EXPERIMENTAL AND COMPUTATIONAL STUDY TO IMPROVE ENERGY EFFICIENCY OF FROZEN FOOD RETAIL STORES

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By

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Abstract

Trends such as online shopping, fast pace of lifestyle and wellness issues are key drivers for consumers' preferences of shopping activities and product selection. There is evidence that food retail has shifted towards smaller in size stores and ready meals or food products which require less time for cooking. In fact, the frozen food market has increased recently and is projected to rise by 27% by 2020. This study focuses on energy efficiency of small size frozen food supermarkets.

The investigation started with in-situ monitoring of energy use and environmental conditions in two frozen food stores with different HVAC but same refrigeration systems and store operation schedules. A dynamic thermal model of frozen food stores was developed using EnergyPlus and validated using the monitored data. The model takes into account interlinked heat exchanges between building, HVAC and refrigeration systems and was used to investigate energy efficiency improvements. Two HVAC systems were examined; coupling heating, air-conditioning and ventilation (coupled system) and separating heating and air-conditioning from ventilation (decoupled system). A number of refrigeration systems (remote, centralised, cascade, transcritical CO_2 booster) and working fluids were investigated.

Analysis of the monitored data has shown that energy use of frozen supermarkets is at the upper range of published supermarkets energy use benchmarks (1085 kWh/m^2/annum). It was also shown that sales area temperature is highly affected by HVAC controls, refrigeration equipment and transient customers' pattern. The computational study has identified energy performance of sub-systems and their interactions. Results indicate that 61% of total energy use is due to the refrigeration system while HVAC and lighting are the next most energy intensive systems. Apart from lighting upgrade to LED which offers high energy savings (23%), energy efficiency can be improved for both coupled and decoupled HVAC systems by incorporating night ventilative cooling and operating remote LT cabinets with lower ambient temperature. Night ventilative cooling can lead to reduction of 3.6% in total energy use. Centralised refrigeration systems change the heating/cooling balance and can reduce the total energy use by up to 20% for a CO_2 centralised system. The results of this research project are a contribution towards better understanding of energy use in food dominant supermarkets and their energy savings potential.

Contents

List of Figures

List of Tables

Acknowledgements

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Ithaka gave you the marvellous journey.
Without her you would not have set out.
She has nothing left to give you now.
And if you find her poor, Ithaka won't have fooled you.
Wise as you will have become, so full of experience,
you will have understood by then what these Ithakas mean.

(Extract from Ithaka by CP Cavafy)

To the memory of my grandparents

Ioanni and Zoi Kotrogiannou

Nomenclature

$T_{surface}$	Surface Temperature
L	Litres
D	Depth
H	Height
h_{go}	gas cooler outlet enthaply
HP	High Pressure
i	coordinator
L	Length
LP	Low Pressure
m	median
m,n,o,p	Equations' coefficients
min	minutes
N	Sample size
NC	Night Cooling
p_{gc}	gas cooler pressure
r	correation
rdg	reading
RH_{rated}	Relative Humidity at rated conditions
sa	sales area
Temp	Temperature
T_{in}	Inside Temperature
T_{offset}	Difference of outside and inside temperature
T_{out}	Outdoor Temperature
T_{rated}	Temperature at reated conditions
t_{sd}	saturated discharge temperature
t_{ss}	saturated suction temperature
y	measured data
y	simulated data
Y_s	Sample mean
σ	Standard Deviation

Abbreviation and Glossary

AC	Air Conditioning
ach	air changes per hour
ANN	Artificial Neural Network
ASCII	Amirican Standard Code for Information Interchange
BLAST	Building Loads Analysis and System Thermodynamics
BWM	Box Whisker Mean
CAV	Constant Air Volume
CDD	Cooling Degree Days
CHP	Combined Heat and Power
COP	Coefficient of Performance
CRC	Carbon Reduction Commitment
CVRMSE	Coefficient of Variation of the Root Mean Square Error
DOE	Department of Energy
DSM	Dynamic Simulation Modelling
DSY	Design Summer Year
DX	Direct Expansion
EIR	Energy Input Ratio
EPA	Environmental Protection Agency
EPBD	Energy Performance in Building Directive
EPC	Energy Performance Certificate
EPW	EnergyPlus Weather file
EU	Europe
GHG	Greenhouse Gas
GVA	Gross Value Added
GWP	Global Warming Potential
HC	Hydrocarbon
HDD	Heating Degree Days
HFC	Hydrofluorocarbon
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IGD	Institute of Grocery Distribution
LED	Lighting emitting diode

LHR	Latent Heat Ratio
LT	Low Temperature
MBE	Mean Bias Error
MT	Medium Temperature
ppm	parts per million
RH	Relative Humidity
SRI	Solar Reflectance Index
TEWI	Total Equivalent Warming Impact
TRY	Test Reference Year
US	United States
VAV	Variable Air Volume
VCD	Volume Control Damper
VRF	Variable Refrigerant Flow
VSD	Variable Speed Drive
ZC	Zero Carbom
ZE	Zero Energy

Chapter 1

Introduction

1.1 Food retail market energy implications

The global food market size was USD 4100 billion in 2015 and increased by 8.5% until 2017. 47% is attributed to the Asian countries with United Sates (US) and Europe following (Statista, 2015). At the same time, the global retail landscape is evolving and new trends such as internet purchasing and home deliveries along with changes in consumers' lifestyle put threat to conventional retail stores.

In 2013, supermarket stores in US (Statista, 2015) represented 5% of the total commercial building primary energy use (Clark, 2015). According to U.S Energy Information Administration (2017), commercial sector energy use accounts for 18% of the total energy use and is responsible for 16% of the carbon dioxide emissions of the country (EIA, 2017).

In the Asian countries forecasts show a sales growth in the retail sector; the fastest in the world presenting an average of 4.6% increase with sales of almost 7 trillion USD in 2014. It is stated that the drive towards convenience stores is well established in Asia (PWC, 2015).

In Europe, the overall retail sector represents 4.3% of the Gross Value Added (GVA). All European countries witness the increasing share (18% over one year-2011) of supermarkets and decreasing share of traditional local food markets in the food supply chain. Over the past decade, the retail landscape has evolved as well for EU consumers due to combination of different factors. The same report characterises the period as a strong development of modern retail across EU (EY et al., 2014). Economic crisis in several countries lead consumers to seek lower prices and along with the changing trends towards new healthy behaviours and increased environmental awareness, have impacted on the retail market in Europe. For example, in Germany discounters take the biggest share (32.2 %) of the stores breakdown while in France supermarkets keep the 39.1% of the stores breakdown (Tackett, 2014). Food retail stores consume a relevant share of Europe's electricity; 4% in France, 3% in Germany (Supersmart, 2017). Moreover, the annual energy use in supermarkets in Germany is estimated to be 16 TWh, in Spain 6.8 TWh, in Italy 8.2 TWh, and in Norway about 1.5 TWh (Supersmart, 2016).

In the UK, it is estimated that the food chain is responsible for 176 $MtCO_2e$ emissions of which 65% are from UK food chain activity and the remainder from food imports

(Defra, 2013). The GVA of the food sector (excluding agriculture) increased 4.1% in 2015, following a 2% increase in 2014. Retail GVA is around £30bn (Defra, 2016) from which £5.73bn are due to frozen food market (Kantra WorldPanel, 2015) .

Direct emissions from buildings rose to 89 $MtCO_2e$ in 2016, accounting for 19% of UK Greenhouse Gas (GHG) emissions (Committee on Climate Change, 2017). Retail food stores are very energy intensive buildings responsible for approximately 3% of total electrical energy consumption (Tassou et al., 2011).

The energy use of the food retail stores depends on business practices, store format, product food ratio, equipment use for in store preservation and display. The smaller the store the highest the energy use due to the higher refrigeration equipment used because of the higher ratio of food and non-food products. As the total sales area increases, the refrigeration energy use share in the total energy use reduces and the lighting becomes more significant. Regarding supermarkets reported energy use by the most energy intensive sub-systems assign (DECC, 2013) (Tassou & Ge, 2008) 35% to refrigeration system and 26.8% to HVAC.

GHG emissions from food retail stores can be divided into two categories; direct and indirect. The first are due to leakages of refrigerants with high global warming potentials (GWP). Indirect emissions are produced from the energy required from sub systems of the food retail stores the building as a whole. Recently climate change has become the prime motivator for concern and change and thus the GWP and TEWI of refrigerant has become important. Due to European F-gas regulation (Regulation (EU), 2014) high GWP refrigerants will be phased out in most of refrigeration and air conditioning applications in order to reduce GHG direct emissions something that will affect the existing European commercial refrigeration systems. Several retailers are committing to reduce or eliminate GHG emissions of refrigeration systems by switching to “natural” refrigerants or refrigerants with lower environmental impact (Osborn, 2013) (Co-op, 2011).

Food retail consumers are unique comprising of groups with different needs depending on the age, demographic areas, professional careers and lifestyle, marital status, access to technology etc. Consumers are one of the most important key drivers of the food retail market and they can affect significantly the food retail stores energy use performance. Changes in food retail stores are complicated by the fact that most of the people using them (the customers) do not have either professional or personal attachment to the building itself. The decision makers who do work within the building will generally make choices to suit customers.

Globally, food retailers supported by research in academia and development by refrigeration systems manufacturers are actively working towards reducing their carbon footprint, in response both to regulatory pressure and customer interest. Recent projects (i.e. Supersmart) work towards the introduction of the EU Ecolabel for food retail stores. Such a label can encourage food retailers to implement environmental friendly and energy efficiency technologies and consequently to reduce environmental impact. Similar type of label (Energy Star) already exists for US, Canada, Australia, New Zealand and Japan (Supersmart, 2016).

