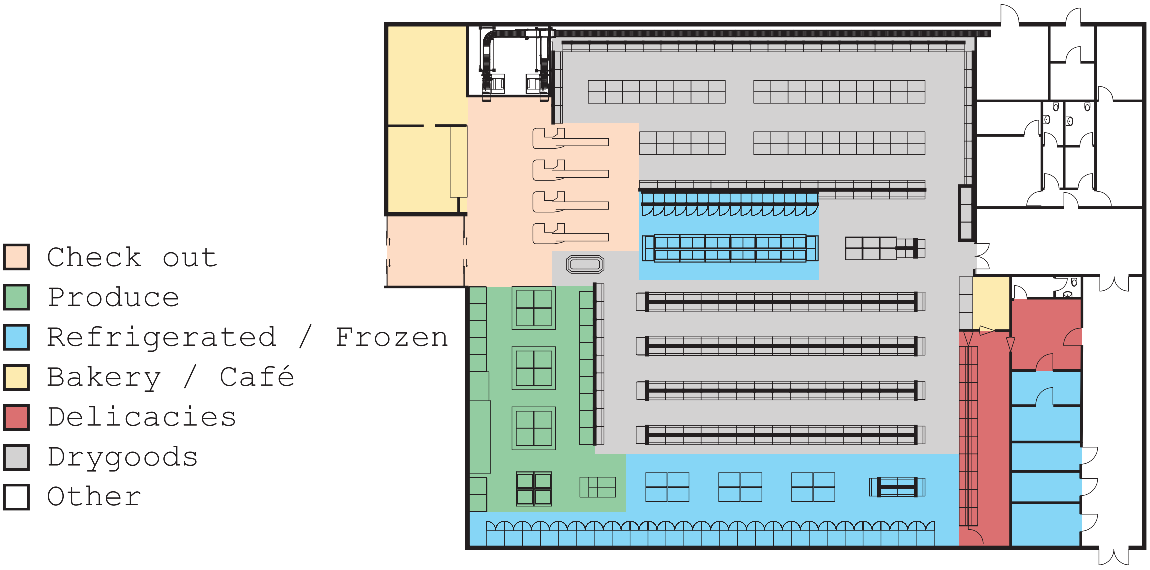

Figure 2.8: Floorplan of a typical 1300m^2 supermarket with some areas and functions marked according to the legend.

Entrance area is designed as a wind lock, keeping the outdoor climate from affecting the indoor by creating a barrier for the draught. The strategy to block the wind varies from store to store, but a common configuration is either a revolving door or a pair of sliding doors working as an air lock. In addition, the entrance is equipped with high power heaters to ensure no cold draught is allowed to pass further into the checkout area.

Checkout area is where the cashiers are seated, located in the entrance and exit area. This area has the highest flow of customers and is often used to expose impulsive purchase goods, such as soda cans, sweets etc. Small freestanding refrigerators are placed in the area where the queue is lining up for to the cash registers. Often single packed ice cream is located in free standing low-temperature RDCs in the checkout area for more impulse purchasing.

Cafe area is also located in the entrance area. Serving coffee, cakes, baguettes etc. for customers entering or exiting the store. The cafe is located in a way that it is exposed to the high flow of people while still keeping a calm atmosphere for the customers seated there.

Bakery is located neighbouring the cafe and the entrance. The bakery is equipped with large ovens and a fully equipped kitchen to prepare food etc. for the cafe.

Produce is the first part of the sales area where fruits and vegetables are exposed. Some of the fruits and vegetables are kept in open refrigerated display cabinets with a water mist spray to increase the quality and life time of the products in the store. Other less sensitive and valuable fruits and vegetables are exposed to the customer on sales tables without refrigeration or moisture control.

Refrigerated goods is in the continuation on the produce area, containing the majority of all medium-temperature refrigerated food stuff sold in the supermarket. Several meters of joint closed refrigerated display cabinets are used to expose the products. Items on sales or campaigns are exposed on freestanding refrigerated open horizontal islands to allow for impulsive buying and easy refilling.

Frozen goods is where the majority of the frozen food, low-temperature refrigerated food, is exposed to the customers in the sales area. A combination of refrigerated closed vertical and horizontal cabinets is used.

General grocery area is the largest area in the centre of the sales area, where the dry goods and non-refrigerated food are exposed. The goods are exposed strategically to the customers and light conditions of the store ensures that the products looks as attractive as possible. The food stuff is exposed on shelves, constantly maintained by the store staff to be full and well organised.

Delicacies department is the area of the store where fresh meat, fish and cheese is sold. It is typically sold over a refrigerated serve over counter by specially trained staff. Behind the counter in the delicacies department, there is a table to prepare food and sinks for hygienic reasons.

Meat preparation room is where the meat is prepared before being exposed to the customers in the Delicacies department. The preparation room is located neighbouring the delicacies department and the cold storage rooms to ensure high hygienic standards. The meat preparation room is a flexible room with large free table areas and a separate air conditioning system to maintain high hygienic standards.

Cold storage rooms are placed neighbouring the preparation room and close to the goods entrance in the back of the supermarket. The cold storage rooms are divided in sub categories of chilled and deep-freezing rooms with temperatures of $3°C$ respectively $-25°C$. The rooms are well insulated and there is only staff inside when refilling the store or unloading incoming goods.

Goods entrance is the area where deliveries enter the supermarket. The area serves as a temporary storage for food stuff arriving before being placed in the sales area or stored in the cold storage rooms. The indoor area is separated from the outdoors by a port at the docking station.

Storage area is a temporary place for arriving goods that does not need refrigeration. The storage area is placed in an easy to access way from the goods entrance and sales area.

Changing rooms for the staff is located in the back of the store. They are equipped with locker, showers and toilets.

Technical room is where all building services and refrigeration system are located. The room is located on the second floor in the far back of the store in contact with the exterior walls to allow access to the outdoor air for ventilation and cooling.

Recycling unit is placed in the entrance area to allow customers to recycle their cans and bottles before entering the sales area. The unit is connected to a storage room for the compacted cans and bottles.

Managers office is located close to the cashiers in the entrance area to be able to respond quickly to any unforeseen event. The manager's office contains a computer, printer and the necessary equipment to manage the administrative tasks of a supermarket.

2.2 Energy map of a supermarket

Based on the previous section describing the content of a supermarket, this section describes the complex energy flows within the boundaries of the building envelope focusing on the energy in form of sensible and latent heat as well as electricity. The system is visualised in flowcharts where flows, feedback loops, gatekeepers and potential leverage points are discussed and analysed in a qualitative and conceptual manner.

An overview of the overall supermarket system is shown in Figure 2.9 where all the departments, functions and areas are visualised as lumps containing a more complex sub-system that will be shown separately in the following sections. Here it can be seen that the electricity node is connected to the majority of functions within the supermarket and that the electricity is then converted to heat within the system boundaries of the building for all nodes except the HVAC and condenser node which is located partly and fully outside, respectively. Concerning the moisture flows it can be seen that there are several sources of moisture within the store, e.g. products, customers, water mist spray etc.. At the same time, there is only three active moisture sinks e.g. HVAC, cold storage and centralised RDCs. These are all connected to the refrigeration system where electricity is used to convert all the latent heat to sensible heat and condensate water to be ejected to the outside by the condenser and sewage system, respectively. This aggregation of moisture and heat sources connected to the refrigeration system indicates that it should be one of the main energy users within the supermarket. In addition, the indoor temperature and moisture content is connected to the majority of the functions, which indicates that they have an impact on the overall system and must be taken into careful consideration to avoid sub-optimisation.

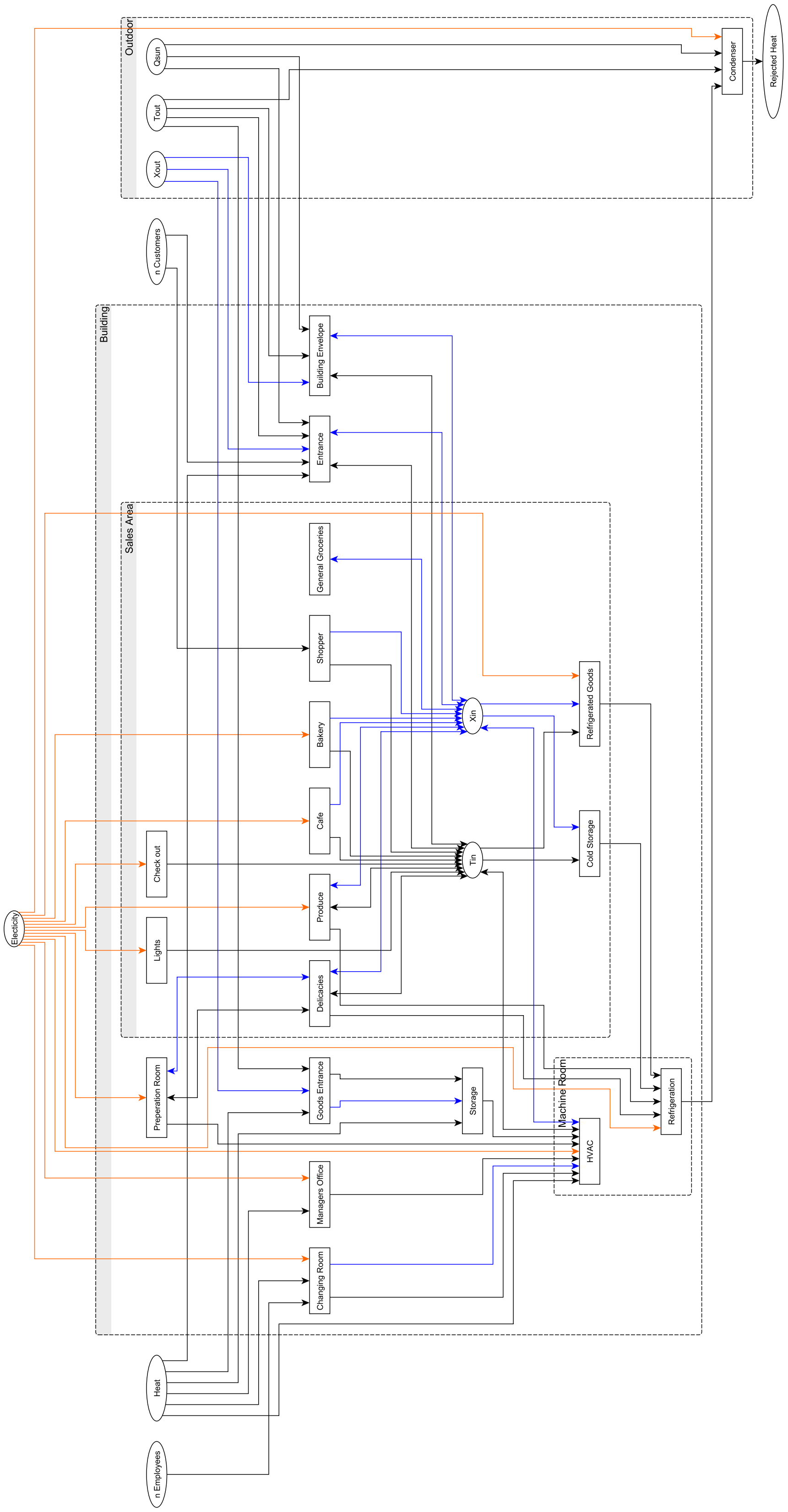

Figure 2.9: Sytematic overview of the conceptual energy flows and connections between subsystems within a supermarket.

In the sub-system of the envelope, as shown in Figure 2.10, it can be seen that the moisture transport thought the envelope is considered to be only via the gaps causing air leakage and through windows while being opened. However, the heat gains transferred from outside to the inside is to be considered as heat transfer by conduction. For this macroscopic study, the convection within the pores of the insulation material needs to be taken into account in the thermal transmittance of the material. This system highlights that the thermal transmittance of the wall, glazing, roof and slab is the key factor affecting the heat transfer through the building envelope. The moisture transfer is connected through the air leakage and the window openings as well as by vapour diffusion through the envelope.

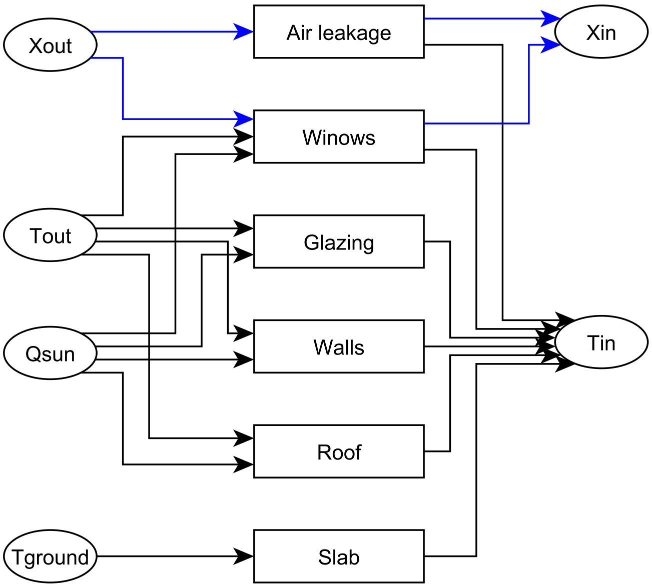

Figure 2.10: Systematic overview of the conceptual energy flows and connections within the sub-system of the envelope of the supermarket.

The entrance subsystem shown in Figure 2.11 is in direct contact with the outside, which in addition to the outside temperature, moisture and sun, is also containing active systems that are dependent on the electricity and heat supply. The flows of both heat and moisture is aggregated to a node called Infiltration before entering the store. In the system, it can be seen that the infiltration is affected by the door openings, which are desirable actions as it allows the customers enter the store. The heat and moisture flow can be affected either by regulating the entrance temperature and moisture content by passive measures, e.g. decreased thermal transmittance of the envelope or by design measures reducing the amount of infiltration per door opening.

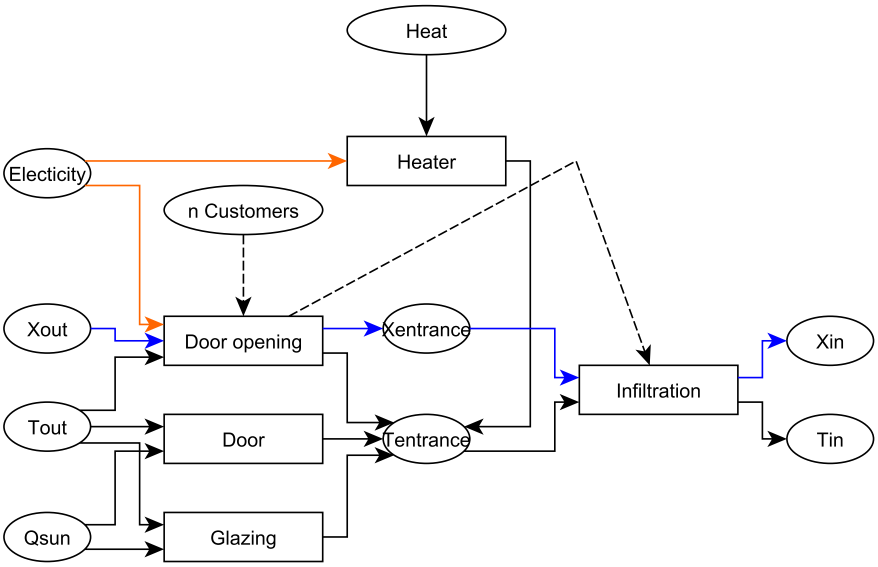

Figure 2.11: Systematic overview of the conceptual energy flows and connections within the sub-system of the entrance of the supermarket.

The goods entrance sub-system shown in Figure 2.12 is not as complex as the customer entrance. In the system it can be seen that the main variable affecting the entrance conditions is the delivery time, meaning the time that the door must be open while unloading the truck. The infiltration node here represents the path that the air must travel to affect the sales area conditions.

The sub-system that has the highest number of connections within the full supermarket system, Figure 2.9, is the HVAC node. As the HVAC system is a technical system with the purpose to condition the indoor air, its connections and energy flows are well represented by the Figure 2.9 and therefore, no further detailed sub-system was generated.

In Figure 2.13 a simplified sub-system of the refrigerated goods area is shown. The directions of the flows should be noticed. For the decentralised refrigerated display cabinets e.g. free standing refrigerated sales islands etc., the electrical energy is used to extract heat from the display cabinet, which is then rejected by the condenser into the indoor air. The condensate generated due to dehumidification at the evaporator is often evaporated by a heater and released to the indoor air as water vapour again. As both the condensate and rejected heat is

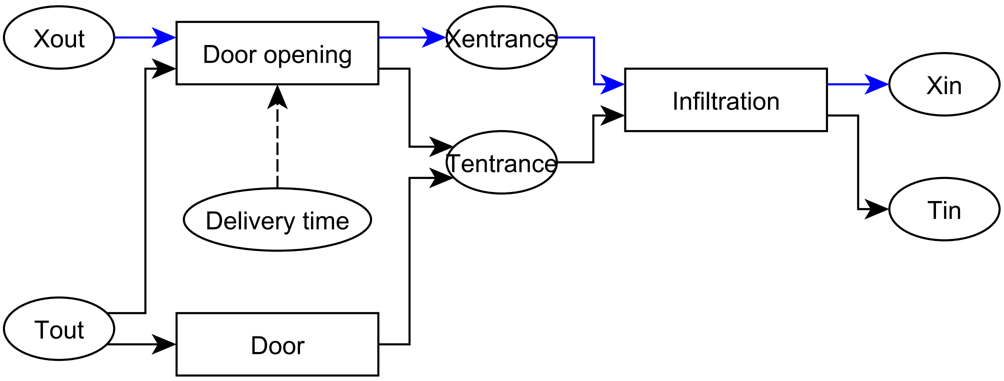

Figure 2.12: Systematic overview of the conceptual energy flows and connections within the sub-system of the good entrance of the supermarket.

brought back to the indoor air, the de-centralised RDC is to be considered as a heat source for the supermarket.