1.2 Modelling energy use of supermarkets

Due to the food retail stores' complexity, the energy demand analysis and prediction is a difficult task because of the interlinked heat exchanged between the buildings, HVAC and the refrigeration systems coupled with varying requirements of stored products, hours of operation and transient occupancy patters. The ability to analyse and accurately predict the energy and thermal performance of food retail stores is becoming increasingly important for businesses as it gives insights for decision making regarding sustainable and energy efficient strategies and forecasts.

Analysis tools to assist in energy performance evaluation of food retail stores include:

- Data driven statistical tools (regression analysis, artificial neural networks (ANN)) which use measured data
- Physical models which require physical description of buildings and systems. These can be simplified tools requiring minimum input data or advanced tools requiring more detailed input specifications

Statistical models are usually restricted by the data used for their development and tend to offer less precision for general cases. In some instances, they have weak robustness due to lack of high quality training data (ASHRAE, 2013). On the other hand, physical models have the ability to represent more accurately the reality of the energy performance of the stores as the exchanges between subsystems are a key driver for their energy performance.

To-date although intermodal calibration exercises have been carried out, there is limited work on whole building energy models which include integrated heat exchanges between refrigeration and HVAC systems and the building envelope validated using operational data from operational supermarkets.

Such models are very useful because they can be used during the design phase in order to estimate future energy consumption or to test more energy efficient strategies for amendments or refurbishments. There exist two categories of physical model tools for modelling and simulation of the energy use of food retail stores (Supersmart, 2016):

- Whole building modelling and simulation (i.e. CyberMart, EnergyPlus, Matlab, SuperSim, Retscreen)
- Subsystems only modelling and simulation (i.e. Coolpack, CoolTool, EES, IMST-ART, PackCalculationPro)

Physical models can also be divided to (a) dynamic thermal simulation tools and (b) steady state or quasi-steady state thermal simulation tools. Their suitability depends on the need of considering the time over which the subsystems performance is changing.

This project has developed such a model using EnergyPlus and validated this by using operational data from frozen food supermarkets.

1.3 Frozen food retail sector

The frozen food market and retail consumption is reported to be on the increase during the last decade. The global market was valued at USD 241.72 billion in 2014 and is projected to USD 307.33 billion by 2020. This is due to the increasing standard of living and lifestyle changes with less time to cook. Frozen food is easy to store, easy to use and easy to carry. It provides an excellent option to customers with limited cooking skills and time (Grand View research, 2016).

The US frozen food market size was USD 51.97 billion in 2015. Frozen ready meals were the largest segment regarding sales in 2015 and accounted more than 35% market share. Europe was the largest regional frozen food market in 2013 and accounted for 38.9% of the total market revenue (Grand View research, 2016). Growing population coupled with increasing disposable income level in countries such as China and India has a positive impact on the overall frozen food market. Emerging economies such as

South Africa and Brazil are anticipated to witness significant growth regarding demand for frozen food products (Grand View research, 2016).

UK represents Europe's largest market for chilled prepared foods with the frozen food market (Fletcher, 2007) to perform well over the retail sector (B. Young, 2016) . In addition, consumer lifestyle impacts on this growth with frozen ready meals being the leading product consumed accounting for over 35% of total market. One explanation for consumer preference is the reduced preservative levels in frozen meals compared with chilled while the economic recession impacts on careful shopping with shoppers opting more for frozen foods (Bank of England, 2012) (Daily Mail, 2012). The UK's frozen food market is steadily growing as consumers continue to demand convenient, high quality food. Time has become precious to consumers and this has shifted the choices towards to small and food oriented retail stores and to meal ideas which offer great value in terms of time –saving, nutrition and taste. The focus on the frozen food fulfils all the previous aspects for fast and easy meals full of taste and with all the quality of the nutrition to have been maintained through the freezing process. Consumers recognise frozen's food benefits of freshness being locked in, no use of preservatives, good taste, less waste, longer shelf life and better value (BFFF, 2010). Climate weather changes towards warmer seasons especially heatwaves of summer, lead to the increase of frozen food sales (BFFF, 2016).

Top few companies in the frozen food industry include Iceland Foods Ltd, General Mills Inc, Ajinomoto Co. Inc., Nestle, Unilever Plc, Allens Inc, Heinz, and Amy's Kitchen Inc (Grand View research, 2016).

This research focuses on the frozen food retail (supermarkets) in the UK. The frozen food chain that facilitated the two case studies used in this research project is a British food retailer (Iceland Foods Ltd) with over 880 stores throughout the UK and 40 owned or franchised in Europe. In late 2016, they started a new store format following a refit and modernisation perspective with state of the art freezers. Energy performance is closely monitored to assess the potential for similar refits in other Iceland stores. Moreover, energy efficiency monitoring of stores is under the interest for a positive change by reducing energy use and carbon footprint emissions.

For a frozen food retailer with a high load of refrigeration load, becoming as carbon neutral as possible is a significant challenge. In many cases, carbon neutral can be achieved for new designs and refurbishments by improving all subsystems which include

- Improvement in building envelope and lighting system
- Selection and optimisation of HVAC system
- Reducing internal heat gains
- Replacement refrigeration systems with more efficient and with lower GWP refrigerants
- Use on site renewables

A recent report (British Retail Consortium, 2015) suggests that progress since 2005 has led to reduced carbon emissions from stores by 35% and are due to improvements in:

- Energy use in lighting systems by using energy efficiency technologies such as LED or daylight control strategies.
- Innovative technologies in heating, cooling and ventilation equipment. Variable Speed Drive (VSD) fans, heat recovery, wind lobbies, combination of mechanical and natural ventilation and roof vents and night ventilative cooling.
- More energy efficient and natural refrigeration system. Efficiency can be increased by closed display cabinets with LED lighting and more efficient control types for defrost and anti-sweat heaters. In order to reduce refrigerant charge centralised systems can be used or secondary or indirect systems. According to studies the use of natural refrigerants is promising in terms both of energy efficiency and environmental impact.
- Energy supply with renewable technologies. These include photovoltaic systems, solar water heating, wind turbines and electricity and heat generation from wastes and biofuels.
- Staff training and behaviour change in energy use. Efficient driving techniques were introduced and software tools for a quick evaluation of the energy performance or individual stores have been studied.

To date although the above changes have promising results in terms of the energy performance of food retail stores, no research has been carried out for frozen food retail stores which differ from conventional food retail stores with more refrigeration equipment that consequently have more significant interactions with the HVAC systems and optimised control strategies are required. Due to high refrigeration equipment, frozen food stores specific needs of heating, ventilation and cooling systems with direct interaction with the refrigeration display cases. Products display and storage and the customers' indoor air comfort levels are two parameters that need to be satisfied simultaneously.

Driven by the aim of the frozen food chain to reformat and modernise its stores, two case study stores were selected strategically in order to represent two different scenarios of HVAC equipment and control strategies. Within this research project the case studies are used to investigate energy performance of the buildings with:

a) scenarios already tested and implemented in food retail stores (lighting system)
b) scenarios for optimised HVAC control strategies which are suitable for stores with high remote refrigeration loads (night ventilative cooling) and have been limited studied for food retail stores
c) comparison of remote refrigeration system with more efficient centralised refrigeration systems with low GWP refrigerants which have been studied only as systems performance and there is limited evidence for their performance in an operational store

1.4 Research aim and objectives

The ultimate aim of this research project is to create and validate a computational model of frozen food supermarkets taking into consideration both building (envelope, HVAC and lighting) and refrigeration systems and their interdependence. Such models can be used to identify opportunities for energy reduction considering the supermarket as a whole system. In order to achieve this, the following specific objectives were set:

Objective 1:

Carry out a state-of-the-art literature review to identify practices and tools in energy use performance simulation and benchmarking of small retail food stores.

Objective 2:

Identify case-study supermarkets with different HVAC systems to source data for the model development and validation.

Objective 3:

Carry out extensive energy and environmental monitoring in the identified case-study supermarkets. Analyse the monitored data to understand energy use and identify factors influencing it. Prepare the monitored data for validation of the computational model.

Objective 4:

Develop and implement a methodology to create a validated 3-D thermal and energy computational model for dynamic simulation capable of predicting energy and environmental performance (including all sub-systems) of frozen food supermarkets.

Objective 5:

Investigate mitigation strategies for improved energy performance considering interactions of subsystems and maintaining required internal environmental conditions.

1.5 Thesis structure

Figure 1-1 presents a map of the research undertaken, its objectives, structure and outcomes. The work carried out is divided into two parts.

The first part comprises of in-situ field monitoring in the two case-study supermarkets. This monitoring includes detailed energy and environmental data which are not widely available for research purposes in academia. Their analysis has led to a detailed understanding of the main drivers of energy use and environmental conditions in frozen food retail stores. These can give useful insights to decision makers (retailers) for the identification of possible inefficiencies and better control strategies for energy use savings.

The second part includes the development of a computational model for frozen food supermarkets. The model uses EnergyPlus as the basic engine and is based on the monitored data which assure validity of the predictions. The model combines all energy carriers in the supermarket and their interdependence during operation. This model was used to evaluate quantitatively the changes on main drivers influencing the energy use in total and of each sub system separately which consequently lead to energy reduction targeting.

The thesis comprises of seven chapters. Chapter summaries are presented below.

Chapter 1

The first chapter provides an introduction of the work in this thesis. It analyses the research motivation according to market trends and research gaps. Finally, the research aim and objectives are explained and the thesis structure is outlined.

Chapter 2

This chapter summarises the findings of the literature review carried out. It starts with a brief review of food retail market trends and the impact of frozen food market. It continues with the review of energy use benchmarks and the operation systems of supermarkets. Finally, state of the art methodologies for analysis and predicting energy use performance of food retail building are discussed.