In contrast to the de-centralised RDC, the centralised system acts as a true heat and moisture sink for the indoor air. The heat extracted is transported outside of the system boundaries of the supermarket by the refrigeration system and rejected to the outdoor air where the influence is considered negligible. The condensate generated is collected and released to the sewage system by a gravity driven flow or a small pump.

A more detailed description and discussion of the centralised RDC energy system will be provided in Chapter 4. However, in Figure 2.14 the complex system for the refrigerated goods area with a higher level of details of the RDCs is shown to visualise the moisture and heat flows described above more clearly.

As can be seen in Figure 2.15, the systematic overview of the produce area is in many ways similar to the one of the refrigerated goods area. The main difference is that within the produce area there are non-refrigerated display cabinets for fruits and vegetables, both packaged and non-packaged, which contributes as a moisture source due to the evaporation of water from the products. In addition, there are active humidifying systems, spraying the

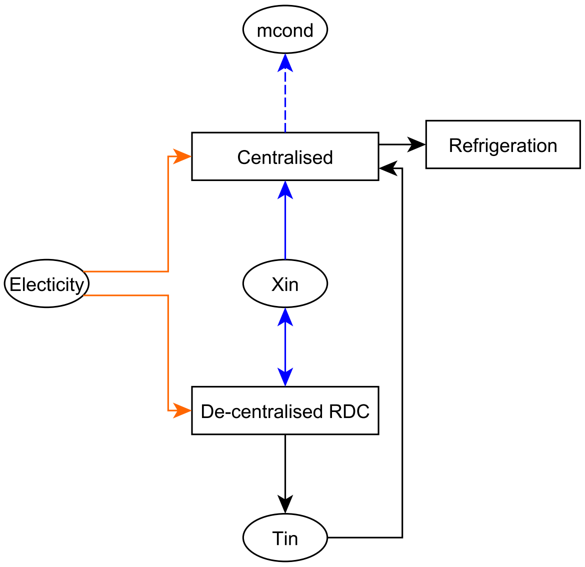

Figure 2.13: Simplified systematic overview of the conceptual energy flows and connections within the sub-system of the area for refrigerated goods in the supermarket.

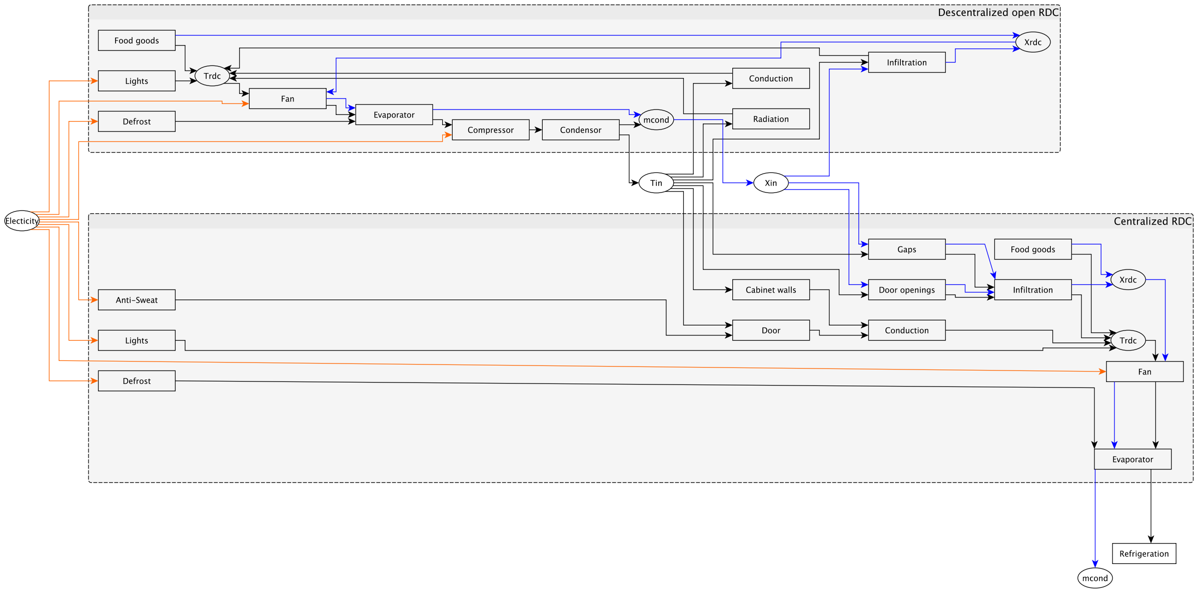

Figure 2.14: Complex systematic view of the conceptual energy flows and connections within the sub-system of the area for refrigerated goods in the supermarket.

products with a water mist to keep the moisture level high in order to increase the lifetime of the fruit and assure high quality. The increased moisture content is reduced partly by the de-humidification from the evaporator in the fruit RDCs.

Figure 2.16 is showing the sub-system of the delicacies department where meat, fish and cheese is sold over the counter. From the system, it can be seen that there are both heat and

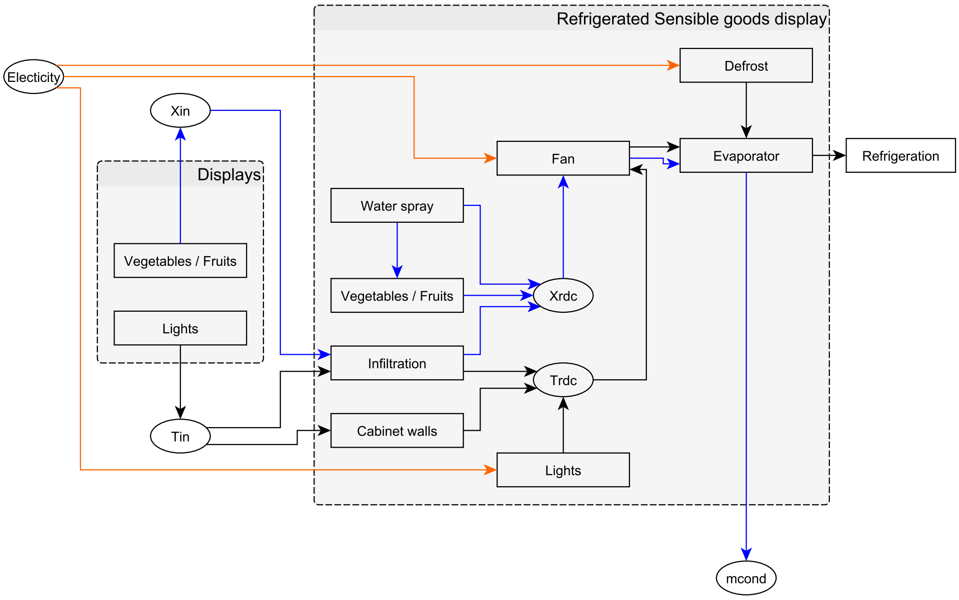

Figure 2.15: Systematic overview of the conceptual energy flows and connections within the sub-system of the produce area in the supermarket.

moisture sources in the form of machines, ovens and water taps. In addition, there is a heat and moisture sink in the refrigerated serve-over counter.

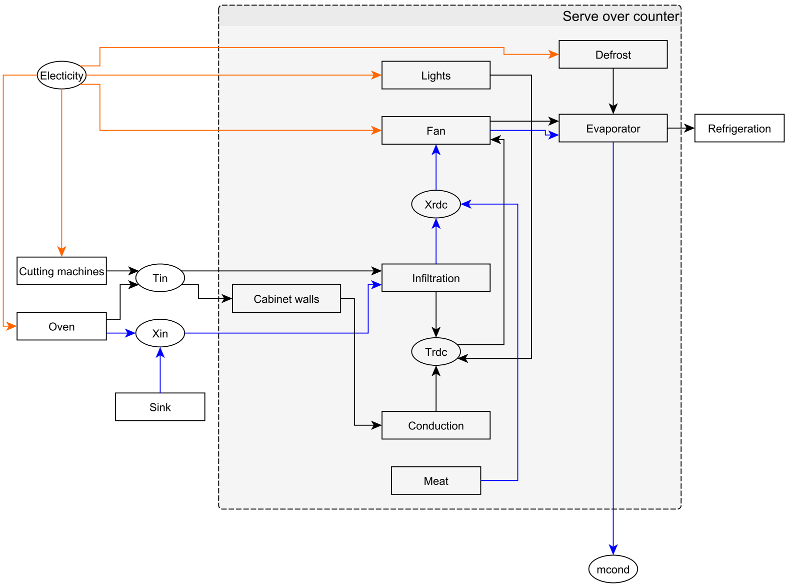

Figure 2.16: Systematic overview of the conceptual energy flows and connections within the sub-system of the delicacies department of the supermarket.

Figure 2.17 shows the sub-system of the cold storage areas in the supermarket. As can be seen in the system, the two factors contributing to its energy demand is the heat transfer through walls and the heat and moisture transport through infiltration while the door is open.

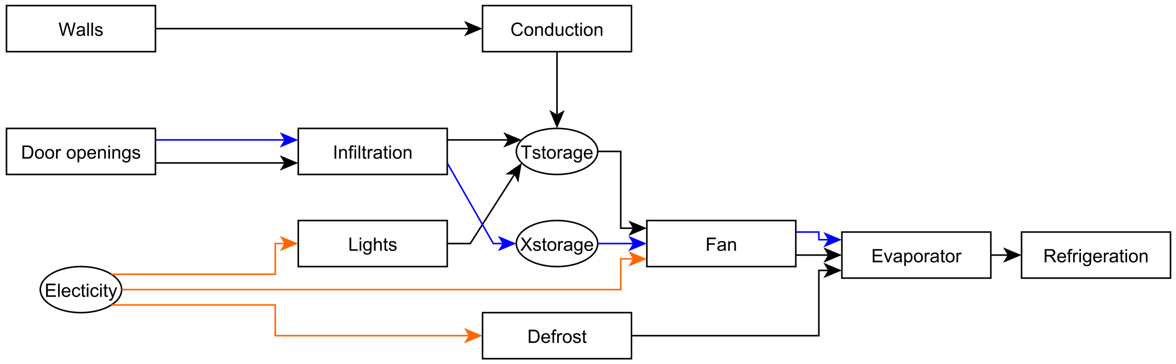

Figure 2.17: Systematic overview of the conceptual energy flows and connections within the sub-system of the cold storage areas of the supermarket.

The systems described above shows the interconnection between the different factors and functions within the supermarket. From the more holistic Figure 2.9, it can be concluded that the indoor temperature and moisture content affect several of the more energy intense functions of the supermarket, e.g. HVAC, RDCs. These indoor conditions are functions of multiple factors related either to the electrical energy demand or to the outside condition. The outside conditions are connected directly through the envelope, entrance and HVAC, which all are changeable functions. Therefore actions can be taken in these areas to affect the indoor climate. Light is transforming electrical energy directly to heat in the sales area. Although it is vital to have the right exposure to generate sales, the technology and strategies to achieve it are changeable.

The number of shoppers can also be seen as a factor is affecting the energy demand. However, the number of shoppers is related to sales and is therefore a desirable factor that should not be decreased.

2.3 Energy efficiency measures

Several supermarket companies around Europe are currently working on strategies and the implementation of energy efficiency measures in their supermarkets. The main driver to implement such measures are according to [29], the financial incentives. The energy use reduction is important for the profitability of supermarkets, as their operating margins are generally low [35]. Therefore, although the cost of energy is a small share in relation to the turnover, there is the potential to increase profitability by 15% if the energy demand is reduced by 50% [2]. Increasing energy prices and a growing need to label companies environmentally friendly have initiated a re-thinking in the food retail sector, causing several promising projects and technologies to be developed [4] [31] [29]. The potential for improving the energy efficiency and thereby lowering the emissions are very high [1].

Most energy efficiency measures are implemented on individual component level rather than taking the full complex system level of the supermarket into account [28]. To keep the shopping environment attractive for the customer while ensuring high food quality, the latent and sensible heating loads should be balanced [5]. When designing a Zero-energy building, the refrigeration system should be included in the system boundaries to avoid sub-optimisation [22]. The greatest potential for improvements of energy efficiency are refrigeration systems, display cabinets, indoor climate control and illumination [3].

In the following sub sections, some energy efficiency measures will be discussed focusing on their individual contributions for reducing the energy demand. In the concluding subsection the effects of these measures will be assessed on a system level in a qualitative manner.

2.3.1 Building services

The HVAC system conditions the indoor air, ensuring thermal comfort and a safe moisture balance within the supermarket. The energy demand for the HVAC system could be divided into heating, cooling and auxiliary electrical energy for fans, pumps and controls. The use of more energy-efficient motors for fans and pumps has reduced the auxiliary energy demand for

HVAC systems. The motors also often have the possibility to run on a partial load, allowing the system to benefit from variable air and heat carrier flow rates in the system, tailoring the supply to the demand. The benefit of variable flows can be utilised by the control system, which conditions the air in accordance with the requested indoor conditions and demands on the indoor environment, so called demand controlled ventilation.

The additional energy needed for heating is provided either via a local boiler, district heating or an electrical heater. As a cost effective energy efficiency measure, parts of the heat might be recovered from the exhaust air through heat exchangers, pre-heating the inlet air or in case of higher outdoor temperatures pre-cooling it. Other systems also utilise a recirculation of air, reducing the need to condition the air from outdoors to the indoor demands. The latter demands a more advanced control system to ensure that a sufficient amount of fresh air is supplied.

A recent development has been to reintroduce the use of ejected heat from the refrigeration system for space heating of the supermarket, which may reduce the energy demand for heating by about $30 - 40\%$ [31]. To do so, the condensing temperature must be increased, which does increase the energy demand by the refrigeration system [2], possibly resulting in sub-optimisation. The balance between the refrigeration load and heating demand must be achieved to ensure a comfortable indoor climate.

A decrease in heat extraction demand for space cooling is similar to heating in favour of recirculation or heat recovery solutions for exhaust air. Recent developments in compressors, refrigerants, floating suction and condensation temperatures has also led to a decrease in electrical energy use for space cooling.

In a study performed in two Swedish supermarkets where occupancy controlled ventilation with recirculation and heat recovery from the refrigeration system was implemented and the energy demand for HVAC was reduced by 63% and 82%, respectively [22].

2.3.2 Building envelope

According to a senior energy manager of a German supermarket company, the ideal supermarket envelope would be when it is so well insulated that the indoor climate is independent of the outdoor. To increase the performance of the building envelope, mainly three parameters are adjusted: thermal conductivity, thickness of the insulation material and air tightness.

Emerging materials, such as vacuum panels and aerogel with thermal conductivities being 50% of regular insulation material reduce the heat loss by conduction and allow new design solutions to overcome the thermal bridges in the building envelope.

Another parameter that is commonly adjusted is the increased thickness of the building envelope, also reducing the heat losses by conduction to the outdoor climate.

In addition, the air tightness is important for reducing the heat loss by convection and limiting the infiltration of air, which reduces the efficiency of the HVAC system.

In sunny regions, alternative roof coatings with high albedo, reflecting the heat from solar radiation, are used to decrease the cooling demand. This should be done carefully because according to energy simulations performed in the climate of Texas, it reduced the cooling demand by about 0.5 % while the heating demand was increased. Resulting in an overall increase in energy demand by 0.2 % [28].

The volume to envelope surface ratio, e.g. shape factor, is also of great importance for reducing the heat losses. When designing in accordance with the passive house standards, this is often used as a conceptual design parameter to reduce the heat losses through the envelope. However, there are no publications on the application and evaluation of this methodology for the specific case of supermarkets.

2.3.3 Lighting

The main design criteria for store light is to provide satisfactory general lighting for customers and staff as well as making the food look attractive [22]. Recent developments on low energy florescent tubes and LEDs has allowed the stores to reduce the electrical energy demand without sacrificing the indoor light quality.

Another established energy efficiency measure is to install occupancy control for lights to eliminate the risk of having unnecessary energy demand for light that is not needed in unattended locker rooms, staff kitchen etc. In the store, the light conditions may be adapted to the available light outside. When daylight is limited, the indoor lighting can be damped to be more comfortable to customers as well as lowering the energy demand [27].

A combination of skylights and demand-controlled lighting has a potential to reduce the electrical energy for lighting of the sales area as it utilises the incoming light from the sun. But it can increase the demand for both heating and cooling. In addition, products sensitive to the heat from direct sunlight must be considered when designing the store layout if a sky light is considered.

2.3.4 Refrigeration system

The refrigeration system can be divided into the cooling plant and the RDCs. The cooling plant efficiency has increased with higher manufacturing precision and new technologies, such as floating evaporation and condensation temperatures being implemented as well as compressors with the ability to run on a partial load.

One energy efficiency measure for RDCs is to reduce the air infiltration by putting glass doors on them. Infiltration causes about $60-70\%$ of an open RDCs needed heat extraction [7]. By adding a door, the temperature fluctuations are limited, which allows the average temperature to be increased [22], lowering the heat extraction demand. Doors also create a more comfortable indoor climate for the customers around the refrigerated areas in the supermarket as they limit the spread of cool air. However, it is a debatable action to take to place a barrier between the food stuff and the customer. A senior manager of a UK supermarket stated: *"As of yet we do not put doors on chilled cabinets because the view from the business is that if you put a door between you and the product you are going to buy less."*[29]. Whereas a year later a Swedish senior manager stated *"We've measured the sales before and after installation of doors and compared to a reference store without noticing any difference. I guess there's a larger acceptance among our customers today as they know it's benefiting the environment"* [17]

Therefore a common compromise measure is to put covers over the openings only during closed hours to reduce the air infiltration without creating a barrier for sales. In an example in [6], the authors state that if adding night covering of a 20m horizontal open refrigerated cabinet, the cost of energy for the affected RDCs is reduced by 40% and the pay-off period is 1.2 years for the investment.

By lowering the relative humidity by 5% the energy use for refrigeration is decreased by 9.48% [8]. Lowering the indoor relative humidity does decrease the running cost for the refrigeration system while increasing the cost of air conditioning [20].

Both of the abovementioned studies with night covers and de-humidification were performed in supermarkets with open RDCs where the latent load due to infiltration is far greater than on closed RDCs. Therefore, the effect would be expected to be reduced if a similar study was performed on closed RDCs.

By smart controls, the refrigeration system could utilise the thermal inertia of the refrigerated food stuff to increase the electrical power flexibility of the supermarket [2]. By implementing such a control system the power demand could be reduced by 60-100% for 10-25 min without any additional thermal storage system installed.

---

[2] Danfoss presentation at the XVI European Conference about technological innovations in refrigeration and air conditioning.

2.4 Conclusions

To conclude Chapter 2, it can be seen in the statistics presented in the beginning that the trend for supermarkets is an increasing sales area with a higher share of refrigeration, causing an increase in the energy demand both per square meter and for the whole building in the future. The complex energy system of a supermarket show potential synergies between technical systems that can be advantageously utilised to increase the energy efficiency as well as for implementing a strategy for demand side management of electrical energy use.

Concerning the energy efficiency measures, a holistic approach must be taken. By increasing the energy efficiency of compressors and other individual components in the refrigeration system, the electrical energy demand can be lowered. However, the electrical energy and power demand is strictly dependent on the heat extraction rate, which must be investigated carefully. As the heat extraction rate is depending on the indoor air enthalpy, heat losses through the RDC envelope and infiltration from door openings etc. the whole building must be treated as an interconnected system.

As the example mentioned on the implementation of high albedo roofs, in sub-optimisation can occur if taking only that single action. However, if combining with heat recovery or another heating strategy. This might potentially lead to an overall reduction in energy demand.

The implementation of low energy lighting also increase the heating demand, while lowering the cooling load. But changing to low energy light does lower the overall energy demand, and the lowered energy demand then comes both from the reduced power to lights and from the reduced heat gains that would be handled by the air conditioning unit [27].

To further increase the energy efficiency of supermarkets it is necessary to have a holistic approach of the overall system. A slight decrease in efficiency on a small scale, could potentially lead to increased energy efficiency in the larger system. As an example, a more complex control system would most likely have a higher energy demand, but would compensate its increased energy demand by a reducing the energy demand of the overall system at a far greater magnitude.

Energy efficiency measures are often compared in a quantitative manner, comparing the useful and supplied energy for different setups. However, as stated in the beginning of this thesis, the temporal scale of energy efficiency measures are crucial when introducing uncontrollable renewable energy sources in the electrical energy generation. This demand for a shift in the approach of the pursuit of energy efficiency to also include the so called power flexibility of the system. If including the energy sources in the system boundaries of energy efficiency thinking and environmental evaluation, the demand side management of energy is a crucial action.

A potential area to be used for demand side management and increase in power flexibility is the electrical energy demand of the refrigeration system, where electrical energy is converted into cooling utilised by the RDCs and air conditioning. Here the thermal inertia of the system is an attractive and already available source for thermal energy storage that would increase the electrical power flexibility of the refrigeration system. Potentially also implementing cold thermal storage units to further increase the capacity of the system would make it more economically attractive.

Chapter 3

Refrigeration in supermarkets

As shown in Figure 2.4, annual energy demand per square meter for supermarkets has increased between 1990[36] and 2009[37] although several energy efficient technologies have been implemented over the years in between. Refrigeration represents the single largest share of the energy demand of a supermarket, and the trend is still increasing. The increase is a consequence of the consumers requesting more and more refrigerated food items, which increases the number of RDCs needed, and therefore, the need for refrigeration. However, for both RDCs and the refrigeration machines, the energy efficiency has been improved by the introduction of doors on RDCs, low energy lights and energy efficient fans, compressors and pumps etc. . However, if trends continue as expected with refrigerated food goods increasing in popularity [16], the heat extraction rate from RDCs must follow. Hence, depending on the energy efficiency measures developed for refrigeration machines, the electrical energy demand for refrigeration in supermarkets might stagnate or even decrease.

The most common refrigeration technology for supermarkets today is the vapour compression cycle, which utilises the latent heat of a refrigerant to transfer heat from the RDC to the condenser. Most often, this is implemented through a centralised direct refrigeration system serving all RDCs with cooling. With this technology, a $1°C$ decrease in the evaporating temperature will increase the energy use by the refrigeration by about 3% [6] [24]. This makes the system vulnerable as a single RDC would influence the overall system performance because the cabinet with highest demand sets the evaporator temperature [25].

The use of refrigerants has been debated for decades and different international agreements have led to phasing out what has been considered environmentally harmful refrigerants. In 1987, the Montreal protocol was established prohibiting the use of so called freons to avoid ozone depletion, and the concept of the ODP, Ozone Depletion Potential, was introduced for filtering refrigerants. In 1997, the Kyoto protocol was established to engage countries to reduce the release of greenhouse gases into the atmosphere to avoid global warming. With global warming being a current problem, the concept of the GWP, Global Warming Potential, was introduced as a measure to compare the environmental impact of refrigerants. This has pushed the development and implementation of synthetic and natural refrigerants with a lower GWP, such as HFC, NH_3, HC and CO_2. In 2006 the EU-commission adopted the first F-gas regulation to reduce the release of fluoridated greenhouse gases (F-gases) to the atmosphere. In 2014, the F-gas regulation was strengthened to prohibit GWP above 150 for supermarket applications from 2022 with the exception of centralised multi-pack refrigeration systems, where GWP under 1500 is accepted as primary refrigerant.

As the refrigeration system of a supermarket often is a large investment with a life time of around 20 or sometimes even 30 years, the above mentioned restrictions on F-gases creates uncertainties on the choice of a technical solution for refrigeration. The other technologies available for refrigeration will be presented in Section 3.2. Different systems for the distribution of refrigeration within the supermarket will be presented in Section 3.3. The chapter will also describe the physical process of the vapour compression cycle, the appearance and function of the most common types of RDCs, the basis of the temperature control systems used today and an introduction to what might be an alternative way of regulating the temperature and energy balance in the future.

3.1 The basic vapour compression cycle

The basic vapour compression uses a circulating refrigerant, which in the evaporating stage, absorbs heat and rejects it when condensing. By assuming no pressure losses within the system, there are only two pressures to consider in the refrigeration system. These two pressures are application dependent and relates to the temperature of evaporation and condensation of the refrigerant, and thereby the system performance.

In Figure 3.1 the basic vapour compression cycle system is shown, with each component marked with a number corresponding to the physical working principle of the refrigerant shown in a generalised pressure-enthalpy chart to the right.

1. The refrigeration cycle begins with high pressure liquid passing through an expansion valve or capillary tube, restricting the flow and lowering the pressure when entering the evaporator.

2. In the evaporator, the pressure is at the level where the boiling point of the refrigerant is. The energy required for the refrigerant to vaporise is absorbed from the ambient air through the evaporator heat exchanger.

3. The refrigerant then leaves the evaporator through the suction line before entering the compressor, where the pressure is increased to where the refrigerant has a temperature for condensation.

4. The high pressure refrigerant vapour then flows into the condenser, where it changes phase into a liquid state rejecting the heat that was absorbed in the evaporator earlier.

5. The high pressure liquid refrigerant is now back at point 1 and the cycle repeats.

To maximise the utilisation of the latent heat of vaporisation, it must be ensured that the refrigerant is in a liquid state when it approaches the expansion device before entering the evaporator. This is achieved by the implementation of a liquid receiver after the condenser and the utilisation of sub cooling by the condenser.

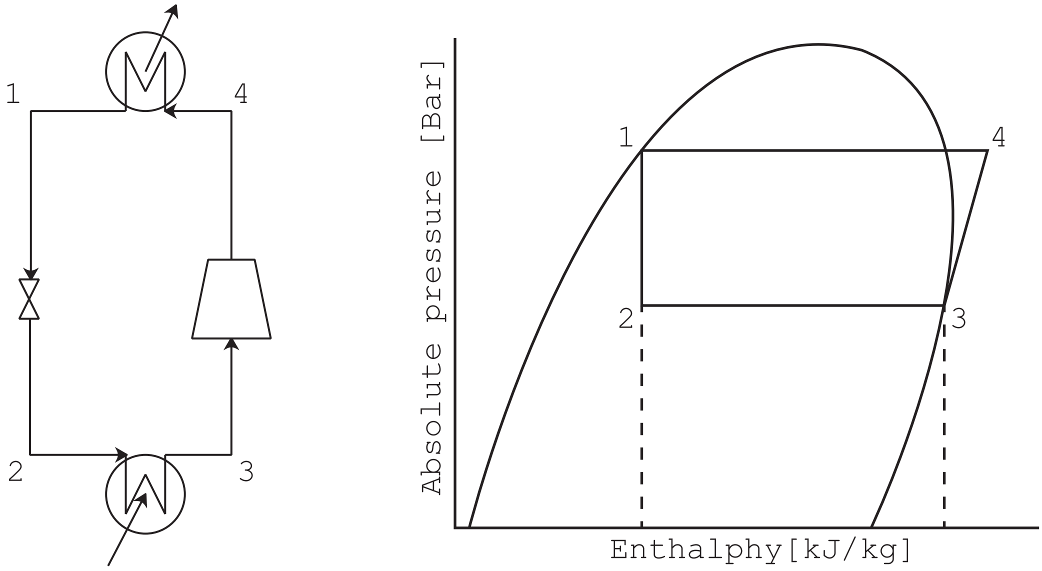

Figure 3.1: A schematic drawing of the basic refrigeration system and the refrigeration process drawn on a generalised pressure-enthalpy diagram

Sub cooling of the refrigerant does lowers the temperature below the saturation temperature at the high pressure side of the refrigeration cycle, resulting in an increasing enthalpy difference between the refrigerant entering and exiting the evaporator, which increases the heat absorbed by the evaporator as shown in Figure 3.2. It should be noted that sub cooling is achieved without affecting the compressor outlet conditions.

The liquid receiver is a container designed to trap any vapour that might pass through the condenser unit. The basic design is an inlet in the top and an outlet liquid line from the bottom, utilising the gravitational effect on the higher density of the liquid.

In the suction line, after the evaporator, it must be ensured that the refrigerant is fully vaporised to avoid liquid hammering, which could cause mechanical damage. This vaporisation is ensured by so called super heating of the refrigerant. A common way to ensure a higher temperature is to lower the mass flow by the expansion valve for the evaporator, resulting in a higher temperature of the exiting refrigerant. Other solutions using external heat sources or having the liquid line and suction line in thermal contact also exist.

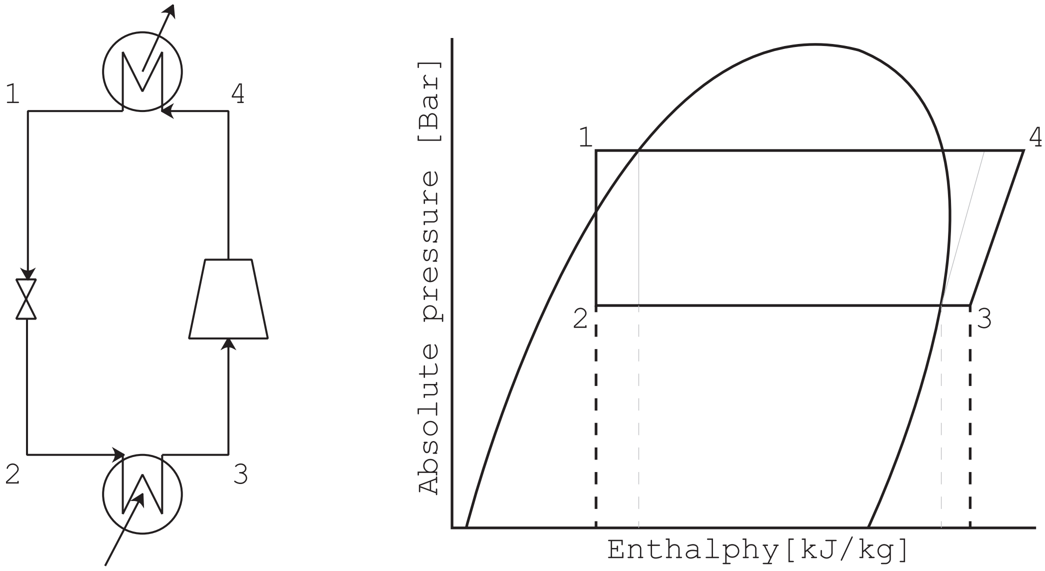

Figure 3.2: A schematic drawing of the basic refrigeration system and the refrigeration process including sub-cooling and super-heating drawn on a generalised pressure-enthalpy diagram

3.1.1 Cascade system

A cascade system is two basic vapour compression cycles connected though a heat exchanger serving as an evaporator and condenser for cycles A and B respectively, as shown in Figure 3.3. The heat absorbed in evaporator A is then transferred to cycle B and rejected at its condenser. The cascade system has the advantage of allowing the use different refrigerants for different stages of the refrigeration, lowering the required pressure for the low temperature cycle condenser. A common combination for supermarkets is a medium temperature R134A cycle connected to a low temperature CO_2-cycle.

The cascade system demands an increased level of controls to ensure a balance between the heat rejected by evaporator A and absorbed by condenser B. An unbalanced system might cause over temperatures, risking failure due to extreme pressures in the condenser of cycle B.

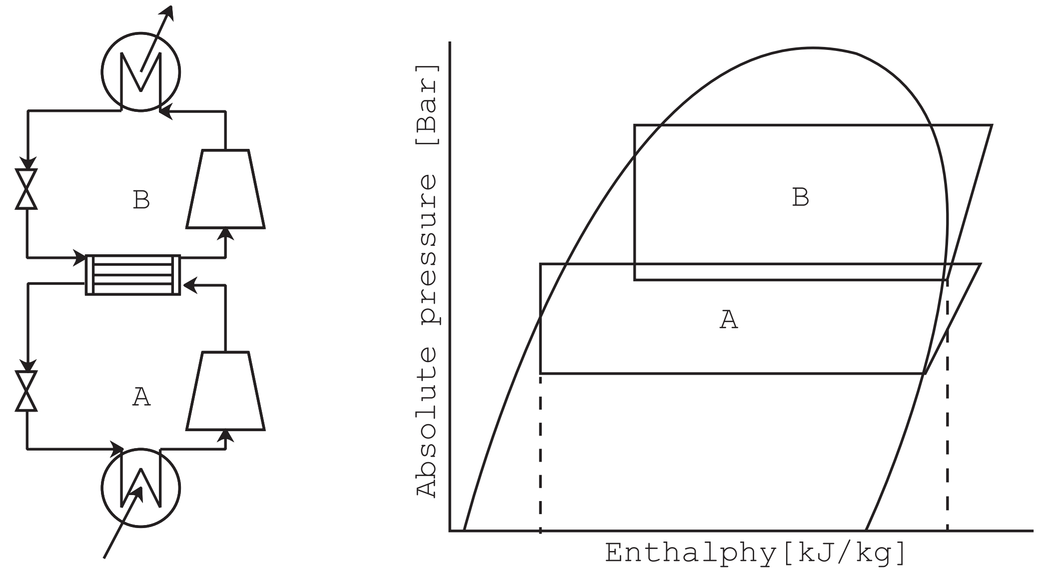

Figure 3.3: Schematic drawing of a cascade refrigeration system and the refrigeration process drawn on a generalised pressure-enthalpy diagram

3.2 Emerging technologies in refrigeration

In addition to the available variations of the vapour compression cycle, there are several other technologies for refrigeration. In a review on emerging technologies from 2009 [40], the characteristics of the different technologies was presented. In Table 3.1, the COP of the technologies presented there is shown.

Table 3.1: Summary of COP of emerging technologies for refrigeration. Based on the table presented in [40].

Technology	COP [−]
Tri-generation	0.3-0.5
Air-cycle	0.4-0.7
Sorption-Adsorption	0.4-0.7
Ejector	<0.3
Stirling	1-3
Thermoelectric	0.6
Thermoacoustic	<1
Magnetic	1.8

Ejector refrigeration is not considered to have a high potential for supermarket refrigeration as it has a COP of < 0.3 and demands a high temperature heat source. The use of tri-generation utilising the waste heat from local electrical energy generation to run a refrigeration cycle is not applicable as the amount of self consumption would be low due to the problem of balancing both electrical, heat and cooling demand in the supermarket simultaneously.

Sorption-Adsorption refrigeration systems are also not considered as the COP is low, in the range of $0.4 - 0.7$. As no free waste heat source is available from the supermarket, the sorption-adsorption refrigeration is not an attractive technology.

For the purpose of refrigeration in supermarkets in the range between -30 to $5°C$, the technologies found to have the highest potential are the Stirling cycle, thermoelectric, thermoacoustic and magnetic refrigeration. They are found to have a high potential as their COP is relatively high and could compete with the vapour compression cycle. A potential driver for implementation would be in case of legislation that limits or prohibits the use of HFCs or flammable refrigerants in RDCs [40].

3.2.1 Stirling refrigeration

The stirling refrigeration cycle has been used commercially for cryogenic refrigeration since 1953[1]. However, in close to room temperature application, the technology has not yet been able to penetrate in the larger market. There are some commercial products available with promising performance. A concept utilizing an oscillating magnetic field instead of pistons allows for the making of hermetically sealed and compact refrigeration units with high efficiency [2].