Chapter 3

Chapter 3 starts with information of the two case study stores selected for field measurements. It then gives a review with the methodology and plans of monitoring process as well as the period of each monitoring. Energy use monitoring is carried out by the frozen food retail contributor and thus only the equipment used for environmental monitoring and its technical characteristics are outlined. The environmental conditions monitoring of the case study stores includes temperature, relative humidity, CO_2 levels concentration and light intensity in the sales area, temperature and relative humidity in the storage area and temperature and relative humidity inside the freezer and chiller coldrooms. Moreover, temperature of the HVAC terminal units is monitored. It continues with transactions' and customers' data and observations. Methodology and equipment for energy use monitoring plan and metering of plugged-in frozen food lift up lid cabinet is discussed finally. This is separated into two parts; in-store monitoring and lab test. Operating temperatures of the cabinets as well as monitoring of opening/closing of the glass lid are set by the outlined equipment.

Chapter 4

This chapter presents the results from the two case-study stores monitoring plan as it is discussed in Chapter 3. It starts with the total energy use analysis of the two monitored stores and sub-systems monitoring of similar store supplements the results for the energy use performance of the two case study stores. It continues with the results from the environmental conditions monitoring in sales areas, storage areas and coldrooms. Identifications of key drivers influencing the environmental conditions inside the sales area are analysed and similarities and differences between the two stores are discussed. It concludes with comparison of the monitoring results with data available from the literature. It then continues with the results from the frozen food display cabinet which included comparison of the energy use metered both in store and in lab as well as the operating temperatures in store and in different environmental conditions in lab test room. Complementary opening/closing monitoring results of the glass lift up lid are analysed and correlated with the energy use. Transactions data are discussed and customers' spot observations are finally presented.

Chapter 5

Chapter 5 analyses the EnergyPlus model development to represent different HVAC systems. This based on the two case study stores identified in Chapter 3. Different phases of the modelling procedure are presented as well as input parameters and configurations of sub-systems and control strategies. The results of the energy and thermal models are compared and validated with the monitoring results and the base line models are established.

Chapter 6

Chapter 6 facilitates comparison of the energy efficiency performance and breakdown of the subsystems of the two case study stores. It continues with sensitivity analysis of subsystems performance mainly of the two most energy intensive systems (HVAC and refrigeration) as they are the only ones which differ from the design operation. Correlations with key drivers of their performance are discussed. After evaluating the total energy use of the two case study stores and the interactions of the subsystems, several applications for retrofit scenarios are analysed. These applications start with building construction amendments and their impact not only on the overall energy use of the stores but of the subsystems as well. Lighting upgrade systems with LED lamps evaluating in simulation results but in store measurements as well because it took place during the completion of the research project. As HVAC control strategy plays important role in energy use of HVAC and refrigeration equipment operation, strategies for night cooling are discussed for both case study stores. It includes parametric analysis and optimisation of free night cooling operation and comparison with conventional active cooling performance. Finally, alternative centralised refrigeration systems are implemented and compared with the current remote refrigeration system in order to evaluate the total energy use performance as well as the impact on the heating/cooling requirements profile. Emissions results analysis supplements the systems adequacy for a frozen food supermarket store.

Chapter 7

The final chapter presents the overall conclusions for the monitoring process results as well as the numerical results from the EnergyPlus model applications. Also, further investigation challenges are outlined.

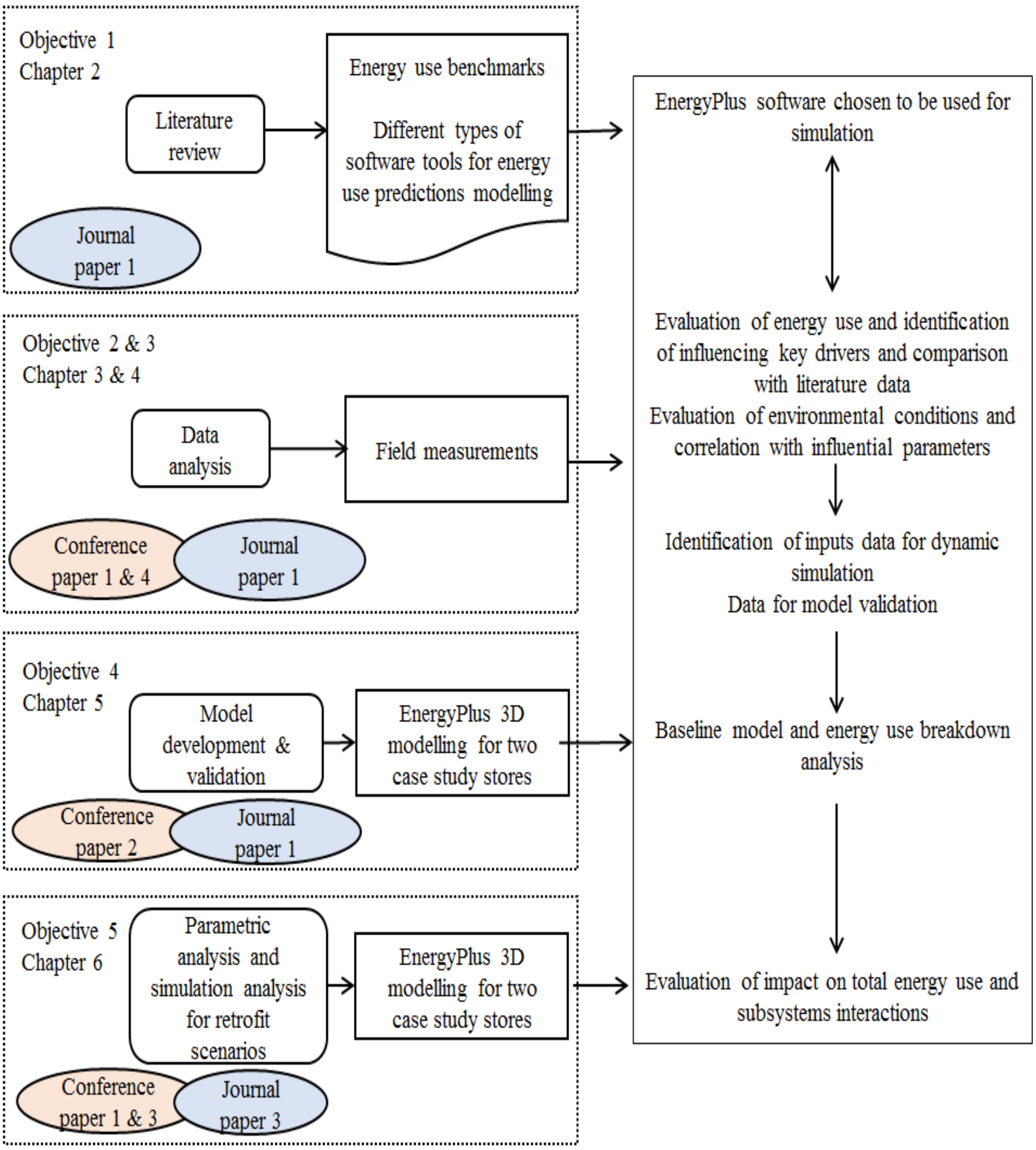


Figure 1-1: Brief map of research undertaken, objectives methodology

1.6 Publications

1.6.1 Journal Papers

1. Z. Mylona, M. Kolokotroni, S. Tassou (2017). *Frozen food retail: Measuring and modelling energy use and space environmental systems in an operational supermarket.* Energy and Buildings, (129) 129-143 https://doi.org/10.1016/j.enbuild.2017.03.049
2. K.M. Tsamos, Y.T. Ge, I. D. Santosa, S. Tassou, G. Bianchi, Z. Mylona (2017). *Energy analysis of alternative CO_2 refrigeration system configurations for retail food applications in moderate and warm climates*, Journal of Energy Conversion and Management, http://dx.doi.org/10.1016/j.enconman.2017.03.020
3. Zoi Mylona, M. Kolokotroni, K. Tsamos, S. Tassou (2017). *Comparative analysis on the energy use and the environmental impact of different refrigeration systems for frozen food supermarket application*, Energy Procedia, International Conference of Sustainable Energy Use in Food Chain, https://doi.org/10.1016/j.egypro.2017.07.234

1.6.2 Conference Papers

1. Zoi Mylona, M. Kolokotroni, S. Tassou (2017), *Coupling night Ventilative and active cooling to reduce energy use in supermarkets with high refrigeration loads*, 38th AIVC - 6th TightVent - 4th Venticool Conference, September 2017, Nottingham, UK
2. Zoi Mylona, M. Kolokotroni, S. Tassou (2015), *A study of strategies to reduce energy use for internal environmental conditions in supermarkets*, 29th EFFoST International Conference, November 2015, Athens, Greece
3. Zoi Mylona, M. Kolokotroni, S. Tassou (2015), *Ventilative Cooling and Energy Use in Supermarkets*, 36th AIVC – 5th TightVent & 3rd Venticool Conference, September 2015, Madrid, Spain
4. Zoi Mylona, M. Kolokotroni, S. Tassou (2014), *Investigation of Energy Performance of Frozen Food Supermarkets,* 13th International conference on Sustainable Energy Technologies, August 2014, Geneva

1.6.3 Awards

Athena Swan Award (2014) for Outstanding Female Engineer, Brunel University London, UK

Chapter 2

Energy use and environmental impacts of supermarkets

Introduction

This chapter summarises the findings of the literature review carried out at the beginning and throughout the research. The review aims to identify the trends of the food retail industry and the reason of frozen food market establishment. It continues with review regarding the energy use benchmarks and the operation systems of the supermarkets and closes with the state-of-the-art methodologies for analysing and predicting the energy use of the buildings. The scope of this chapter is to give information about the needs to investigate the frozen food retail food stores which are similar to conventional supermarkets in size but significantly different in food products and refrigeration system. Moreover, it aims to justify the software used after reviewing and evaluating up-to-date tools.