The ideal Stirling refrigeration cycle as shown in Figure 3.4 can be described as in the list bellow. It should be mentioned that there are several variations on the principle available for practical applications.

1. The refrigeration cycle starts with the gas in the left chamber being in thermal equilibrium with the surrounding air.
2. The gas is then compressed by the left piston and the heat is released to the surrounding environment.

---

[1] http://www.iuac.res.in/reres/cryo/icc/TBhowmick.pdf,Accessed: 20160602

[2] http://fpsc.twinbird.jp/legacy/en/index.html,Accessed: 20160510

3. The right piston moves further expanding the gas.
4. The expanded cold gas absorbs heat from the surrounding causing it to further expand.
5. The cold gas is then moved through the re-generator, absorbing heat and returning to the position and condition as shown in 1.

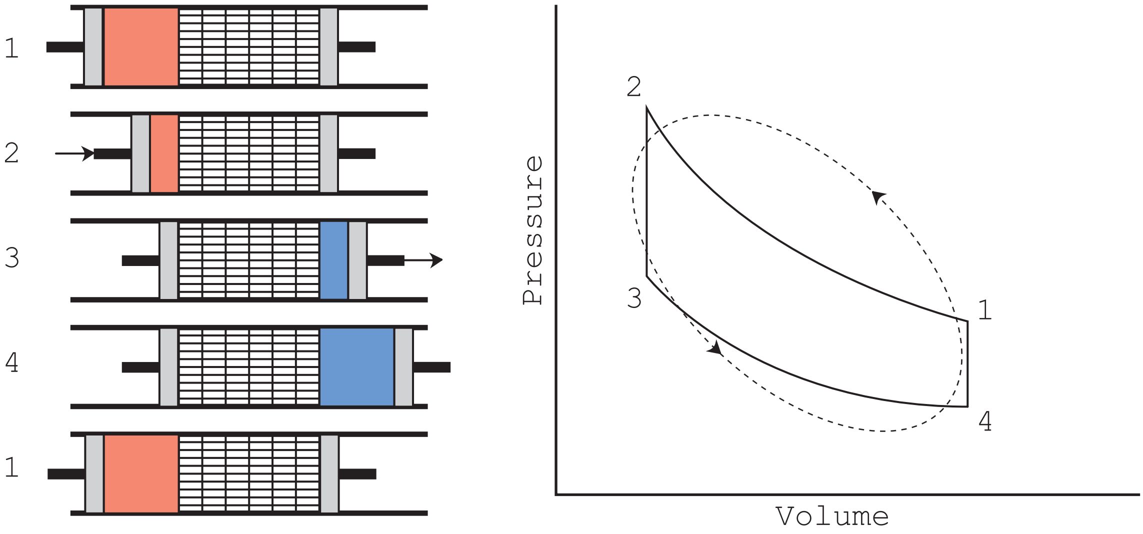

Figure 3.4: The working principle of the stirling cycle refrigeration. To the left, a schematic drawing of the process and to the right the process in a pV diagram. The dashed line illustrates the practical cycle and the solid line represents the ideal cycle.

3.2.2 Magnetic refrigeration

Magnetic refrigeration is based on the magnetocaloric effect, causing a material to change its heat capacity when exposed to a magnetic field. The magnetic refrigeration is a technology that demands no moving parts except the moving fluid. This makes the technology attractive as it can be built into quiet and compact machines. The main barrier for implementation is the currently high cost and limitations of the magnets and working fluids. However, the research interest is increasing, hopefully enabling the required development [18].

The working principle of the magnetic refrigeration can be explained by Figure 3.5 as described in the list below.

1. The refrigeration cycle starts with the magnetocaloric material being in thermal equilibrium with the surrounding.

2. Between 1-2 a magnetic field is introduced which reduces the materials magnetic entropy and heat capacity. The process is adiabatic, so the material's temperature increase.

3. Between 2-3 the material is exposed to a heat sink, reducing the temperature to be in equilibrium with the surrounding.

4. The magnetic field introduced between 1-2 is removed at 3-4, causing the material to retain its original magnetic entropy and heat capacity. This change is results in a decrease in temperature.

5. The material is exposed to a heat source, increasing the temperature to be in equilibrium with the surrounding. The material is now back to its original conditions and the cycle repeats.

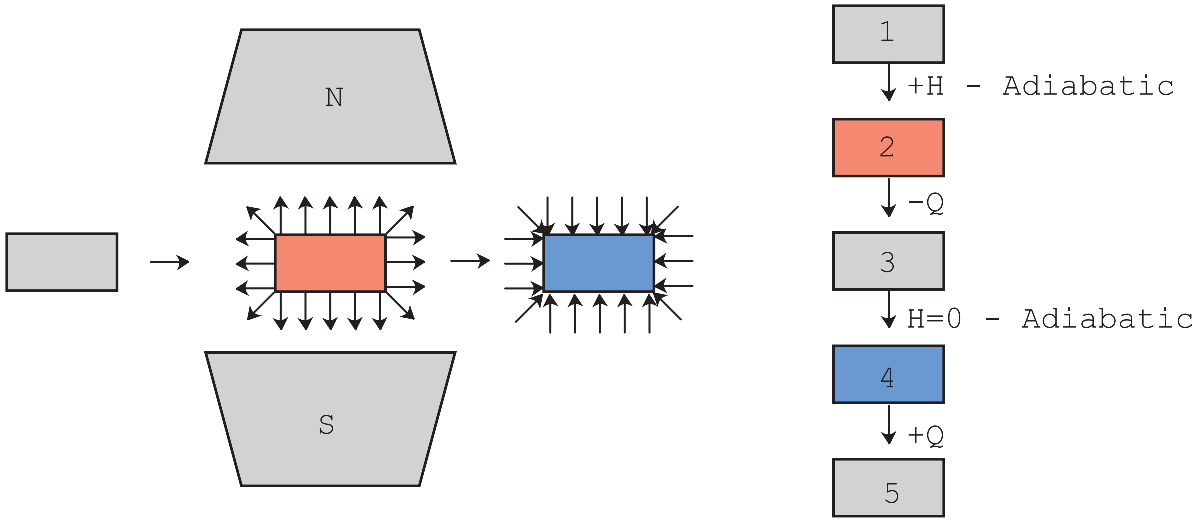

Figure 3.5: Showing a schematic drawing of the magnetic refrigeration machine to the left and the working principle diagram to the right.

3.2.3 Thermoelectric refrigeration

The thermoelectric refrigeration process is often referred to as the Peltier heat pump, solid state refrigerator, or thermoelectric cooler (TEC). The process is based on the Peltier effect where a current induces a heat flux between the junction of two materials. In opposite to the other the other emerging technologies described in this thesis, the thermoelectric cooling does not have any moving parts. To the right in Figure **??** a thermoelectric device is shown. This type is used in smaller camping refrigerators, water coolers etc. The active part of the thermoelectric plate is embedded between layers of ceramics to protect it. The thermoelectric film itself is flexible and could be shaped freely. The working principle is shown to the left in Figure **??**. It is based on a current that is induced over semiconductors, causing the electrons or protons to move which induces a heat flux.

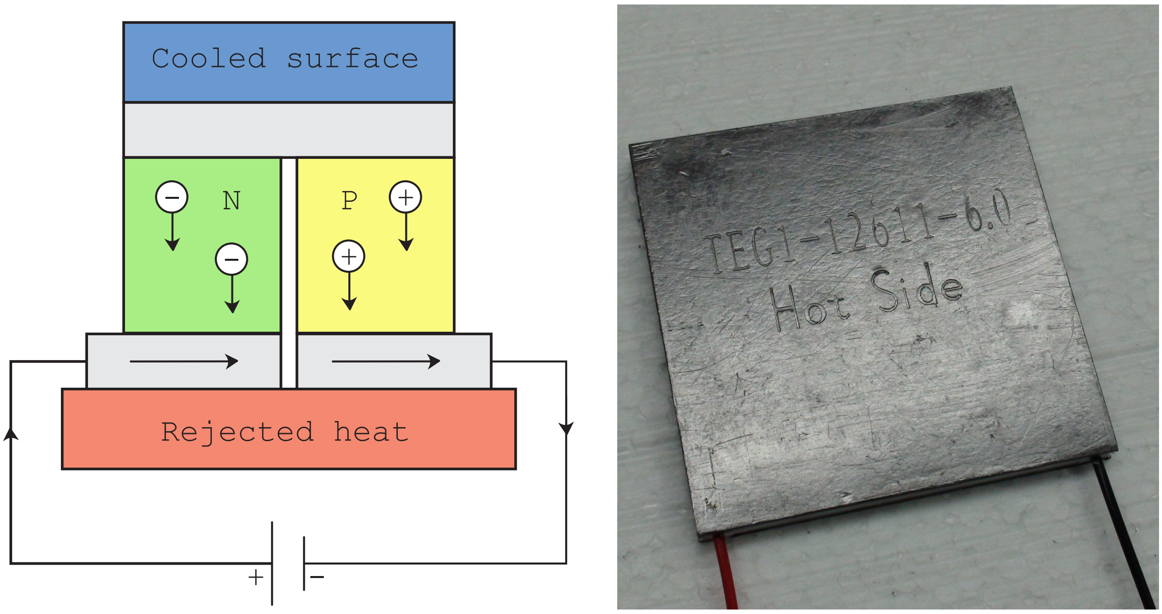

Figure 3.6: Showing the working principle of a thermoelectric refrigeration element to the left and a product photo of a thermoelectric cooling plate from a camping refrigerator. Image source: *https : //en.wikipedia.org/wiki/Thermoelectric_effect/media/File : Thermoelectric_Seebeck_power_module.jpg*

3.2.4 Thermoacoustic refrigeration

Thermoacoustic refrigeration benefits from having few moving parts. The thermoacoustic refrigeration machine consists of a pressure wave generator (Speaker), a resonator tube and a stack where heat exchange occurs. A schematic drawing of the thermoacoustic refrigeration machine is shown in Figure 3.8. The working principle of the machine is shown in Figure 3.7 and described as:

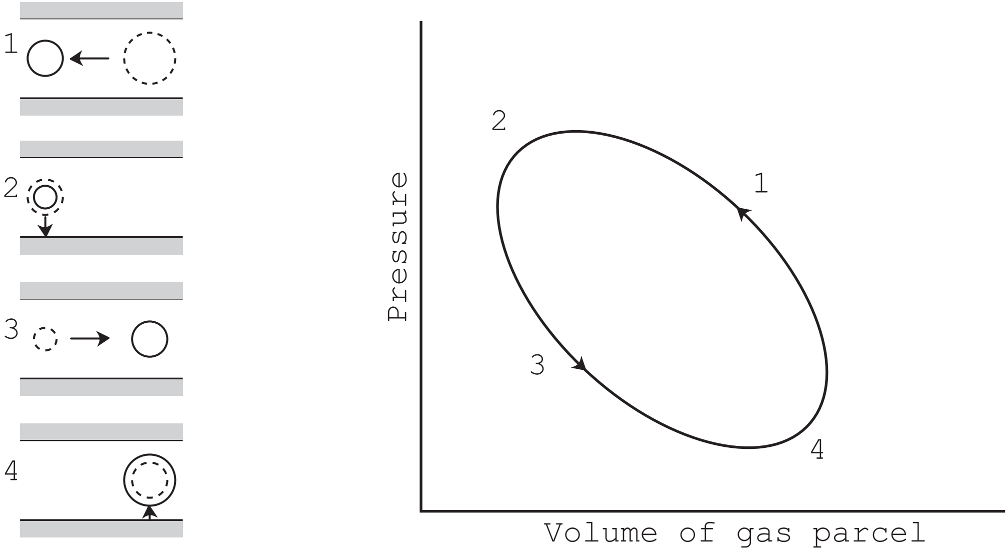

Figure 3.7: Showing the working principle of a thermoacoustic refrigeration process.

1. The refrigeration cycle starts with the gas parcel in the stack being moved towards the left. Being compressed by the increasing pressure.
2. The compressed gas parcel releases the excess heat to the stack.
3. The pressure is then decreased, transporting the expanding gas parcel to the right.
4. The expanded gas parcel absorbs heat from the stack and then the cycle repeats.

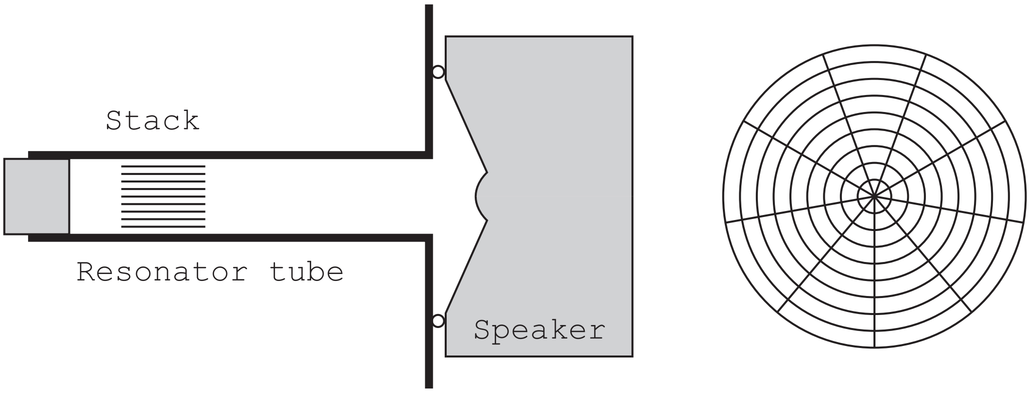

Figure 3.8: Showing a schematic drawing of a thermoacoustic refrigeration machine to the left. To the right, a top view of the stack.

3.3 Distribution of refrigeration

In supermarkets, there are two main categories of the distribution system of refrigeration within the store, either direct or indirect. A direct system can be described as it is transporting the heat from the refrigerated space to where the heat is released directly, whereas an indirect system includes a secondary fluid transporting the heat from the refrigerated space to a refrigeration machine. The heat rejected by the chiller is then transported by another secondary fluid to where the heat is released. Within these categories, there are several types of variations between partially indirect or direct, distributed systems etc., which this thesis will not describe in any further detail. A schematic drawing showing the two main categories is shown in Figure 3.9.

Direct systems are the most commonly used systems with the benefit of a lower mass flow demand of refrigerant through the heat exchanger, evaporator, in the RDC because they utilise the latent heat of vaporisation of the refrigerant. This reduces the energy needed for pumping the refrigerant in the system. As the heat exchange occurs directly between the refrigerant and the RDCs air, the evaporation temperature can be kept higher than for an indirect system. In indirect systems, the heat exchange with the RDCs air is on a secondary

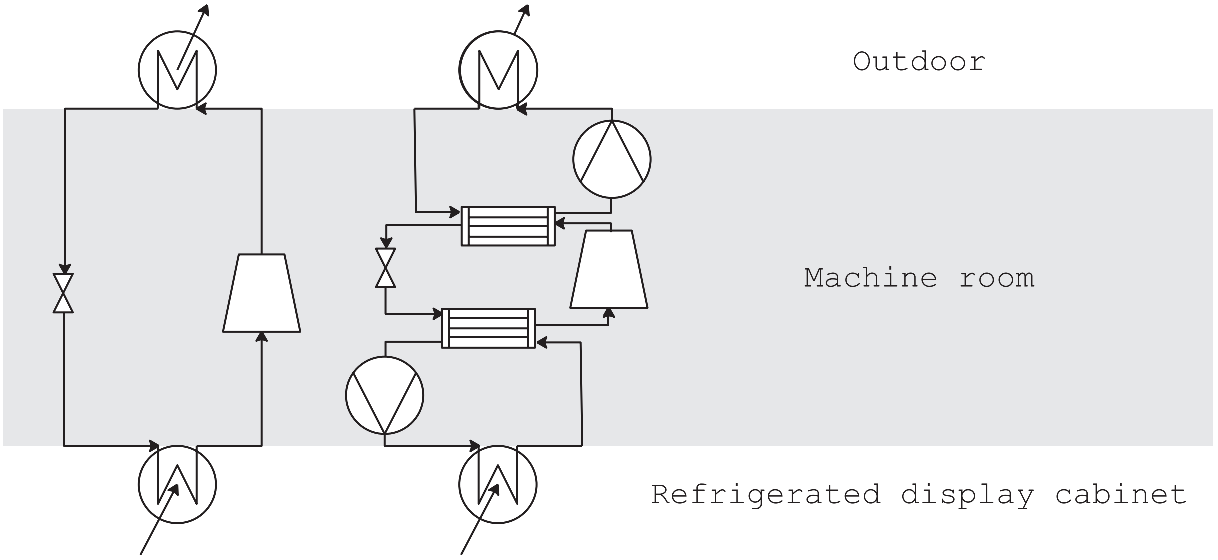

Figure 3.9: Schematic drawing of a direct (Left) and Indirect (Right) refrigeration system.

loop, demanding the evaporator temperature be lower in the primary loop, increasing the energy demand as a result of the lower COP for the refrigeration plant.

However, in indirect systems, the refrigerant charge can be reduced to $5 - 15$ % of the original charge [12]. In addition, indirect systems can be made industrial and compact which increases the precision of manufacturing and by that reducing the risk of leaks. The higher precision and possibilities to fine tune also improves the efficiency.

Despite the introduction of secondary loop and increased need of pump work for the secondary fluid, indirect systems have shown a reduction in energy demand in practice [12]. This is an effect of the above mentioned increase in manufacturing precision. However, the indirect systems benefits from an easier way to store and regulate the refrigeration by speed controlled pumps[6].