2.1 Trends in food retail and energy use

2.1.1 Food retail trends and the frozen food market

There is a move to convenience foods dictated by changing lifestyles as well as increases in ready meals and frozen products. These changing trends are outlined below.

Food retail trends

In the US, 20% of the retail chains are grocery store and supermarket chains. This shows the power of the supermarket and grocery store retailers in the US which has 3 out of 10 of the biggest retailers worldwide. Traditional supermarkets have been losing market share because customers are seeking convenience and better value (Business Insider , 2015). According to latest data from Prosper Insights & Analytics in 2016, US consumers shopped for groceries online. Given that discounters share is increasing and well established in US market, the price is no longer a competitive differentiator. Grocery shopping turns to be a position for healthy and wellness lifestyle with high quality products (Skrovan, 2017). Moreover, progress in research and evidence about the quality of products and food have enhanced the preference on ready meals and frozen food products. The growing number of working women worldwide is a key driver as well.

Analysis in the Asian market showed that 30% of the world's retail growth through 2017 will come from Asia's emerging markets. Retail markets are varying from large full service supermarkets to outdoor local markets. There are several obstacles that make Asia a region with controversial outcomes due to high percentage of the local market share which enable fresh products in lower costs (Forbes, 2014). According to IGD, China has the biggest grocery market value and India and Japan follow. The same report outlines that online and convenient stores will present the fastest growth in Asia, while hypermarkets and supermarket will present a reduction in their share. Asian consumers tend to require bigger variety of products and in better quality (IGD, 2015).

In 2016, an increasing level of innovation in small retail stores has been observed in Australia. New style of convenient store formats is tested focusing on delivery better quality food-for-now, ready to cook or home cooked and fresh option of big variety of products (IGD, 2017).

The retail landscape in Europe has remained stable over the past years with the small supermarkets and convenient stores to account almost 40% of the share. France and UK have been dominated by hypermarkets. Figure 2-1 presents in more details the market shares per European country in 2014. Moreover, the market share of discount supermarkets stores in Europe reached 21% in 2015 (Grocery Universe, 2016). For example in Belgium there are 7161 grocery stores which number has a downtrend with the percentage shares of the different format share remaining stable over the years with a small increase in the supermarket share the last years. Small supermarkets and convenient stores represent the 62.5% of the total grocery stores in Belgium in 2015.

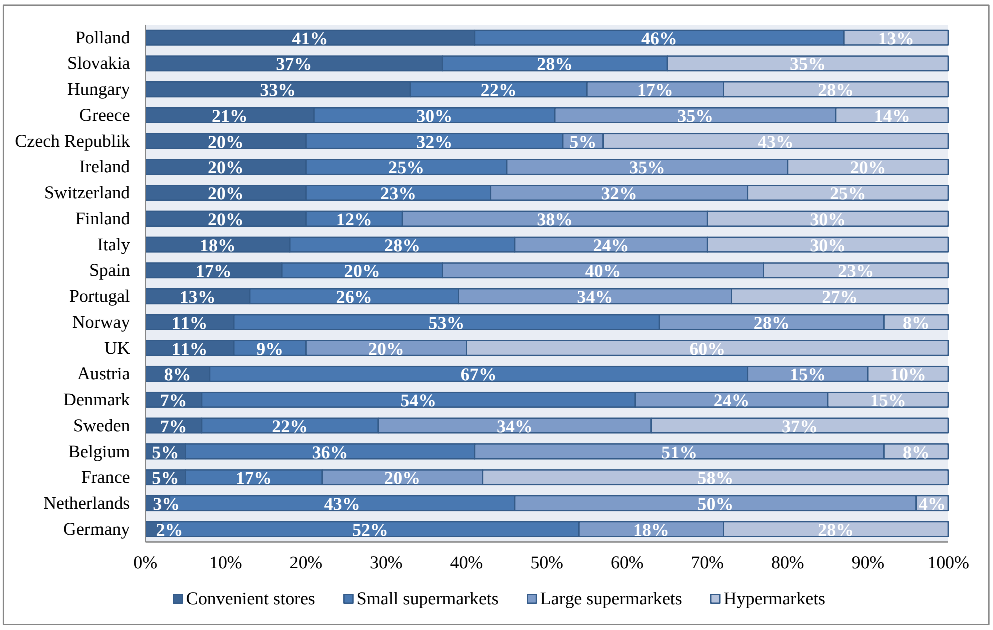


Figure 2-1: Market share by categories per country in 2014 (EU)

Frozen food market

The growth of frozen food market is driven by the growing demand for frozen food in developing markets across Asian countries such as India and China. The establishment of the hypermarkets and supermarkets in Asian countries have enhanced the demand in frozen food but the lack of appropriate refrigeration equipment in retail stores and transportation are the major challenges (Upadhyay, 2015).

Ready meals in Australia presented 5% growth in 2016. The preference for frozen food ready meals have been changed as well as supermarkets offer better quality meals and appealed packaging, Consumers are becoming more accepting of the use of frozen food as natural and the frozen food value growth was 3% in 2016 (Euromonitor International, 2016).

The same applies for the European countries; it is estimated to be USD 75.9 billion in 2016 and forecasted to reach USD 98.26 billion by 2021 (Market Data Forecast, 2017). Figure 2-2 presents the share of the Western Europe frozen food market share in 2015. Germany and UK are the largest frozen food markets. Seasonality is limited for these countries and for this reason a vast majority of products are frozen in order to be widely available throughout the year. However, there is a debate between the frozen food versus chilled food and survey has shown that in Germany the vast majority of ready meals are frozen. For the second biggest frozen food market in Europe, equilibrium is maintained between the frozen and chilled food meals (Koric, 2016).

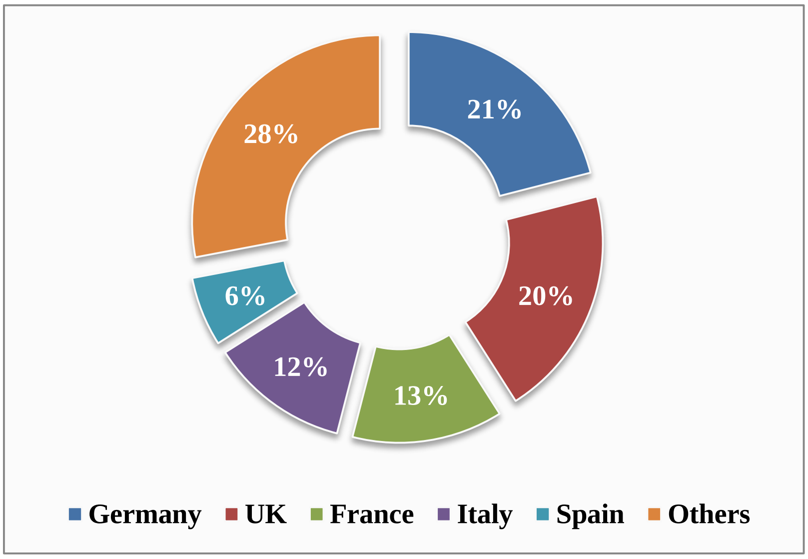


Figure 2-2: Western Europe frozen food market share

In conclusion, the changing in the food retail store shares across the world towards smaller in size stores is apparent and lack of time and economic issues enhance the preference of the consumers to the small food retail stores and discounters. Hypermarkets share although reduced, continue to prosper with changing format, appealing to consumers, such as products and services driven by customers' lifestyle.

In parallel to convenience, the health and wellness issues have brought into attention the frozen food market. Frozen food sales are increasing continuously as they offer variety of products all year around with evidence of nutrition quality in comparison with the chilled food.

2.1.2 UK food retail trends

Figure 2-3 shows the share of 85031 grocery stores in UK while figure 2-4 illustrates the sales share (USDA, 2015) by store type (as defined in Table 2-1 (Defra, 2006)). The categorisation of the store types in UK is different than those followed by Europe. The size of convenient stores in UK is assumed smaller but superstores' and hypermarkets' sales area in UK is consider bigger (Table 2-1 and Table 2-3).

Convenience stores and supermarkets have a combined share of 59% representing 41% of total sales. According to IGD, the UK grocery market worth will increase by approximately 14% mainly due the fast increase of sales in convenience stores, discounters and online (Institure of Grocery Distribution, 2016). Convenient stores and supermarkets are located in central urban areas, near stations and shopping malls. This enables customers rapid shopping of meals and non-perishable meals as they prefer to pop into discounters for bargains (discounters sales area is similar to supermarkets). Consumers' lifestyle is the key driver of the market and impacts the sales share by store type.