By choosing an indirect system, the refrigeration machine can be adapted to new legislation without changing the full system. In addition, the system can be modified easily to match the increased or decreased need for refrigeration by adapting the chiller to the demand.

3.4 Refrigerated display cabinets

There is a great amount of variation of RDCs used for different purposes in supermarkets. In this section, the most common models are presented with a section drawing and a short description of their use.

3.4.1 Serve over counter

The serve over counter is commonly used in the delicacies area, where only the staff have access to the food, but still allowing the customer to have a clear view of the products and the possibility to point and choose their selection. A section drawing is presented in Figure 3.10.

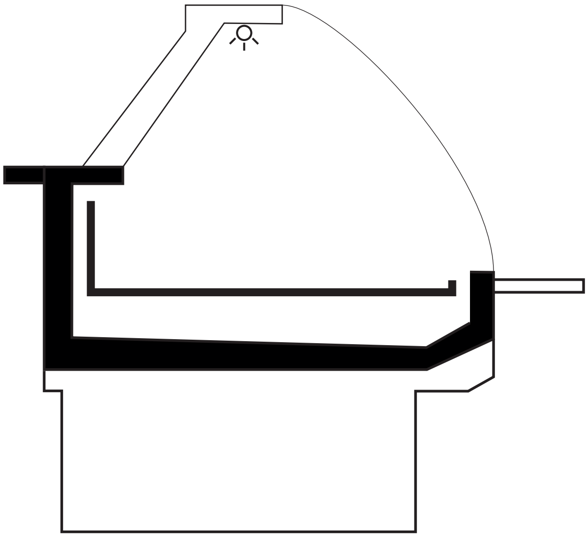

Figure 3.10: Section drawing of a serve over refrigerated display counter typically used in the deli area.

3.4.2 Horizontal open display cabinet

Horizontal open display cabinets are used for impulsive sales, often less sensitive products, such as sodas, fruits and packed smoked ham, etc. The disk gives the customer a quick overview and no barriers to access the food stuffs. The horizontal open display cabinets are mainly used for medium temperature food. A section drawing is presented to the left in Figure 3.11.

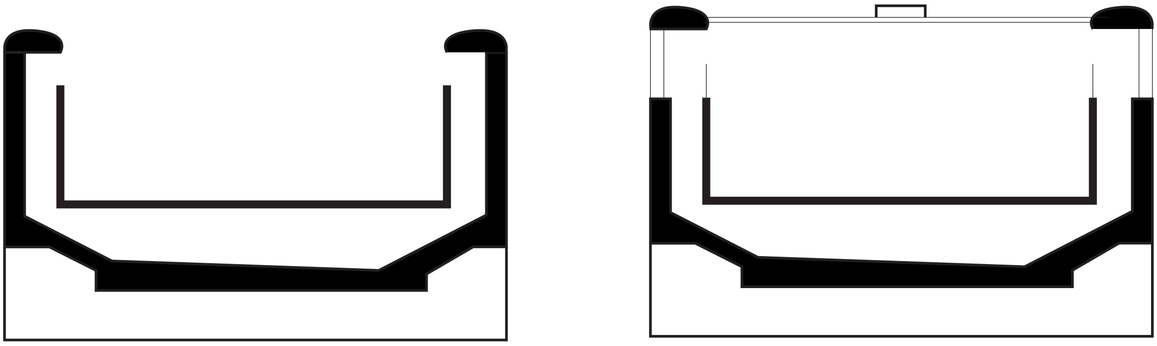

Figure 3.11: Section drawing of an open and a closed horizontal refrigerated display cabinet on the left respectively right.

3.4.3 Horizontal closed display cabinet

The horizontal closed display cabinets are commonly used for frozen food stuffs. The lid reduces the infiltration of air, but also creates a barrier between the products and the customer. A section drawing is presented to the right in Figure 3.11.

3.4.4 Vertical open display cabinet

Vertical open display cabinets are often used for products with a high exchange rate requiring a medium temperature cabinet. This type is also used for sensitive fruits, vegetables and flowers, sometimes in combination with a humidification system ensuring a high relative humidity to preserve the products. The vertical cabinets allows the customer to gain a quick overview of several products at the same time. A section drawing is presented to the left in Figure 3.12.

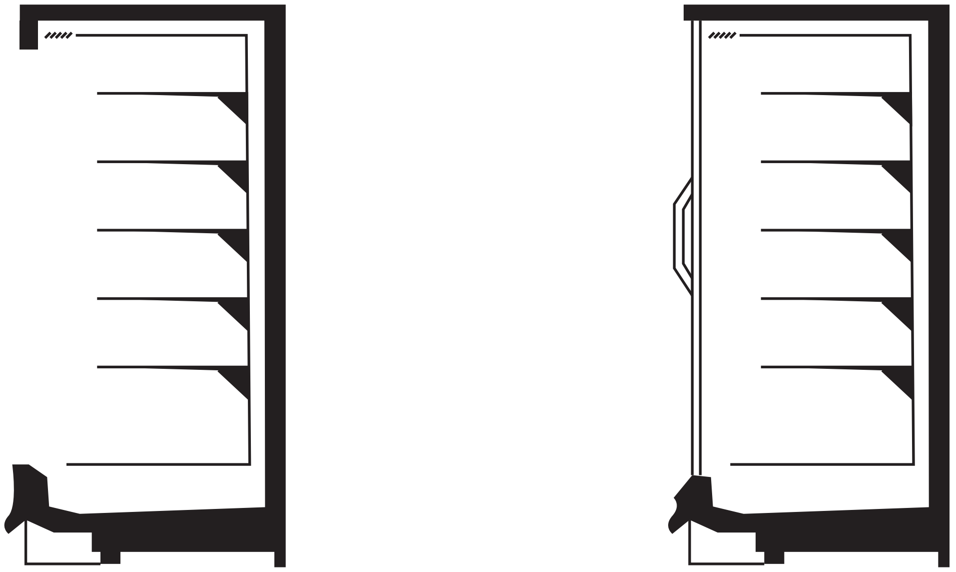

Figure 3.12: Section drawing of an open and a closed vertical refrigerated display cabinet on the left respectively right.

3.4.5 Vertical closed display cabinet

The vertical closed display cabinet is the most common cabinet type for medium temperature products and often used for low temperature products. The vertical closed cabinet has the benefit of having a more stable temperature than the open, making it ideal for sensitive products such as meats. Just like the open vertical cabinet, it allows the customer to gain at quick overview of the products, but having a door as a barrier between them and the products. A section drawing is presented to the right in Figure 3.12.

3.5 Temperature control system

For an RDC to be able to manage the temperature of the food goods, it uses a control system that is balancing the heat extraction rate with the heat gains. In the case of an excessive heat extraction rate, there is a risk of frost damaging the food goods due to the sub temperatures. In addition, the heat extraction is linked directly to the electrical energy demand by the refrigeration machine, making it a non-economically viable strategy. As too low heat extraction would cause over temperatures in the RDC and potentially lead to food loss, it has severe economic consequences. With these two scenarios encircling the preferred heat balance, it is crucial to have a temperature control system to maintain the demanded temperature range of the products. By non-destructive testing, it is not possible to measure the real food temperature, so it must be predicted by other measurements.

The most common way of predicting the food goods temperature is by measuring the air temperature in the air discharge and return. These temperatures are then used to predict the food temperature as a temperature in between them using a weighting set by the refrigeration technician when installing the RDC. The food goods temperature can be expressed mathematically, as shown in 3.1 with a weighting of $x = 0.5$ [3].

$$T_{Food} = xT_{Discharge} + (1 - x)T_{Return} \tag{3.1}$$

These values are then used for the control system to adapt the refrigeration strategy to the assumed demand of the RDC, either by increasing the frequency and duration of refrigerant supply or by changing the evaporation temperature of the refrigerant.

3.6 Conclusions

From this chapter it can be seen that the refrigeration systems of supermarkets are large and complex systems that holds almost endless possibilities of adapting to the specific needs of any supermarket. The vapour compression cycle is by far the most common technology used for refrigeration in supermarkets, but promising and emerging technologies will potentially enter the market in the future. For supermarkets to be able to adapt to both new legislation, profitable new technology or changes in consumer trends it is important to have a built in flexibility in refrigeration system design. Thus, the indirect distribution system for refrigeration is more beneficial than the direct. By de-coupling the RDCs from the technology used for generating the refrigeration the supermarkets can easier take advantage of new and

---

[3] Interview with Chris Clausen, Kälteanlagenbauermeister, Clausen Systemkühlung, 2015-05-20

emerging technologies that otherwise would not have been economically feasible if the full refrigeration system must be replaced. In addition, by replacing the high pressure pipework in the sales area, the flexibility increases as the secondary refrigeration fluid can be pumped at lower pressures which allows more flexible pipework to be used.

The indirect system also benefits from being able to better adjust the heat extraction rate to the demand, and it can also be used to re-distribute heat within the refrigeration system to better utilise the thermal mass available.

Concerning the emerging technologies, reducing the number of moving parts and increasing the compactness is an attractive goal from a financial and engineering perspective because it reduces the need of maintenance and hence, the running cost. Whether there will be any technology that will replace the vapour compression cycle or if it will be used in combinations is yet to be seen. However, with the current research focus on energy efficiency and the trend towards more and more refrigerated food goods being sold, it is most likely that there will be measures taken to further increase the energy efficiency of the refrigeration machines. As profit margins are low in supermarkets, it is a great advantage to be able to adapt to such measures lowering the running costs in an easy way to avoid excessive initial costs. Therefore, the flexibility of the indirect refrigeration system is preferred.

Introducing the temporal scale into energy efficiency measures would demand further development on the control systems for the refrigeration system. Proactive systems with the possibility to forecast coming events affecting the heat balance would maximise the utilisation of the thermal capacity of a supermarket.

Chapter 4

Energy mapping of vertical closed refrigerated display cabinets

As concluded in the previous section, the heat extraction from RDCs represents a large share of a supermarket's electrical energy demand and significantly influences the heat energy required within the supermarket. To be able to have a more in-depth understanding, analysing and improving the overall energetic system of a supermarket, developing a highly detailed understanding of the RDC behaviour is necessary.

Similar to the introduction of supermarkets, the RDC will be introduced with a conceptual systematic overview in Figure 4.1. A brief literature review on current and previous research is then performed to understand the energetic behaviour of RDCs. Based on the findings in the literature review, a two-dimensional (2D) computational fluid dynamics (CFD) model was produced to visualise the temperature field of the RDC. From this model, inhomogeneity in the temperature field of the air return channel was found at the position of the temperature sensor feeding the control system. The effects and the practical implementations of these findings are presented in Chapter 5

4.1 Systematic overview of a refrigerated display cabinet

In Figure 4.1, an isolated systematic overview of the energy flows in a RDC is shown. As the temperature within the RDC should never exceed the indoor temperature, the RDC can be seen as a permanent heat sink for the supermarket. The flows within the system are directed towards the evaporator and thereby the refrigeration system of the supermarket. The latent heat of the indoor air is affecting the heat extraction demand by infiltration, either through gaps between doors or door openings. Door openings are considered to be so-called desirable action because they generate sales. However, the gaps between the doors are a consequence of tolerances when designing, building and using the RDC that is a non-desirable feature. The latent heat is also affected by water vapour from foodstuffs being exposed to air in the RDC, leading to more humidity. Additional sensible heat is transferred by conduction through the door and cabinet envelope.

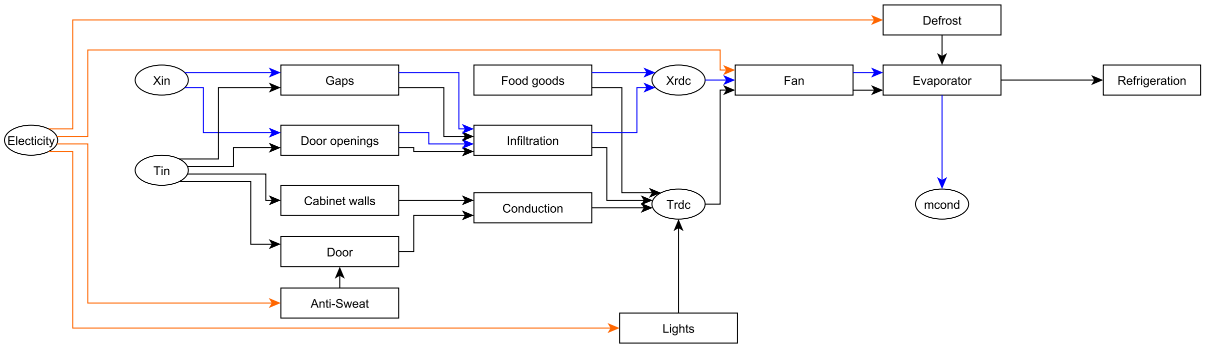

Figure 4.1: Isolated systematic overview of the conceptual energy flows and connections of a refrigerated display cabinet in a supermarket.

In addition to the latent and sensible heat extracted from the ambient air, the electrical energy for fans circulating the air inside the RDC generates heat that also needs to be extracted. Lights present within the RDC to make the products appealing to the customers are another heat source that needs to be balanced by the heat extraction of the evaporator. The defrost cycles and anti-sweat heaters also generate heat that must be extracted to maintain the temperature within that specified in the food safety requirements.

As seen in addition to the heat that is extracted from the indoor air, a large amount of heat is generated within and directly extracted from the RDC to the refrigeration system. In a holistic perspective, it is attractive to connect such heat flow back into the heating sytem of the supermarket.

4.2 Overview of previous work

In [15] the authors describes how a open RDC can be modified to decrease the energy demand by approximately 5% while also increasing the food safety by lowering the duration of over temperatures. In the article the authors state that: *"The use of CFD to understand the problem and test possible solutions was invaluable in improving the cabinet"*. In the review presented in [34] it is shown that CFD is utilised by many researchers to understand and improve the energy efficiency in food refrigeration.

A majority of previously published papers on the subject of CFD-aided modelling of refrigerated display cabinets focused on open cabinets, especially, on the behaviour of the air curtain and infiltration. As closed cabinets are increasing in numbers, the need for accurate CFD models of the energy flows, temperature fields and air infiltration is on an increase.

There are several similarities between the model setup between open and closed RDCs where the previous knowledge from the former can be transferred to the latter. Physics coupling, including latent heat transfer, treatment of the evaporator in the model and air flows within the cabinet, are some of the examples. The major difference that creates a challenge is the modelling of air infiltration owing to door openings. This dynamic part of the model adds complexity as the calculation domains are forced to be moving to represent the swinging or sliding doors. Mapping the velocity, pressure, temperature and moisture field onto a deforming and regenerating mesh causes a severe increase in computational effort to keep the convergence criterion.

For open RDCs the flow is predominantly two dimensional allowing the computational domain to be reduced to two spatial dimensions[19]. However, the doors add another spatial dimension in the longitudinal direction of the cabinet, which lowers the representativeness of a two dimensional CFD model. Two dimensional models are thou still representable for static simulations of the air flow i.e no moving parts.

In a study from 2013, the dynamic behaviour of a closed RDC with door openings was developed in a finite volume model, both in commercial CFD software and an in-house developed code. The paper describes the difficulties with mapping the previous solution onto the updated meshes causing convergence problems of the solution [30].Also the article shows a 20% difference in the results provided by the different software.This highlights the need of development of accurate and validated CFD models for improving the closed RDCs.

In a literature review from 2006, the authors investigated what turbulence model was most commonly used in other research papers to model the airflow within RDCs. k-ϵ is used in 11 of 17 papers, whereas LES was used in 3 of 17 papers [34]. The papers only considered open RDCs where the inlet airflows are higher and there were no doors to limit the occurrence of turbulence; thus, turbulence was expected to be higher for these cases.

4.3 Sensible 2D Non-Isothermal CFD model

To provide an overview of the temperature field within a closed RDC, a CFD model was created using the commercial software, COMSOL Multiphysics 5.2. The model serves as a starting point for the future investigation of the energy flows within a RDC. The geometry is based on a Carrier Monaxis 63.C3 DL 375 R404A, which is a common RDC in German stores and also the type available for validation in the laboratory of Chalmers University of Technology. In Figure 4.2, the geometry along with the boundary conditions is shown.

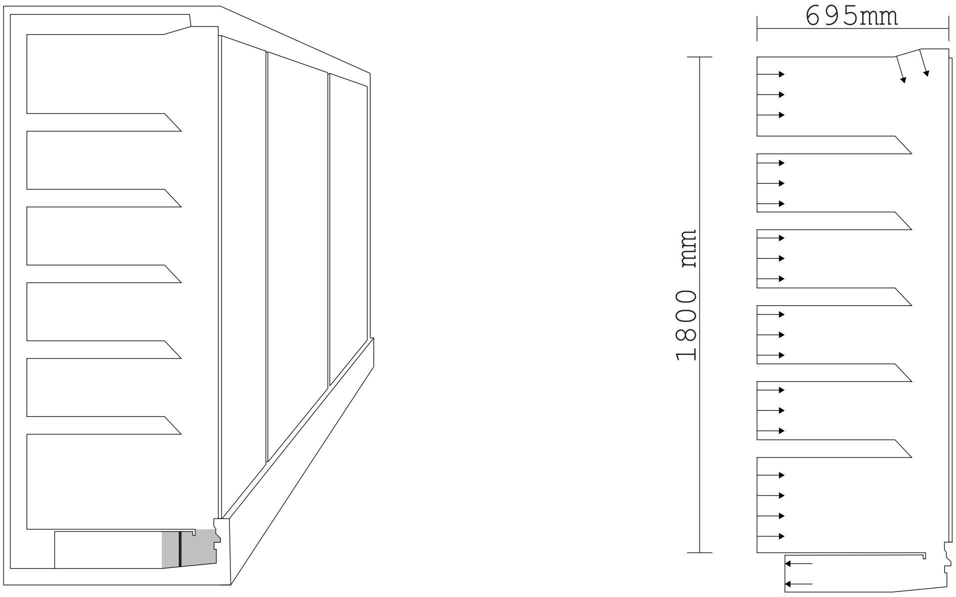

Figure 4.2: Geometry of the RDC used in the CFD model. To the right, the boundary conditions are highlighted with arrows symbolising the direction of airflow

Based on the high Reynolds number that occurs in the volume between the shelves and door, it can be assumed that the airflow within the RDC is in the turbulent regime, and therefore, a turbulence model must be applied. However, the air-flow from the rear grille through the gaps between products will have a lower Reynolds number in the laminar regime. As airflow does occur in both the laminar and turbulent regimes, direct numerical simulation (DNS) or transitional models would be attractive to apply. The DNS modelling is unrealistic to apply on such a spatial scale owing to the high computational demand that would be required for the chosen geometry. The transitional models would increase the accuracy of the solution in the areas where such flow occurs, e.g. in between food products. As the model will be used to generate a temperature field overview, the standard $K - \epsilon$ model was chosen for its wide range of applications, robustness and in accordance with the majority of CFD-aided RDC models published in scientific journals and conferences [34].