Table 2-1: Retail store categories (UK)

Category	Sales floor area (m^2)
Convenience store	<280m^2
Supermarket	280 m^2-1400 m^2
Superstore	1400 m^2-5000 m^2
Hypermarket	>5000 m^2

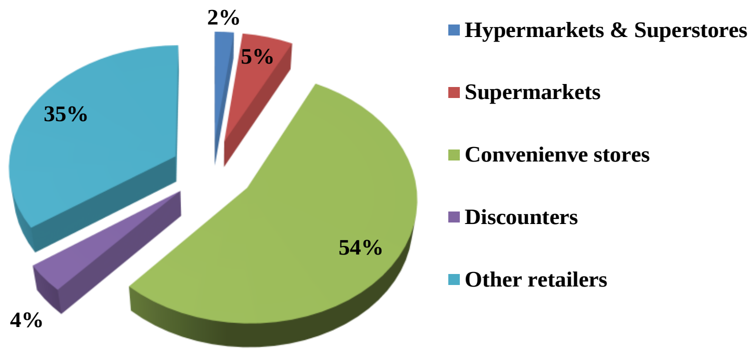


Figure 2-3: Grocery stores share (Source: Institute of Grocery Distribution, 2015)

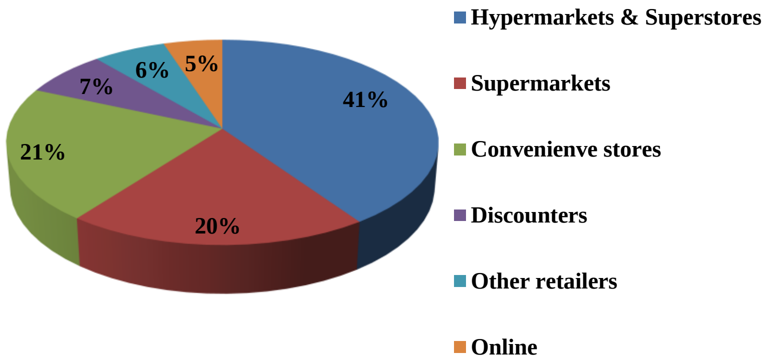


Figure 2-4: Sales share by store type (Source: Institute of Grocery Distribution, 2015)

Four supermarket chains dominated the UK food retailing, accounting around 70% of the market (MSCI & Colliers International, 2017). Tesco is the market leader with Sainsbury's and Asda to follow sharing the same share (~16%). Morrison's is the last from the big four with around 11%. Other UK supermarket chains include The Co-Op, Waitrose, Iceland, Lidl and Aldi (Figure 2-5).

Discount supermarkets have begun to cut into the big retailers' market. Following the vote favouring Brexit, the value of pound against the dollar and euro dropped. The decline in value of the pound translated to a higher price for the supplier. For food retail, the trade with the EU is the most significant to UK retailers and consequently the food prices which are paid by UK consumers. Tesco and other big market sharers not only postponed plans to open new stores in other locations but also initiated job cuts by replacing stores with convenient stores with lower shifts (Armstrong, 2015) (Williams-

Grut, 2017). In 2012, the Big Four (Tesco, Sainsbury's, Morrison's and Asda) had almost 78% of the market share but at the end of 2016, this percentage was reduced to 70% with discounters reaching up to 10% in the share market (MSCI & Colliers International, 2017).

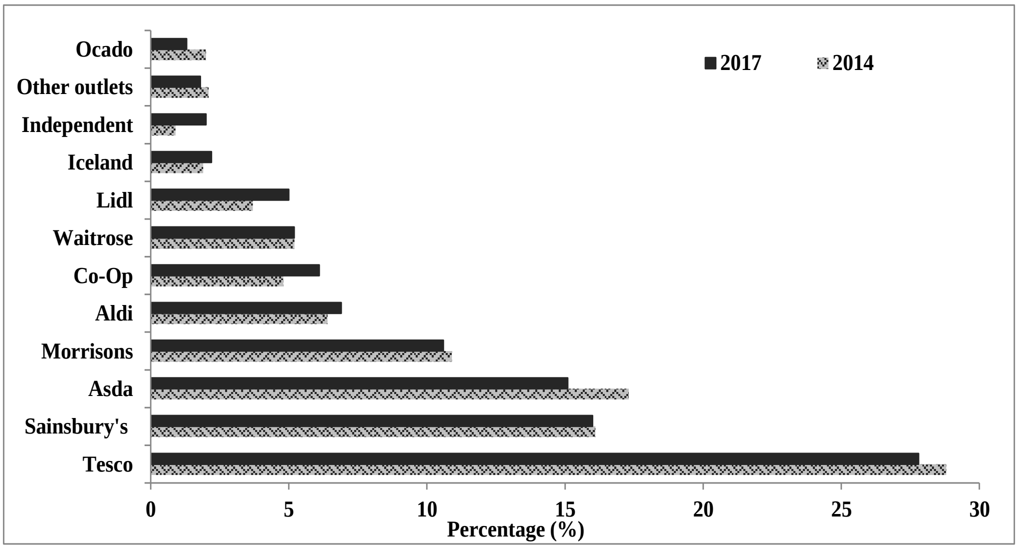


Figure 2-5: Grocery Market Share in UK (Kantar Worldpanel)

Discounters have submitted applications for building a big number of new build stores. After discounters, Marks & Spencer (convenient store) has the most ambitious store opening plans (Ruddick, 2015). On the other hand, consumer lifestyle impacts on this growth with frozen ready meals being the leading product consumed accounting for over 35% of total market. News headlines (FMCG News) highlight growth of 5.8% in the UK in 2012 with ready meals having the highest volume growth. One explanation for consumer preference is the reduced preservative levels in frozen meals compared with chilled while the economic recession impacts on careful shopping with shoppers opting more for frozen foods (Bank of England, 2012) (Daily Mail, 2012). Winners in food and grocery in the next year will be those who remain customer focused, providing solution that make grocery better value for money.

In parallel to this, market research on consumer behaviour (Vend, 2016) suggests that variety of merchandise and choice does not increase customers who are short of time and focused during shopping. This tendency has created a shift towards new relatively small convenience food shops instead of out-of-town hypermarkets with a variety of products. IGD (IGD, 2014) estimate that spending in convenience stores will rise over the next five years but they also warn that supermarkets might have overestimated their profit potential as convenience stores are more expensive to build and operate (Ruddick, 2015) (Barford, 2014).

In summary, the development of the UK food retail market is influenced firstly by consumers' preferences; (a) convenient location of the store within walking distance from stations, (b) pricing and competition with discounters, (c) brands, and (d) products. It is also influenced by the new way of shopping which focus on daily needs from physical shopping in stores while weekly/monthly shopping is done online. Consequently, a slowdown in big out of town stores development is apparent and food retail market is growing with food-focused store formats. The competition between retailers leads to an increase in the supermarket and convenient store format which include a high ratio of food to non-food products. The saturation of hypermarkets and superstores in combination with the fast pace of life has enhanced the popularity of ready and frozen food meals. Finally, retailers seek for energy efficient and sustainable systems to operate the stores because data has shown that smaller in sales area stores are more energy intensive is due to the high volume of food products.

UK frozen food market trends

According to British Frozen Food Federation (BFFF) it is estimated that the current British frozen food market is at £8.13 billion with the 46% to be from food retail sales. It is also stated that it will present 2% growth over the next five years (M. Stones, 2016).

Dietary health concerns have increased to double during the past 15 years in UK and the average shopping basket is getting healthier with consumers choosing healthier options. Fresh and chilled food consumption has remained almost stable since 2014 while frozen food consumption has increased by 6% during the same period (Hayward, 2017).

Frozen desserts/ice-creams and ready meals are the key drivers in frozen market with the frozen meat to be a challenging area but preparation of meals is where frozen food products are used. Results from survey regarding the reasons to buy frozen food products in UK has shown that customers are willing to spend more money if the product gives solutions for meals in order to save time (Hayward, 2017).

As the frozen food market is growing fast, there is a need for innovative solutions that will retain more customers and increase sales of the frozen food supermarkets. The scope is to deliver clear communication of the retailer's unique benefits. Frozen food stores are food dominant stores which require a significant load of Low Temperature (LT) refrigeration equipment. However, they have also similarities with conventional supermarkets. Table 2-4 presents the characteristics of these two categories based in UK food retail market trends.

Table 2-2: Frozen food stores Vs. Conventional Supermarkets

	Frozen food supermarkets	**Conventional supermarkets**
General Characteristics		
Location convenience	√	√
Convenient size for fast shopping	√	√
In store services		√
Food dominated	√	
Mix of products		√
Food products Characteristics		
Daily necessities	▲	▲▲
Frozen food products	▲▲▲	▲
Frozen food ready meals	▲▲▲	▲
Chilled food products	▲	▲
Chilled food ready meals	▲	▲▲
Fresh food products	▲	▲▲
		▲ size of variety

Although all the food chains in UK offer a big variety of frozen food products, Iceland Foods Ltd specialised in frozen food sales and has contributed the most to the frozen food market growth in UK (Hayward, 2017).

2.1.3 Energy use in food retail

Retail stores are among the most energy-intensive commercial buildings, consuming two or three times as much energy per unit floor area as office buildings. In the UK, energy consumption in food supermarkets is around 3.5 % of the total UK energy consumption (Tassou et al., 2011). The reduction of the energy consumption of these stores is important for their profitability as well as for the national CO_2 emission targets; cutting by 80% below 1990 levels by 2050 (DECC, 2011).

The energy consumption of food retail stores depends on business practices, store format, product nature, sales area, construction, shopping activity, external weather, instore equipment for preservation and display. It is expected that the stores with a larger area for refrigeration cases will consume more electricity. Consequently, one of the main factors affecting the energy demand of the food retail stores is the ratio of food products against total products; the greater this ratio is, the more energy is consumed. This is explained by the fact of how many products need to be kept in cooled/frozen conditions (Mavromatidis et al., 2013) (Spyrou et al, 2014). In current literature, the energy use in food retail buildings is usually normalised in kWh/m^2 sales area per year and the ratio of food and non-food products is used to compare the energy use of similar stores.

As mentioned in Chapter 1, supermarkets are high energy consumption complex buildings for which energy demand analysis and prediction is a difficult task because of interlinked heat exchanged between building and operational sub-systems (HVAC, refrigeration) coupled with varying requirements of stored products, hours of operation and transient occupancy patterns. Although major parts of supermarket systems and subsystems are regulated by national regulations in terms of environmental sustainability, there is a lack of legislation considering the supermarket system as a whole.

For the US, the Energy Star Score for food retail stores provides an assessment of the energy performance of the store taking into account the climate, weather and business activities based on statistical analysis of the peer building population energy use. The peer building population data in the US are based on data from the Department of Energy, Energy Information Administration's (IEA) 1999 and 2003 Commercial Building Energy Consumption Survey (CBECS) (Energy Star, Portfolio Manager, 2014). Energy Star score also exists for Canada, Australia, New Zealand and Japan. For example, the average energy use in Canadian supermarkets has been evaluated to 800 kWh/m^2 per year (Annex 31, 2012).

According to data from the US Environmental Protection Agency's (EPA) Energy Star Portfolio Manager from 9158 properties in US for the period of 2010-2015, supermarkets are quite big with average 4650 m^2 total area including cooking facilities and remain open almost 18h per day. However, there are supermarkets of all shapes and sizes benchmarking in Portfolio Manager of Energy Star. The same report states that the higher the number of workers per m^2 (workers occupancy density), the higher number of refrigeration load per m^2 (food product ratio) and the cooking facilities (usually bakeries) lead to more energy consumption on average. For example, food retail stores with cooking facilities consume approximately 3% more than food stores without cooking facilities (EPA Energy Star, 2015).

In Europe, food retail stores are defined by sales area, Table 2-3 (Grocery Universe, 2016). According to Annex 31 (Annex 31, 2012) research in 146 supermarkets in Sweden showed that the average energy use in supermarkets is around 500-550 kWh/m^2.

Table 2-3: Retail store categories (EU)

Category	Sales floor area (m^2)
Convenience store	<400 m^2
Supermarket	400 m^2-1000 m^2
Superstore	1000 m^2-2500 m^2
Hypermarket	>2500 m^2

A new EU Ecolabel for food retail stores is under research and construction within the Supersmart H2020 project (Supersmart, 2017). It will provide food retailers with criteria on how to reduce the impact and energy efficiency of their stores. This is motivated by targets to reduce energy consumption and consequently the greenhouse gas emissions in Europe.

Existing similar criteria for food retail stores already exist in Europe: (a) the Blue Angel which belongs to German Government, (b) the Nordic Swan Ecolabel officially from Scandinavian countries and (c) the good environmental choice from Sweden (Supersmart, 2017).

In UK, there are three government regulations addressing the energy benchmarking of the food retail sector; the Greenhouse Gas Emissions (GHG) reporting, the Carbon Reduction commitment (CRC) energy efficiency scheme and the transposition of the Energy Performance in Building Directive (EPBD). The GHG reporting is required for all companies listed on the main market of the London Stock Exchange and it is applied since October 2013 (Carbon Trust, 2013). The CRC Energy Efficiency Scheme is also a mandatory scheme to cover large public and private organisations in the UK in order to cut emissions and encourage changes in behaviour and infrastructure. However, it will be abolished following the 2018-2019 compliance year (Carbot Trust, 2007). Both of the above are mandatory to big companies/chains with high turnover.

The EPBD is introduced to both private and public commercial buildings to achieve reductions in energy use and CO_2 emissions. All properties are required to have an Energy Performance Certificate (EPC). They rate the buildings' performance against benchmarks for the same type of buildings. (Energy Performance of Building Directive, 2010). However, EPCs if not calculated by authorised software which are not appropriate to simulate food retail as a whole (see Section 2.4.1), do not take into account the refrigeration systems of retail food (energy use, heat exchanges with the indoor air environment of supermarkets) which lead to unreliable results which does not represent the real energy performance of food retail buildings. Moreover, EPCs are required for buildings with total useful area greater than 1000 m^2.

Currently in the UK, there is lack of available recent data of energy consumption of supermarkets. CIBSE Guide F (2012) is the latest benchmark available in UK available based on a sample of 207 for supermarkets with data collected in the early 2000's. Therefore, they may not reflect recent energy efficiency improvements undertaken in the sector. For all electric served supermarkets with the sales area ~40% of the gross floor area, the energy use estimated 1155 kWh/m^2 for typical practise and 1034 kWh/m^2 for good practice (CIBSE, 2012). This is higher than other benchmarks in Europe, for example Sweden where average energy consumption has been evaluated at 350-450 kWh/m^2 (Annex 31, 2012).

Tassou et al. (2011) presented the energy consumption of a large sample of retail food stores (50% of stores of the main supermarkets chains and representative of the four main store categories (Table 2-1). Data presented indicate a positive correlation between the sales area and energy consumption. They also showed that smaller supermarkets are more energy intensive. Results from supermarkets within Annex 31 report (Annex 31, 2012) agrees with this fact by stating that larger supermarkets are more energy efficient than smaller supermarkets. One explanation could be that supermarkets and convenient stores are mainly only served by grid electricity. Moreover, the energy use of supermarkets drops in comparison with the convenient stores due to the shift from food dominant to non-food dominant stores and the reduction on the refrigeration systems energy use per sales area. As the total sales area increases, the refrigeration energy use share in the total energy use reduces and the lighting becomes more significant (Tassou et al., 2011). Regarding supermarkets reported energy use by sub-systems assign (DECC, 2013) (Tassou & Ge, 2008) 35% refrigeration, 26.8% to HVAC and 18.6% to lighting. Hypermarkets refrigeration system accounts 29% of the total energy use while lighting reaches up to 23% (Tassou et al., 2011) (Spyrou et al, 2014).

This project focused on small size supermarkets energy use which is basically food dominant. As mentioned before, there is limited range of published data for supermarkets energy use and no data are available for frozen food supermarket stores.

Table 2-4 summarises data available from previous research projects in the UK. They focus on the two food dominant categories (convenient stores and supermarkets) and frozen food stores are incorporated into one of these two categories depending on size.

Table 2-4: Comparison of energy use intensity with previous research projects (UK)

Description	**Energy Use Intensity (kWh/m^2/year)**	**Reference**
Convenience stores	1320-1700	(Tassou et al., 2011)
Supermarkets	850-1500	(Tassou et al., 2011)
Convenience stores	1050-1330	(Spyrou et al, 2014)
Supermarkets	747-1082	(Spyrou et al, 2014)
Supermarket	795	(DECC, 2013)
Supermarket	810	(DECC, 2013)
300 m^2 mainly food store	840-1200	(Granell et al., 2016)
Table (2-1) Convenience store: less than 280 m^2 Supermarket: 280 m^2-1400 m^2		

2.2 Energy efficiency in food retail buildings

Energy efficiency measures in supermarkets usually focus primarily on refrigeration and HVAC systems. However building design can have a major contribution to energy consumption reduction. Section 2.2.1 presents summarized results from literature regarding building design and lighting while HVAC and refrigeration systems are discussed in sections 2.2.2 and 2.2.4 respectively.

2.2.1 Building design and lighting to achieve Zero Carbon and Zero Energy supermarkets

There exist examples of low carbon supermarkets and guidelines on how to achieve low carbon and energy efficient supermarkets. These guidelines refer even to Zero Energy (ZE) and Zero Carbon (ZC) food retail stores. ZE food retail stores have as much as possible reduced energy demand and low or zero carbon sources energy suppliers. Most major supermarket chains have constructed low or zero carbon stores in the past years and similar stores can be found in US.

As mentioned in section 1.3 energy efficiency improvements in retail stores has increased during the last decade with 35% reduction of carbon emissions. The UK Government has announced its aspiration for new non-domestic buildings to be ZC by 2019 (Target Zero, 2011) and is compromised by the followings:

- Energy efficient measures for fabric construction, heating, cooling, ventilation and lighting system
- Carbon compliance using on-site and offsite scenarios
- Additional beneficial solutions by exporting low carbon or renewable energy to neighbouring and grid

Four reports have been identified with proposals on how to achieve ZC and ZE supermarkets focusing on building design parameters.

1. Hill et al. (Hil et al., 2010) with a study for ZE food retail stores presented results of solutions' investigation implemented in one of the biggest food retail chain in UK
2. Target Zero (Target Zero, 2011) for guidance on the design and construction of sustainable, low and ZC building in the UK presenting energy efficiency solutions for cost effective supermarkets based on an operational supermarket

3. Supersmart (Supersmart, 2016) a European project for guidance in efficient solution in supermarkets
4. The Advanced Energy Design Guide for Grocery stores (ASHRAE, 2015) providing guidance, case study examples and efficiency recommendations for supermarkets in order to achieve 50% less energy when compared to those same facilities designed to meet minimum requirements by ASHRAE (Energy standard for buildings except low-rise residential buildings, 2004)

In summary to the above reports along with other real case studies or research projects (Passivent, 2015), (Richens, 2010) (Sawaf et al., 2012) (Strein & Kung, 2012) in order to achieve ZE and ZC supermarket the following aspects have been highlighted:

- Improved building construction and orientation
- Combination of natural and mechanical ventilation with ventilation heat recovery
- Improved refrigeration cabinets in terms of efficiency and heat exchange with the ambient
- Daylight control strategy and LED display lighting
- Renewable energy technologies such as biomass, wind power and photovoltaic panels
- Infiltration reduction from main door openings by air curtains or lobby area

Lighting technology is changing rapidly and more energy efficient lighting systems (LED) have been deployed in many food retail stores already. There are easy to install with relatively low cost and have been reported to have significant energy savings and reduction in the cooling loads. This is highlighted further in this section because is one of the largest consumers in the total energy use of supermarkets (the third in energy use breakdown-section 2.1.3) and has already been implemented in the majority of the stores of the frozen food case study chain.

Lighting is a key factor for attracting customers and increase profit of the supermarkets. Specific lighting levels are required for display products and to make transactions easier. Lighting is a major and standard consumer in supermarkets and its consumption increases by increasing the sales floor area. CIBSE Guide A (2015) recommends light intensity levels between 750 and 1000 lux for supermarkets and 500 lux for convenient stores (CIBSE, 2015). A supermarket chain is specified near the upper range (Acha et al., 2012) while surveys indicate lower than the minimum range (Ticleanu et al., 2013).