Another assumption used to reduce the non-linearity and thereby the computational time is that the flow is assumed to be incompressible. The assumption is commonly considered to be valid for fluid velocities of less than 0.3 Mach, which is the case within the RDC. The highest air speeds are found around the air return grille and are in the range of 3-4 m/s.

The model is based on the non-isothermal turbulent single phase flow module (NITF) embedded in the software. One way coupling of the heat transfer in fluids interface with the turbulent single phase flow module is used in this specific case as all material properties for air is assumed to be constant over the temperature and pressure variations in the RDC.

By evaluating the Richardson number, as described in 4.1, it can be seen that Ri <0.1, meaning that the influence of natural convection can be neglected. For the air return Ri is in the range of $0.002 - 0.01$.

$$Ri = \frac{g\beta(T_{hot} - T_{ref})L}{V^2} \tag{4.1}$$

The equations solved by the turbulent NITF module are the Reynolds-averaged Navier-Stokes (RANS) equations for the conservation of momentum and the continuity equation for conservation of mass as shown in 4.2 and 4.3.

The turbulence is modelled using the standard two-equation $k - \epsilon$ model with realisability constraints. The flow in the near wall region is modelled using wall functions.

The closure coefficients used are; $C_\mu = 0.09$, $C_{\epsilon 1} = 1.44$, $C_{\epsilon 2} = 1.92$, $\sigma_k = 1.0$ and $\sigma_\epsilon = 1.3$.

$$\rho(\bar{u}\nabla)\bar{u} = \nabla\left[-p\bar{I} + (\mu + \mu_T)(\nabla\bar{u} + (\nabla\bar{u}^T))\right] \tag{4.2}$$

$$\rho\nabla(\bar{u}) = 0 \tag{4.3}$$

The transport of turbulent kinematic energy, k, and turbulent dissipation, ϵ, is modelled as shown in 4.4 and 4.5.

$$\rho(\bar{u}\nabla)k = \nabla\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right] + P_k - \rho_\epsilon \tag{4.4}$$

$$\rho(\bar{u}\nabla)\epsilon = \nabla\left[\left(\mu + \frac{\mu_T}{\sigma_\epsilon}\right)\nabla\epsilon\right] + C_{\epsilon 1}\frac{\epsilon}{k}P_k - C_{\epsilon 2}\rho\frac{\epsilon^2}{k} \tag{4.5}$$

The turbulent viscosity is modelled as shown in 4.6.

$$\mu_T = \rho C_\mu \frac{k^2}{\epsilon} \tag{4.6}$$

The production of k is modelled as shown in equation 4.7

$$P_k = \mu_T\left[\nabla\bar{u} : \left(\nabla\bar{u} + (\nabla\bar{u})^T\right)\right] \tag{4.7}$$

As the model is stationary, the heat capacity of materials can be neglected. Therefore, solids can be modelled as Neuman boundary conditions adjacent to the fluid. The heat transfer equation is shown in 4.8 with $\bar{q}$ defined, as in equation 4.9.

$$\rho C_p \bar{u}\nabla T + \nabla\bar{q} = Q \tag{4.8}$$

$$\bar{q} = -k\nabla T \tag{4.9}$$

4.3.1 Boundary conditions

The inlet boundary conditions applied is stated as in 4.10 with a reference velocity in the opposite direction of the normal to the boundary. The inlet turbulent kinetic energy and dissipation rate are calculated as shown in 4.11 and 4.12, where the length scale and turbulent intensity were estimated, as in 4.13 and 4.14.

$$\bar{u} = -U_0\bar{n} \tag{4.10}$$

$$k = \frac{2}{3}\left(U_0 I_T\right)^2 \tag{4.11}$$

$$\epsilon = C_\mu^{3/4}\frac{k^{3/2}}{L_T} \tag{4.12}$$

$$I_T = 0.16 Re^{-1/8} \tag{4.13}$$

$$L_T = 0.07 * L \tag{4.14}$$

The air discharge inlet velocity is defined by multiplying the highest velocity with a ramp function to account for variations over the inlet, as shown in 4.15.

$$U_0 = f(s) * U_{inlet} \tag{4.15}$$

where f is defined, as shown in 4.16, on the normalised boundary coordinate system s along the inlet boundary.

$$f(x) = \begin{cases} 2x & \text{for } x < 0.5 \\ 1 & \text{for } x \geq 0 \end{cases} \tag{4.16}$$

The rear inlet velocity is defined as a fixed ratio of the highest air discharge U_{inlet}, as shown in 4.17. The factor is derived from an empirical study to balance the volumetric flow ratio between the air discharge and rear grille to $11:6$ as measured in the lab.

$$U_0 = 0.028203 * U_{inlet} \tag{4.17}$$

The inlet temperature in the reference RDC for both the air discharge and the rear grille is set to 278.15K.

The boundary condition used for heat transfer from the adjacent solids is defined as in 4.18. where q_0 is defined as in 4.19

$$-\bar{n}\bar{q} = q_0 \tag{4.18}$$

$$q_0 = h\left(T_{ext} - T\right) \tag{4.19}$$

The door facing the ambient is assigned a Neuman boundary condition, where the temperature is set to 300.15K with a heat transfer coefficient $h = 2.67[W/m^2K]$, representing the thermal conductance of the door including the outside surface resistance.

The model is using a simplified approach for taking the effects of radiation into consideration. A Neuman boundary condition is applied, as shown in 4.20 with an ambient temperature assumed to be equal to the inlet temperature. This assumption gives a good indication of how the radiation will affect the warmer areas within the RDC. However, the boundary condition does apply a fictitious heat sink at the boundary, causing a non-realistic energy balance within the RDC. The heat flux is absorbed by the linear heat sink instead of being transferred to the rear parts of the RDC and partly absorbed by the air.

$$-\bar{n}\bar{q} = \epsilon\sigma\left(T_{amb}^4 - T^4\right) \tag{4.20}$$

For the reference cabinet an emissivity of 0.9 was assumed.

4.3.2 Validation

A validation experiment was performed with a Carrier Monaxis 63 C3.DL RDC connected to a Silensys SIL4524Z R404A remote compressor. The RDC was filled with 120 canisters containing 5 litres of water each to introduce a thermal mass of 624 kg. The ambient room temperature was kept at $200 - 201\ K$ $(27 - 28°C)$ during the experiment by a radiator and supplementary convective heaters to compensate for the heat extraction through the RDC. In Figure 4.3, the experiment setup including the supplementary heaters can be seen. The canisters were arranged to create a scenario in the middle section of the RDC reflecting the one in the simulation.

Figure 4.3: Photo showing the experimental setup with water filled canisters and one of the convective heaters.

The vertical temperature profile of the air return channel was measured using 7 K-type thermocouples mounted at a height of 2, 5, 10, 15, 20, 30 and 40mm on a bracket, as shown in Figure 4.4. The support for the thermocouples was designed in house and installed to have minimal impact on the airflow to ensure an undisturbed temperature profile.

Before the experiment was performed, the RDC was running for more than 200 hours to ensure that a periodic steady state scenario was reached. In Figure 4.5, the transient temperature profile of the inlet air during the experiment is shown. During the 455 second intervals between the compressor cycles, the inlet temperature varies between 2.2 to $7.10°C$. This periodic behaviour limits the development of the heated air layer in the air return, reducing both its magnitude and height and causing an offset between the simulated and measured results. Therefore, the results shown in Figure 4.8 have been offset with the

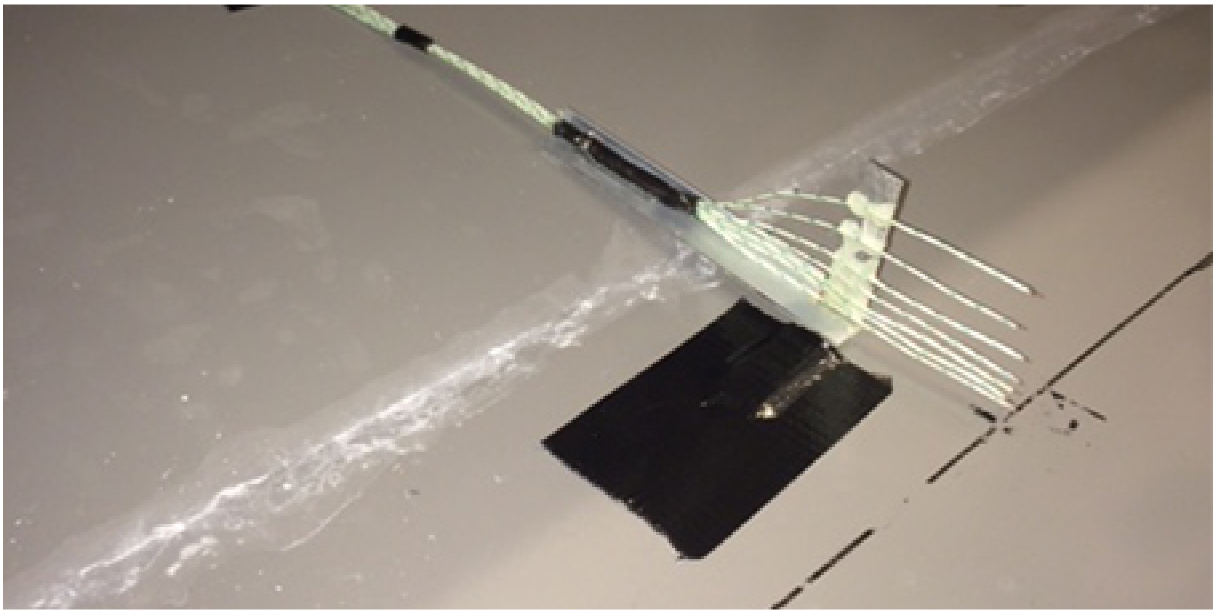

Figure 4.4: Photo showing the in house-designed support for the seven thermocouples in the air return channel of the RDC.

temperature at a height of 2mm, to ease the comparison.

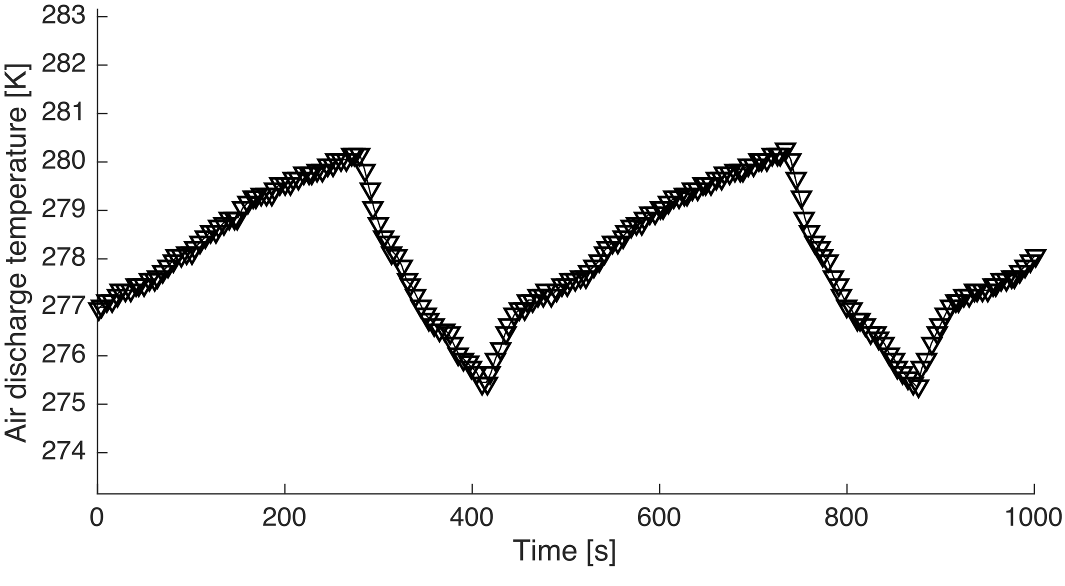

Figure 4.5: Plot showing measured air discharge temperature during the validation experiment

The vertical temperature profile in the air return is transient because the RDC cannot maintain a constant heat extraction rate over time. To compare the steady state simulation with the transient experiment, data of the measurements was collected every 5^{th} seconds during 45 minutes and presented in Figure 4.8.

4.3.3 Results

A temperature field overview was created for variations of ±20% from the reference case velocity (0.656 – 0.984 [m/s]) to represent the variations in food stuff placement blocking the airflow within the RDC. In Figure 4.6 the temperature field of the reference case with an air discharge velocity of 0.82 [m/s] is shown. The warm air layer builds up along the front glass door and then follows the airflow to the floor of the air return. To the right in Figure 4.6 a close up of the temperature field of the area close to the air return grille is provided. The geometry of the reference RDCs air return front is causing a pocket of slower moving air to develop in the front. This air pocket is heated by the warm air from above as well as by conduction through the lower front bumper of the RDC. Another warm air pocket is also formed in the top front of the RDC. This upper heated region is distant to both the food stuff and the temperature control sensors and will therefore not be considered in further investigations.

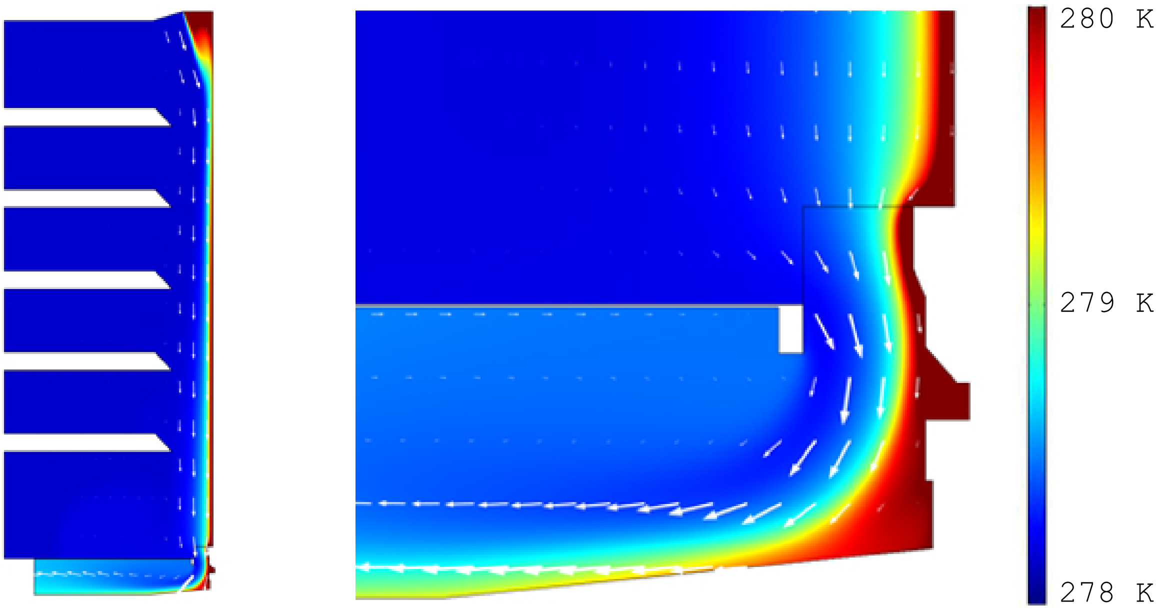

Figure 4.6: Temperature field overview with arrows visualising the velocity field for the reference case within the RDC. On the left, a zoom towards the air return grille area is shown. Clearly showing the warm air layer following the outer wall and floor towards the evaporator in the rear

From the simplified CFD model it can be concluded that there is a temperature profile perpendicular to the airflow with the warmer parts adjacent to the floor and glass door. This temperature profile was visualised in Figure 4.7 for all variations of velocity and also for variations of emissivity between 0-1 to represent the appearance of dust, dirt and condensate. As the inlet temperature was kept constant in the performed study, the average temperature of the RDC increases with decreasing air discharge speed due to reduced heat extraction. This can explain the variations 20 mm above the floor in the figure. The emissivity variations is affecting the temperature of the surface, which by convection affect the air temperature close to the surface.

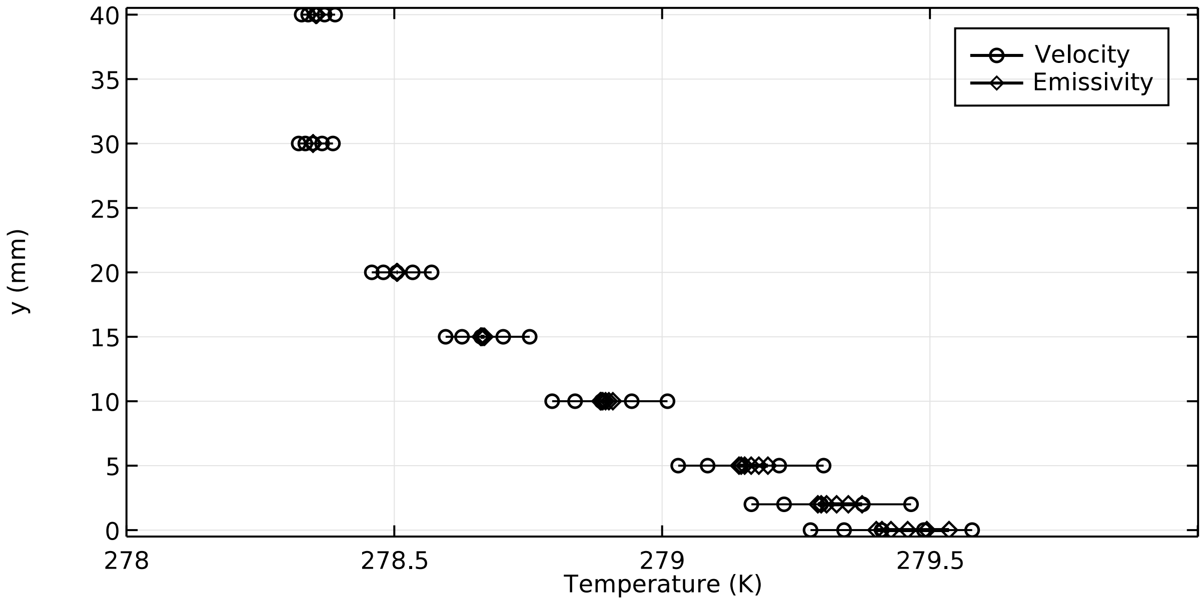

Figure 4.7: Temperature profile variations along a vertical line located 100mm rear of the front.

In Figure 4.8 the temperature profile from the validation experiment is shown. The plot is showing the temperature profile relative to the temperature at 2mm. The plot shows that the magnitude of the temperature variations are greater in the laboratory than in the CFD model. This is a consequence of the transient behaviour of the temperature control system of the RDC, varying the discharge air temperature during the validation experiment. However, the validation confirms the results from the CFD model and it can be concluded that there is a temperature variation in the air return channel causing the lowest air layer to be warmer.

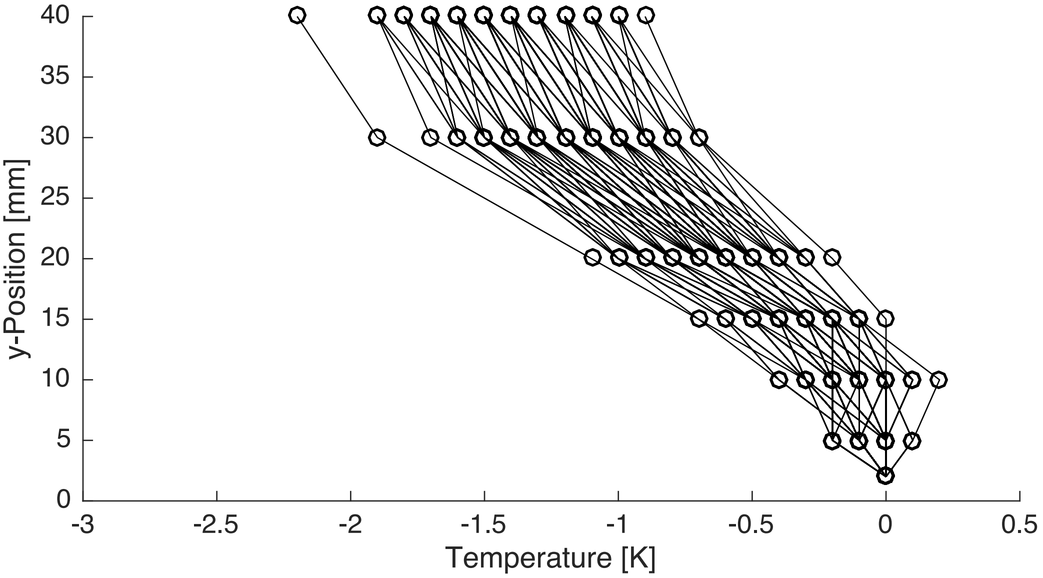

Figure 4.8: Temperature profiles from the validation experiment of the CFD model. Temperatures are relative to the temperature measured at 2mm.

4.3.4 Discussion

As shown in the previous result section, there are temperature gradients within the RDC that could threat the correctness of the control systems temperature input from the sensors placed in the air return. However, the warm air pocket in the top front of the cabinet is located in a way that it will not affect any of the temperature probes within the RDC, neither does it pose any threat to food safety as the air discharge act as a barrier in between.

The temperature variations in the area of the return air channel does pose a threat to the temperature probe of the control system. The return air probe is commonly mounted with a clip about 5 mm above the floor and in the area close to the return air grille for easier service. As can be seen in the results, this would cause it to indicate an approximately one degree higher temperature than the average air temperature. This could potentially cause the RDC to overcompensate for the temperature increase and by that increase, the heat extraction to an unnecessary high level. The air layer is heated by the inner surface of the doors, which in a supermarket would be exposed to cyclic heating and cooling as a consequence of the refrigeration strategy of the control system. These variations would then impose a temperature variation that depending on the stability of the control system, might be amplified due to the incorrect measurements.

This hypothesis on unnecessary heat extraction and temperature fluctuations was followed up by two field studies that are currently being processed for publication in a journal and therefore, will only be presented briefly in Chapter 5 of this thesis.

Chapter 5

Field study of temperature sensor placement in refrigerated display cabinets

The heterogeneity of the temperature field within RDCs was concluded to exist owing to the CFD model and laboratory validations of the results shown in Chapter 4. To follow up the importance of this finding, a field study of the physical placement of air return temperature sensors in supermarkets in and around the area of Hamburg was conducted. The field study was carried out in two steps. First, the position in 235 RDCs, including low-temperature RDCs, were scouted to find out the location of the temperature sensors. The study was then continued by a second field study where the temperature sensor position in medium-temperature RDCs was registered and then moved to an area where the air flow temperature was assumed to be better representing the average temperature of the RDC.

5.1 Method

In the first field study, the sensor position in depth and height was measured by the author. Metadata on the RDC type, manufacturer and model was gathered.

In the second field study, the sensor placement was measured by a refrigeration technician visiting the different supermarkets. The technicians were first introduced to the previous results and supervised by the author to ensure high-quality measurements. The measurements were in equivalence with the first study taken by placing a ruler perpendicular to the front of the cabinet to obtain the sensor position depth. The vertical position was then measured with a vertically placed ruler, perpendicular to the bottom of the cabinet.

As the measurement was taken during the opening hours of the supermarkets and with fully packed RDCs, the obstructed view and limited space caused some accuracy loss in the measurement. However, the accuracy of the vertical measures were assumed to be within approximately ±2 mm and in depth within approximately ±5 mm.

In addition, metadata for each RDC measure was collected to ensure possible follow up on the energetic and temperature effects of the sensor repositioning. he following metadata was collected during the follow up study:

- Market ID
- Date of re-positioning
- RDC manufactor
- Manufacturing year
- RDC FrigoData ID
- RDC Model
- RDC Module width
- RDC Door width
- Glazing type in door
- Number of doors
- Electrical power of Anti-Sweat
- Electrical power of Defrost 1
- Electrical power of Defrost 2
- Electrical power of Lights in RDC
- Electrical power of Ventilators

In addition to the temperature sensor position in section of the RDC, data on the position in the longitudinal direction was gathered. All temperature sensors where photographed before and after repositioning to verify the measures and to allow an analysis of the appearance of dirt in the return air channel. An example wherein photographs taken for every sensor repositioning during the field study is presented in Figure 5.1.

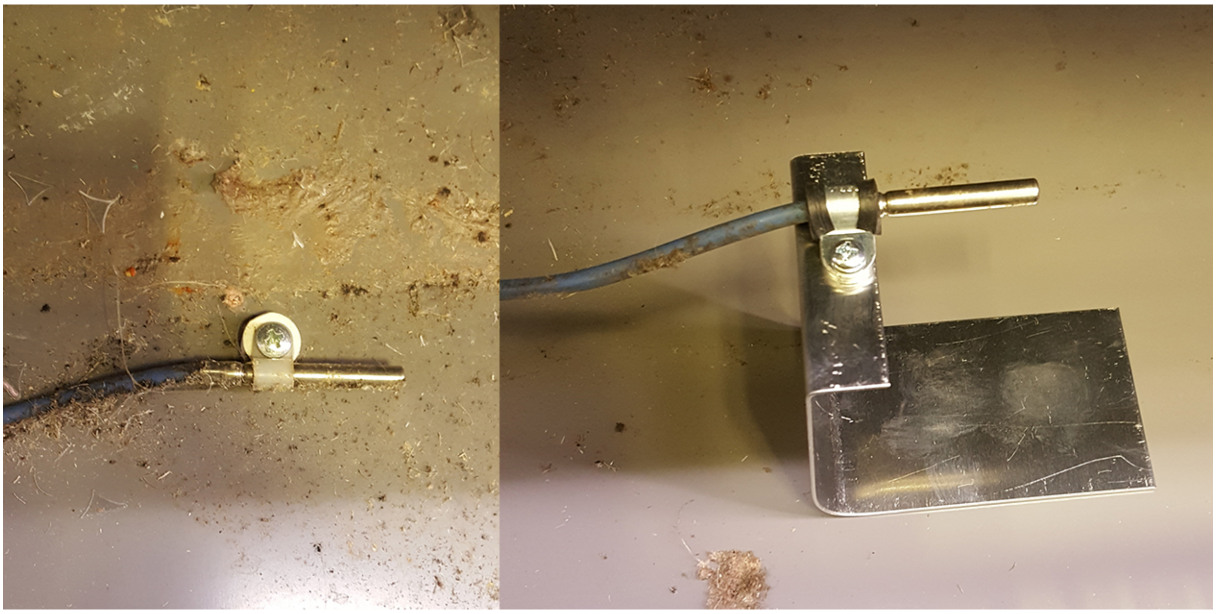

Figure 5.1: Photograph showing the original position of a temperature sensor in an RDC is shown on the left; the new position and prototype holder is shown on the right

5.2 Results

From the scout field study performed at the start of 2015, it could be concluded that there exists a great variation regarding the temperature sensors position in the return air channel. The 235 positions registered are plotted in Figure 5.2, where they have been grouped by manufacturer.

Within the variations, some clustering can be noticed around certain positions. This is a consequence of the different geometries and their unique possibilities to fix the temperature sensor in different models of RDCs, which varies within the brands. In addition, the temperature sensors and controls are often mounted in a later stage of the process of

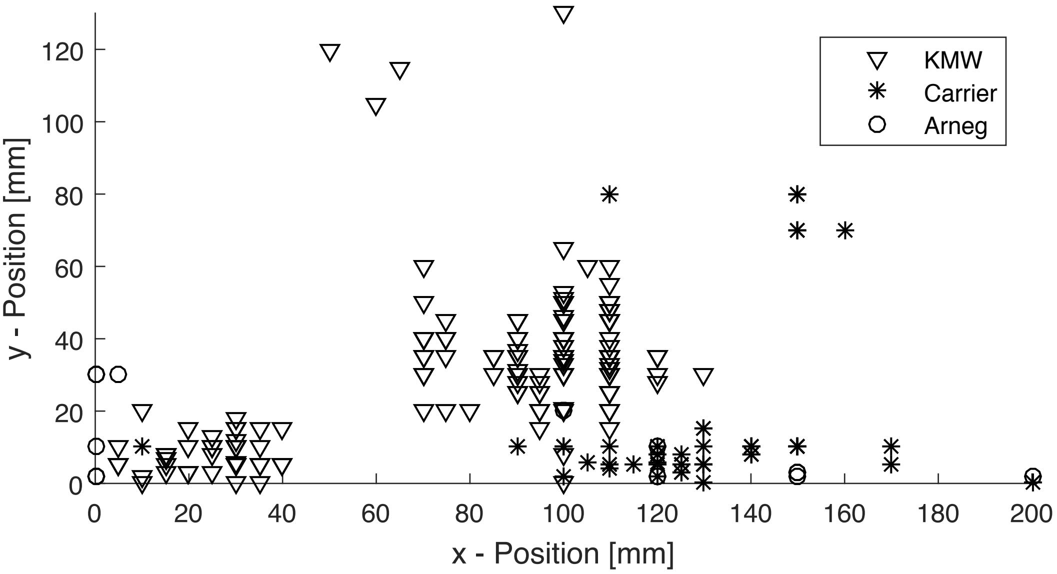

Figure 5.2: Plot showing the position of temperature sensors during the scout field study.

installing the RDCs in the supermarket. This means that it is outsourced to refrigeration technicians, who do the final attachment of the installation.

With the preliminary study showing such large variations and the static 2D CFD model together with the validation, indicating a risk of over temperatures in these specific position, a second field study was planned and conducted.

The measured position of the temperature sensors in the second field study is shown in Figure 5.3. Here only the medium-temperature RDCs was considered.

The Carrier RDCs within the study were mounted at the same height of 10 mm with the exception of one, which had been dislocated and was in contact with the floor of the return air channel. The strict position in height because all sensors are mounted with similar clips directly attached to the metal floor, as seen to the left in Figure 5.1.

From the static 2D CFD model, it was hypothesised that the temperature fluctuations would decrease as a consequence of moving the temperature sensor to a position that better represents the RDC average temperature. In Figure 5.4, the discharge and return temperature is plotted, showing a visible decrease in variation. The temperatures were adjusted/normalised to the set point temperature of the respective RDC.

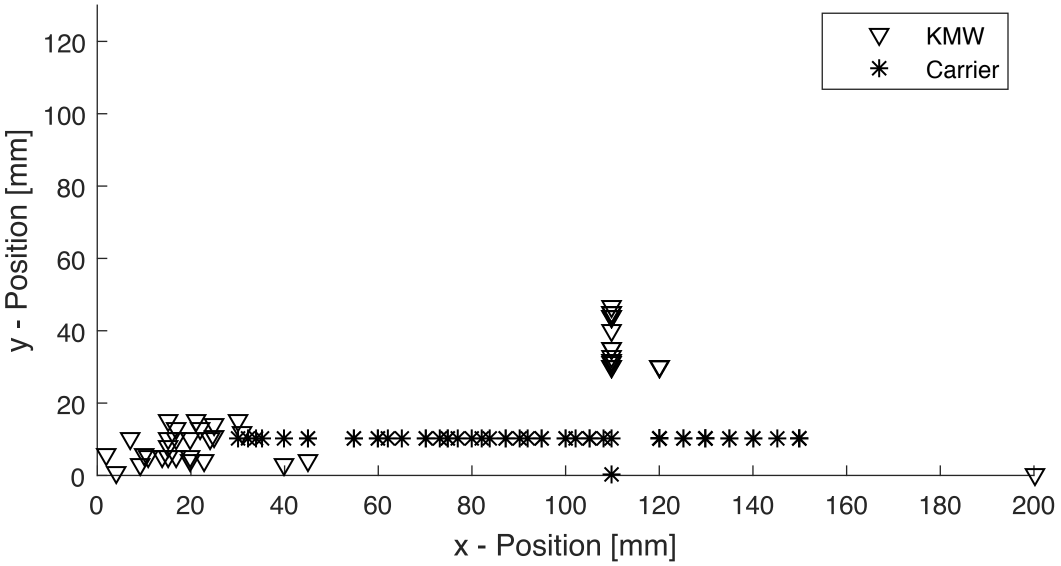

Figure 5.3: Plot showing the return air temperature sensor positions for the RDCs in the final field study around Hamburg.

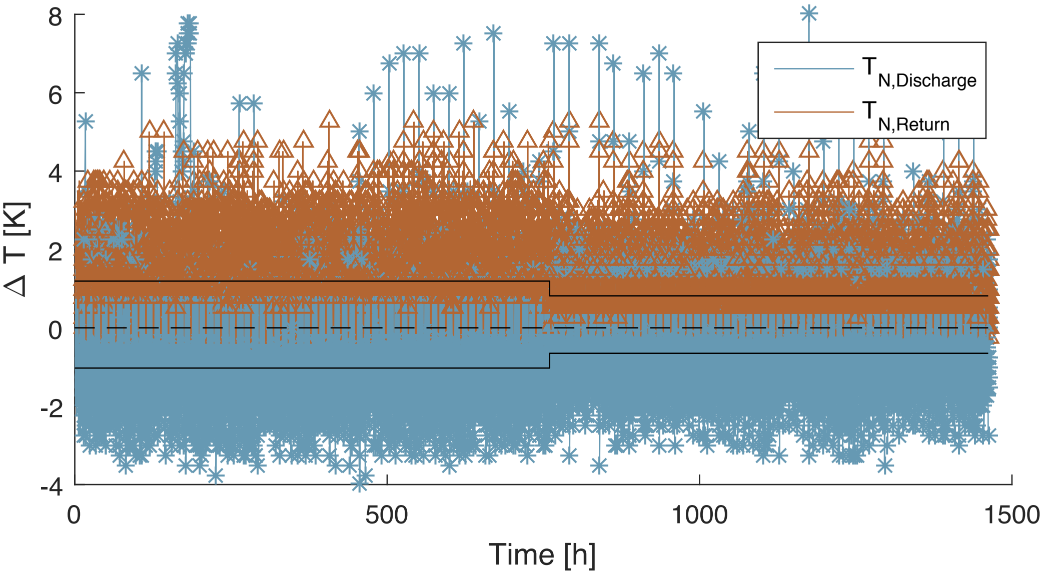

Figure 5.4: Plot showing the air discharge and return temperatures normalised to the set point temperature of each RDC. The black lines represents the monthly average before and after the re-positioning.