Fluorescent lighting is widely used in supermarkets with T8 tubes. However, many supermarkets have upgraded their lighting systems with LED lamps to achieve energy use reductions according to British Retail Consortium (British Retail Consortium, 2014; BRC, 2015). They do not contain mercury (unlike fluorescents), they have very long operating lives and they operate effectively at low temperatures which enable them to be used in refrigerated cabinets. Lighting energy consumption can be reduced by 50% as well as the cooling loads.

LED lamps are also replacing the refrigeration cabinets' lamps as they perform well in cold temperatures and provide uniform lighting inside the cabinets, unlike fluorescent lamps. Also, the waste heat from fluorescent lamps influences the ambient air inside cabinets which consequently affects the cabinets' energy use. Many retailers are currently use LED lighting in display cabinets' which has the potential for significant savings over fluorescent lighting lamps (Tassou et al., 2011).

Moreover, daylight control strategies are implemented in several cases and achieve by harnessing benefits of daylight reduction in the lighting energy use. This is done either by glazing facades or by roof light system. Campbell et al. analyse the daylight control that is introduced in a superstore and Deru et al. analyse the effect of the daylight control strategy for a food dominant supermarket (Campbell & Riley, 2009) (Deru et al., 2013). Sainsbury's has introduced natural light wherever possible. Roof lights and lux meter on top of the products adjust the artificial light levels. Lighting levels are maintained at 650 lux and in stores with natural lighting lux levels reach up to 800 lux while non trading times 300 lux are measured in stores (Pearson, 2013). UK's largest food retailer, Tesco, moving towards ZC targets, has implement sun-pipe lighting (Innovate UK, 2011)

2.2.2 Indoor environmental control systems in supermarkets: HVAC systems

As already mentioned, supermarkets have a unique mix of heating, ventilation and cooling systems for building conditioning and interactions with the refrigerated display cases. Products display and storage and customers' indoor air comfort levels need to be satisfied simultaneously. Heat gains/losses from the transient occupancy with peak value, high refrigeration load, high solar heat gains mainly in shop front, high lighting gains from display purposes and localised high equipment loads if any food preparation is applicable add to HVAC systems requirements (CIBSE, 2016).

The display cases provide significant sensible cooling and increase the latent load on the HVAC system. Despite doors and air curtains designed to reduce the infiltration between cabinets and environment, cold air spills into the sales area. For the HVAC, this cold air spillage represents the "cold aisle". Ways to reduce the infiltration load from open refrigeration cabinets are to use closed ones or to improve the performance of the air curtains. This will analysed further in the section with the refrigeration system (Section 2.2.3).

Temperature set points for heating and cooling in the sales area specified in the range 19^oC – 21^oC for winter and 21^oC-25^oC for summer according to CIBSE Guide A (CIBSE, 2015). Tesco supermarkets typically use a heating set point of 18^oC and a cooling set point of 24^oC along with 17^oC and 25^oC during non-trading times respectively (Campbell & Riley, 2009). Another report for Tesco states that set points for their hypermarkets are between 19^oC and 21^oC (Campbell & Riley, 2009). Whole Foods HVAC control operation is to maintain the indoor air temperature at 23.3 ^oC. Reduced temperature set points has been proved to reduce in the refrigeration energy but the balance point in order not to increase the heating loads or dehumidification to be required (Deru et al., 2013) (Acha & Shah, 2016).

HVAC systems in supermarkets can be divided into two categories:

1. coupled HVAC system where heating, ventilation and AC are provided by the same system
2. decoupled HVAC system where heating and AC is separated from the ventilation system

Coupled HVAC systems

The coupled HVAC system is the most common and provides air through overhead distribution ductwork to different parts of the store. Return air ducts return the air to the Air Handling Units (AHU) where part of it is mixed with fresh air and returned to the store and the rest is discharged to outdoors. They can be single or dual duct depending if heating and cooling are required simultaneously. The AHUs are mounted on the roof of the supermarkets.

The AHU heating coils can be electric, or served by a gas boiler circuit. In cases where CHP is also used for supermarkets requirements, the CHP lead the boiler. Campell and Riley (2009) mentioned that in a superstore in Manchester by installing a CHP for combined cooling, heating and power, half of the store's electricity can be produced and up to 80% of the heat demand can be covered by CHP (Campbell & Riley, 2009).

Cooling coils are usually direct expansion (DX) thereby being a component of the electricity demand. Savings in cooling demand of cooling coils can be achieved by extracted cold air from the cold aisle and mixing with the incoming fresh air. The same applies for the heating extracting from refrigerated display cabinets if the refrigeration system is remote. The warm air can be extracted and mixed with the incoming fresh air by reducing the heating coils energy requirements. This extraction can save up to 32% of the latent load ratio of the area. Moreover, cold air can also be used for fulfilling the cooling requirements of other parts of the store (ASHRAE Handbook, 2015) (CIBSE, 2016).

In addition, in all-air HVAC systems, the humidity control is achieved easier by humidistat controls in order to reassure an efficient operation of the refrigeration system which require 55% or less RH (ASHRAE Handbook, 2015).

The coupled HVAC systems can be further divided into the following categories: (a) Constant Air Volume (CAV) AHU, (b) Variable Air Volume (VAV) AHU and (c) all-water system. The latter is very rarely used for retail food applications due to risk of water leaking from overhead fan coils into the sales area. CAV systems accomplish cooling and heating by varying the supply air temperature while maintaining the air volume constant and VAV systems change the quantity of air supplied to a space in response to changes on the load. The changes in the quantity of the air supplied can lead to more efficient systems as the energy consumption depends on the load profile but indoor air quality may suffer on low demand conditions. Acha et al. (2016) showed that reductions on the operation of all air CAV HVAC can be achieved by using Variable Speed Drive (VSD) fans which operate according to temperature needs or pressurisation needs (Acha & Shah, 2016).

In general, the coupled HVAC systems can provide uniform air distribution in large areas with similar cooling requirements such as the retail shops and with the potential to incorporate heat recovery can be a very efficient and trustworthy solution.

Decoupled HVAC systems

The decoupled HVAC system is a non-duct air conditioner where heat is transferred to or from the space directly by circulating refrigerant to evaporators. In contrast, conventional systems transfer heat from the space to the refrigerant by circulating air in ducted systems throughout the building. They are more sophisticated multi-split systems with many evaporators and refrigerant management and control systems. As they do not provide ventilation, a separate ventilation system is necessary. They are Variable Refrigerant Flow systems (VRF) because the amount of the refrigerant flowing to each of the cassette is controlled, and consequently enabling individualising of controls, simultaneous cooling and heating in different zones and heat recovery from one zone to another. These systems are lightweight and modular and do not require big and specific structure on the roof of the buildings so they are convenient for retrofit installations. Condensing units are placed outside and as ducts are not needed, only for ventilation system, building costs and space are saved. Energy efficiency is also improved due to the elimination of duct losses. Moreover, compressors are variable speed enabling the control of the required load. Maintenance costs include mainly the changing of filters and cleaning of coils. However a drawback is that these systems have longer refrigerant piping runs and significant amount of refrigerant passes through the sales area and this could cause problems in case of leaks (Goetzler, 2007).

These types of systems are widely used in small supermarkets and convenience stores due to lack of space as they are located mainly within town centres.

Night (free) cooling

Considerable potentials for reducing the energy use of HVAC system and consequently in the total energy use can be achieved by allowing free cooling when the outdoor temperature is lower than the inside air temperature. Few studies to date have considered free cooling strategies for supermarkets. Wu et al. has concluded that longer night cooling activation results to fewer hours of AC system operation and higher energy savings (Wu et al., 2006). Other strategy that can improve the indoor air thermal comfort and the efficiency of the indoor air conditioning system by using variable speed fans is the demand controlled ventilation using CO_2 measurements or shopping activity (Tassou et al., 2011).

In addition, roof vents have been included in low energy supermarkets to provide controlled ventilative cooling strategy in combination with roof light. This technique achieved 37% energy use reduction (Campbell & Riley, 2009). Hill et al. (2010) propose savings by combination of natural and mechanical ventilation with heat exchange (Hil et al., 2010).

2.3 Refrigeration systems

Refrigeration system which is essential for the preservation of products has remarkable negative environmental impact due to greenhouse gases (GHG) emissions: indirect emissions from electricity consumption and direct emissions due to leakages and refrigerant type.

Recently climate change has become the prime motivator for concern and change and thus the GWP and TEWI of refrigerant has become important. Due to European F-gas regulation (Regulation (EU), 2014) high GWP refrigerants will be phased out in most of refrigeration and air conditioning applications in order to reduce GHG direct emissions; this will affect the existing European commercial refrigeration systems.

The high GWP of the hydrofluorocarbon (HFC) refrigerants commonly used in supermarkets systems, coupled with the high refrigerant leakage rates leads to significant contribution to the increase in global warming. The consequences of the release of massive amounts of synthetic refrigerants with high GWP to the environment are the main reason for the increasing interest in using natural refrigerants such as ammonia (NH_3), hydrocarbon (HC) and carbon dioxide (CO_2) which are the most prevalent in the last two decades (Sharma et al., 2014).

One way of reducing significantly the refrigerant charge in supermarket centralised refrigeration systems is to use a secondary or indirect system arrangement. This arrangement gives the opportunity to use natural refrigerants as a primary fluid and a different secondary fluid which is circulated to the coils of the display cabinets (Tassou et al., 2011)

The indirect environmental impact of the refrigeration system can be reduced by decreasing the energy consumption of the refrigeration systems. This can be done by increasing their efficiency by using for example closed display cabinets instead of open ones, LED lighting and more efficient control types for defrost and anti-sweat heaters (Evans et al., 2016), (Bahman et al., 2012), (Deru et al., 2013), (Evans, 2014).