In Figure 5.5, the hourly average difference between return and discharge air temperature from Figure 5.4 has been evaluated. The data was also processed with a locally weighted scatterplot smoothing (Loess) to better show the trends in the variation.

Here, in Figure 5.5, the decreased variations within the RDC are clearly visible. By increasing the lowest temperature, the heat transfer by conduction will be reduced. In addition, the sub

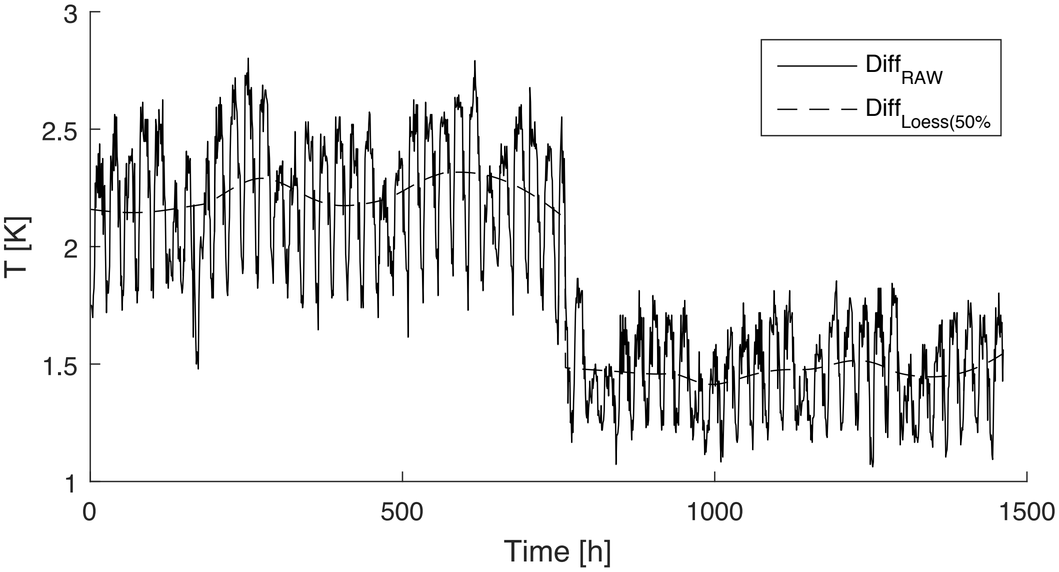

Figure 5.5: Plot showing the accumulated average temperature difference between the air discharge and return temperatures for the RDCs in one store from the study.

cooling and heating of products is reduced, increasing the food safety while reducing the energy demand.

The electrical power demand by the two medium-temperature compressors in a specific store was monitored one month before and after the change. The results are shown in Figure 5.6. From the plot, the effects cannot be distinguished due to the noise caused by weather, customer behaviour etc. .By normal distribution fitting of the measured values, it can be seen that the mean energy demand was lowered by 2 - 5 % and the variance was also decreased.

According to an separate internal study performed by REWE, the data showing a tendency of a reduction in energy demand for the stores where temperature sensors has been repositioned[1].

---

[1] From interview with York Ostermeyer.

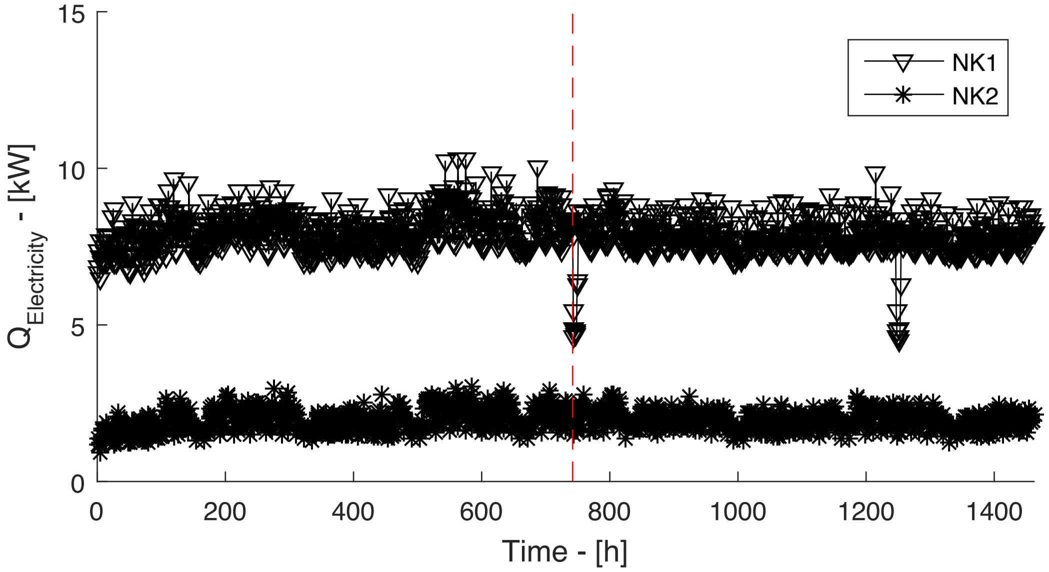

Figure 5.6: Electrical power demand by the two compressor units in a supermarket. The dashed red line indicates the time of sensor re-positioning.

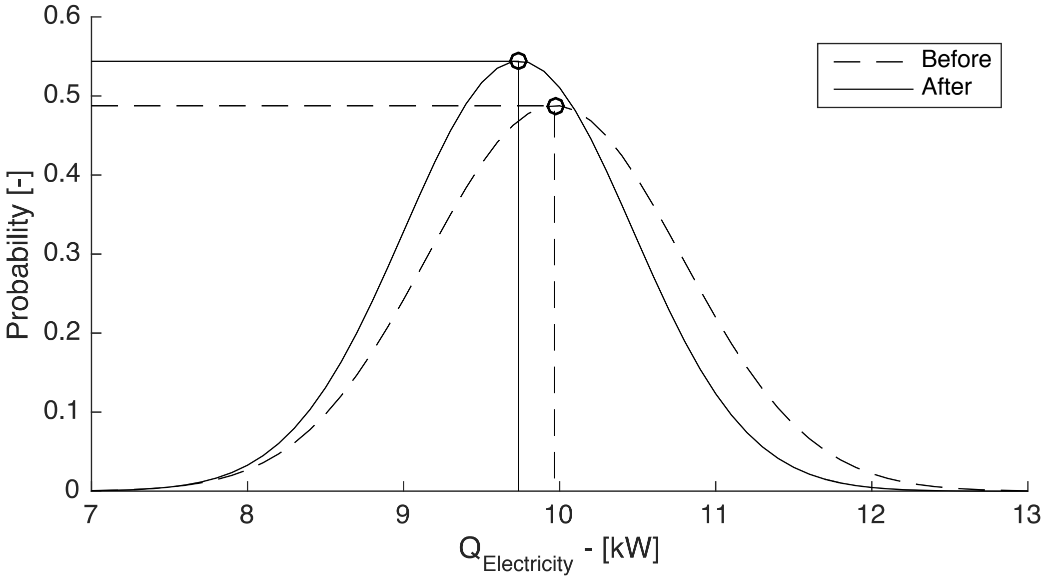

Figure 5.7: Normal distribution fit of the electrical energy use by a medium-temperature refrigeration machine before and after repositioning the temperature sensors in one specific store.

5.3 Conclusion

By not moving the sensors, the supermarkets will continue having a higher than necessary risk of food losses due to over temperatures. In addition, the temperature variation that occurs due to the inaccurate position of the temperature sensor will cause stress on the refrigeration system. Both are due to temperature variations that cause wear on the pipework and joints as well as the refrigeration system that must compensate for the higher temperatures, which demands a higher heat extraction rate.

The reduced energy use justifies the repositioning from an economic perspective because it directly reduces the running cost of the supermarket. In addition, the increased temperature readings quality is an important step towards the implementation of future advanced control systems, which would further reduce the energy demand and increase the power flexibility of the supermarket.

As the refrigeration system is concluded to be sensitive to incorrect positioning of the temperature sensors, it is necessary for supermarket owners to regularly check that sensors are not being moved accidentally.

By combining the results of the field study of the current position and the temperature field overview, it can be concluded that a large share of the supermarkets would benefit from a repositioning of their sensors.

Chapter 6

Conclusion

6.1 Summary of Thesis Achievements

This licentiate thesis serves as a basis for future work within the PhD project ”Supermarkets as thermal buffers for renewable electricity grids” and has summarised the current state of energy flows and design of supermarkets based in Sweden and Germany.

From the systems analysis of the supermarket, it was concluded that the refrigeration system holds great potential to increase the power flexibility of the supermarket as electric energy is turned into cooling that can be stored. The indoor climate was found to be the parameter connected to most functions of the supermarket, and it should, therefore, be considered as a leverage point for energy efficiency measures.

The development of a CFD-aided model to visualise the temperature field in RDCs revealed an inhomogeneous part causing the temperature prediction in RDCs to overestimate the temperatures, causing a larger variation of the temperature of the products due to inadequate refrigeration strategy. The effects of this problem were investigated in German supermarkets and corrected with a positive result, increasing the quality of the temperature readings and thereby ensuring a better refrigeration strategy with less variation. In addition, a decrease in energy use could be seen in the selected supermarkets. This highlights the importance of small details and shows the vulnerability of such complex and interconnected systems that supermarkets are.

The thesis concludes that there is potential for further increases in energy efficiency and power flexibility of supermarkets. However, such actions demand a systematic and holistic approach when being implemented to ensure full potential utilisation and avoid sub-optimisation.

6.2 Applications

The results from this thesis may be used to design a temperature sensor holder or placement practice that avoids positioning the temperature sensor in the warmer areas of the air return.

The results of the systems analysis and numerical model for temperature overview in refrigerated display cabinets may serve as a basis for future work on both energy efficiency and power flexibility of supermarkets.

6.3 Future Work

To allow supermarkets to utilise the full potential of its power flexibility and maximise their energy efficiency, there is a need for further research within the field of controls for the overall supermarket system and cold thermal energy storage specifically designed for supermarkets.

The control systems must be able to create forecasts of the energy demand of the RDCs and the overall supermarket to reduce the storage power demand. This can be achieved either by implementing new technology (such as image recognition), alternative sensor types or by differently interpreting the current available data from sensors.

To enable that such control systems are developed, the energy flow system of supermarkets must be further analysed and the detailed level must be increased beyond the scope of this thesis. In addition, the systems must include the transient parameters and quantifiable energy flows to ensure actions justifiable from economic and environmental perspectives.

Bibliography

[1] Luca; Ardito and Giuseppe Procaccianti. Smart Grid Technologies in Europe: An overview. *Energies*, 6(1):251–281, 2013.

[2] Jaime Arias. *Energy Usage in Supermarkets - Modelling and Field Measurements.* PhD thesis, Royal Institute of Technology, 2005.

[3] Jaime Arias and Per Lundqvist. Heat recovery and floating condensing in supermarkets. *Energy and Buildings*, 38(2):73–81, feb 2006.

[4] A Arteconi, C Brandoni, and F Polonara. Distributed generation and trigeneration: Energy saving opportunities in Italian supermarket sector. *Applied Thermal Engineering*, 29(29):1735–1743, 2009.

[5] ASHRAE. *Advanced Energy Design Guide for Grocery stores.* W. Stephen Cormstock, Atlanta, 2015.

[6] Monica Axell. Rapport Effektiv 2001:05 - Butikskyla. Technical report, EFFEKTIV, Borås, 2001.

[7] Monica Axell. *Vertical display cabinets in supermarkets - Energy efficiency and the influence of air flows.* Doctoral thesis, Chalmers University of Technology, 2002.

[8] Ammar Bahman, Luis Rosario, and Muhammad M. Rahman. Analysis of energy savings in a supermarket refrigeration/HVAC system. *Applied Energy*, 98:11–21, 2012.

[9] M. R. Braun, H. Altan, and S. B M Beck. Using regression analysis to predict the future energy consumption of a supermarket in the UK. *Applied Energy*, 130:305–313, 2014.

[10] John Cook, Dana Nuccitelli, Sara A Green, Mark Richardsson, Winkler Winkler, Rob Painting, Robert Way, Peter Jacobs, and Andrew Skuce. Quantifying the consensus on anthropogenic global warming in the literature: Rejoinder. *Environmental Research Letters*, 8:709, 2013.

[11] Delfi. Dagligvarukartan 2014, 2015.

[12] Benny Ekman, Eric Granryd, Tommy Nilsson, Lennart Rolfsman, Brenntag Nordic, COOP, KTH Energy Technology, Frigotech, ICT, IVT, Kemetyl, NIBE, Nowab, KTF, Stainless Engineering, Temper, WICA, and WILO. *Handbook on indirect refrigeration and heat pump systems*, volume 46. Svenska Kyltekniska Föreningen, Kullavik, 1 edition, 2008.

[13] Agentur für Erneuerbare Energien. Renews Special Ausgabe 57, 2015.

[14] Hassan Farhangi. The path of the smart grid. *IEEE Power and Energy Magazine*, 8(1):18–28, 2010.

[15] A. M. Foster, M. Madge, and J. A. Evans. The use of CFD to improve the performance of a chilled multi-deck retail display cabinet. *International Journal of Refrigeration*, 28:698–705, 2005.

[16] Kaarin Goodburn. Chilled Food Association - Market Data, 2014.

[17] Marie Granmar. De siktar på att nå nollvisionen. *Energi & Miljö*, 86(7-8):26–30, 2015.

[18] K.A. Gschneidner and V.K. Pecharsky. Thirty years of near room temperature magnetic cooling: Where we are today and future prospects. *International Journal of Refrigeration*, 31(6):945–961, 2008.

[19] Abas F Hadawey, Tawfiq J Jaber, Waleed Abdul Ghaffar, and Abu Dhabi. Air Curtain Design Optimization of Refrigerated Vertical Display Cabinet using CFD. *International Journal of Scientific Engineering and Technology*, 1(4):76–88, 2012.

[20] Roland H. Howell. Effects of Store Relative Humidity on Refrigerated Display Case Performance. *ASHRAE Transaction*, 99(1), 1993.

[21] IGD. UK Grocery Retailing, 2014.

[22] Sara Jensen, Svein Ruud, Lennart Rolfsman, and Ulla Lindberg. Konceptbutiken som närmar sig noll - Förstudie. Technical report, Lågan, Borås, 2014.

[23] United Kingdom. Grocery Store Tricks, 2001.

[24] Ulla Lindberg, Monica Axell, Per Fahlén, and Niklas Fransson. Supermarkets , indoor climate and energy efficiency field measurements before and after installation of doors on refrigerated cases. In *Refrigeration And Air Conditioning*, 2008.

[25] Tommie Månsson and York Ostermeyer. The potential of thermal energy storage in food cooling processes in retail markets for grid balancing. In *Nordic Symposium on Building Physics 2013*, pages 1–6, Lund, 2013.

[26] Caroline Markusson and Patrik Ollas. Avfuktning av luft i butiker. Technical report, SP-Energiteknik, Borås, 2013.

[27] Naomi Miller. DELTA Portfolio: A&P Food Market, Old Lyme, Connecticut. *DELTA Portfolio*, 1(1):12, 1994.

[28] Jaya Mukhopadhyay and Jeff Haberl. Reducing Energy Consumption in Grocery Stores: Evaluation of Energy Efficiency Measures. *ASHRAE Transactions*, 120:416–436, 2014.

[29] E. G. Ochieng, N. Jones, a. D F Price, X. Ruan, C. O. Egbu, and T. Zuofa. Integration of energy efficient technologies in UK supermarkets. *Energy Policy*, 67:388–393, 2014.

[30] M Orlandi, F M Visconti, and S Zampini. CFD assisted design of closed display cabinets. In *2nd IIR International Conference on sustainability and the cold chain*, volume 2, Paris, 2013. International Institure of Refrigeration.

[31] York Ostermeyer, Holger Wallbaum, and Christian Brand. Energy saving concepts for supermarkets. In *Nordic Symposium on Building Physics 2008*, pages 1–3, Göteborg, 2008.

[32] Intergovernemental panel on climate Change. No Title.

[33] SCB. SCB Företagsregister, 2014.

[34] N.J. Smale, J. Moureh, and G. Cortella. A review of numerical models of airflow in refrigerated food applications. *International Journal of Refrigeration*, 29(6):911–930, sep 2006.

[35] Maria S. Spyrou, Kirk Shanks, Malcolm J. Cook, James Pitcher, and Richard Lee. An empirical study of electricity and gas demand drivers in large food retail buildings of a national organisation. *Energy and Buildings*, 68(PARTA):172–182, 2014.

[36] State. STIL - Energianvändning i Handelslokaler. Technical report, Energimyndigheten, Stockholm, 1990.

[37] Statens Energimyndighet. STIL 2 - Energianvändning i handelslokaler. Technical report, Energimyndigheten, Stockholm, 2010.

[38] Nicolas Stern. STERN REVIEW: The Economics of Climate Change Executive Summary. *October*, 30(3):27, 2006.

[39] S.A. Tassou, Y. Ge, A. Hadawey, and D. Marriott. Energy consumption and conservation in food retailing. *Applied Thermal Engineering*, 31(2-3):147–156, feb 2011.

[40] S.A. Tassou, J.S. Lewis, Y.T. Ge, A. Hadawey, and I. Chaer. A review of emerging technologies for food refrigeration applications. *Applied Thermal Engineering*, 30(4):263–276, mar 2010.