As mentioned before the use of natural refrigerants such as ammonia, HC and carbon dioxide is increasing. The high toxicity of the ammonia and the size restrictions of the HC systems, make carbon dioxide as a strong competitor for the centralized supermarket systems. However, researches have shown that there are difficulties in food retail to make a final choice when it comes to refrigerants and system type.

ATMOsphere Europe 2015 conclusions made it clear that the natural refrigerant market is increasing. It was quoted also that transcritical refrigeration systems observed to have an increase of 63% in one year only with hypermarkets to be the emerging adaptors of CO_2 systems. Lately CO_2 is becoming a mainstream refrigerant in the refrigeration systems for retail stores and a number of novel designs are being used in the industry including cascade transcritical, transcritical booster, and secondary loop. CO_2 systems are emerging as one of the most efficient, safe and clean refrigerants for food retail (ATMOsphere, 2015).

In supermarket applications three types of systems are used; (a) the centralised systems, (b) the remote systems and (c) condensing units. For convenience stores, the remote and condensing units are widely used due to low refrigerant capacities required. For bigger capacities (more than 20kW), centralised systems are the best choice. Two stage CO_2 systems are recognized as an efficient option especially in moderate climates and plug in units with air and/or water cooled condensers are gaining market share (UNEP, 2014). Figure 2-6 presents the European market trends for refrigeration systems in correlation with the size of the store. Medium and big size supermarkets are going to CO_2 transcitical systems while small to medium formats use more air cooled plug in cabinets, waterloop systems and condensing units with smaller CO_2 racks.

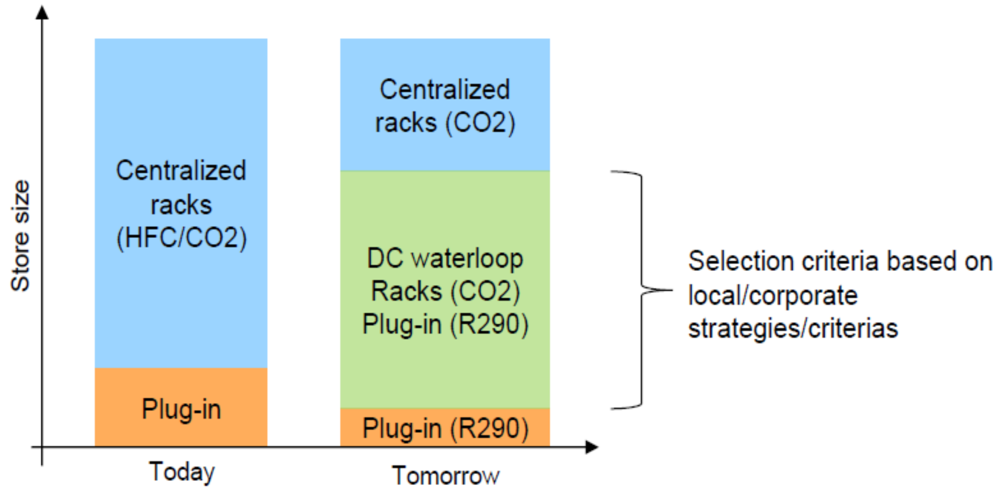


Figure 2-6: European market trends for refrigeration systems in correlation with the size of the stores (Source: CAREL, 2016)

2.3.1 Centralised system

Refrigeration systems in supermarkets are commonly of the centralised type where the evaporator with the display cases in the stores are served by refrigeration systems located mainly outside the store. The evaporators in the refrigeration display cases and coldrooms are fed with refrigerant from the outside refrigeration compressor rack through pipework installed under the floor or along the ceiling of the sales area (direct centralised system) (Tassou et al., 2011). HFCs are mainly used in Europe in LT and MT refrigeration systems. CO_2 refrigerant is also used in direct systems with a transcritical cycle for both LT and MT loads.

In indirect centralised systems there is a secondary refrigerant fluid which exchanges the temperature at a heat exchanger with the primary refrigerant fluid which is then pumped to the display cabinets. Indirect systems have gained considerable attention in supermarkets due to the fact that they permit lower refrigerant charge and allow the use of flammable or toxic fluid for the high temperature circuit. Depending on the country, HFCs, NH_3, HCs and CO_2 are used as refrigerants (UNEP, 2014).

The extensive pipe-work, the huge number of pipe joints and the poor maintenance in refrigeration plants increase the possibilities for refrigerant losses in the existing refrigeration systems. This leads to high direct emissions from the refrigeration systems.

The MTP (2008) stated that estimations showed a range of 9%-25% for refrigerant leakage in supermarkets (MTP, 2008). The estimated annual refrigerant leak rate for these systems in U.S. ranges from 3% to 35% with the higher annual leakage rates (>25%) being more characteristic of older equipment (ICF Consulting, 2005). Due to pressure from regulations and environmental agencies, these leakage rates have been reduced in recent years (Evans et al., 2016). Some retailers are committing to reduce or eliminate this emission by switching to natural refrigerants or low environmental impact refrigerants. Sainsbury's and Co-op have set targets to be completely HFC free by 2030 (Osborn, 2013) (Co-op, 2011).

The use of the indirect systems is becoming more popular in recent years because the design allows the use of a flammable or toxic fluid for the high temperature circuit side.

2.3.2 Remote system

The stand-alone refrigerated cabinets are self-contained refrigeration systems. This type of refrigeration systems is widely used in convenience stores and small supermarkets. The biggest advantage is the ease of maintenance/replace for case of faulty unit without causing any disruption to the rest of the refrigerated cabinets. On the other hand, the low compressor efficiencies lead to lower performance comparing with the centralised refrigeration systems. One reason for the low compressor efficiencies is due to the one speed operation without effect from the required load capacity. Energy reduction can be achieved by varying the compressor speed with respect to load required. This can easily achieved by installing a compressor variable speed inverter. Nowadays, a lot of effort focuses on this solution. Nonetheless, this application is still in very early stage and more data required to prove the concept of variable speed inverters for low capacity compressors. In addition, the cost for this solution needs to be further investigated.

Research regarding the refrigerant emissions and leakage prevention mentioned that the stand-alone refrigeration systems for commercial applications presents a significant smaller leakage rate, around 2% (I.P Koronaki et al., 2012).

The remote type cabinets mainly include HFC refrigerants while manufacturers lately have produced several models with CO_2 and HC such as NH_3 refrigerant.

Water cooled systems

Some installations of remote display cabinets are designed with water-cooled condensers in order to allow the release of the heat to outdoors. This trend gains interest lately and offers less refrigerant charge with higher efficiencies. The main difference with the remote systems is that instead of condensing the refrigerant into the air and increase the store temperature, the refrigerant condensed to water cooled system. The water cooled system consists of water dry cooler, water pump and expansion vessel. The first trial occurred in Bologna in 2012 with promising results. It is a unique solution suitable for all store format(CAREL, 2016).

2.3.3 Condensing Units

Condensing units are designed for capacities from 5 to 20 kW with a refrigerant charge to vary from 1 to 5 kg. However, companies are offering hydrocarbon condensing units for smaller capacities. They are not widely used in supermarkets due to the restrictions in capacity and are preferred as a solution in small convenience stores or butcher shops (UNEP, 2014).

2.3.4 Refrigerants review and limitations imposed by EU Regulation

The EU F-Gas regulation was introduced from 1 January 2015, and places restrictions on the use of HFCs refrigerants. By 2030 high GWP refrigerants will be banned. In particular, R404A /R507 will be phased out of all commercial systems (European Commission). The investigations to replace currently used refrigerants are focused on finding safe, energy efficient and environmental friendly replacements. These are outlined below.

Hydrofluorocarbon (HFC) refrigerants: R134a and R404A

With the high environmental impacts of CFC and HCFCs refrigerants to the ozone layer, the HFC family of refrigerants has been widely used as a replacement.

R404A (GWP=3992) is widely used in medium and low temperature refrigeration systems in retail sector and for refrigerated transport. It is flammable but non-toxic and has been found to be more efficient than low GWP HFC refrigerants (Mota-Babolini et al., 2015a). R404A cannot be used in any of the commercial refrigeration applications considered by EU F-Gas regulation due to its high GWP.

R134a (GWP=1430) is used in domestic and medium and low temperature commercial applications. Despite the fact that it is low flammable and less efficient than high GWP HFC refrigerants, it is non-toxic and the limitations by F-Gas regulations will not present a problem for R134a systems (Mota-Babolini et al., 2015a) (Mota-Babiloni et al., 2015b).

In multipack centralised refrigeration systems, R134a could be used as primary refrigerant circuit of cascade systems, using CO_2 (R744) in the low stage (Mota-Babolini et al., 2015a).

Natural refrigerants

Carbon dioxide (R744) is the only natural refrigerant replacement known as nontoxic, non-flammable and not harmful to the environment. According to recent studies it is one of the most promising refrigerants for refrigeration systems (Bansal, 2012). Several studies have been conducted for refrigeration systems with R744 as a refrigerant regarding their efficiency and environmental impact. Sharma et al. (2014) compared a R404A multiplex direct expansion (DX) system with seven R744 refrigeration systems. The better performance of transcritical booster systems with bypass compressor performed equivalent to or better to a R404A system in cold climates (Sharma et al., 2014). Ge and Tassou (2011) studied parameters of a R744 booster system energy performance and conclude that the performance benefit from a lower ambient temperature (Ge & Tassou, 2011a) (Ge & Tassou, 2011) . Da Silva et al. (2012) compared a R404A/R744 cascade system with R404A and R22 direct expansion systems. The cascade system they proposed had lower energy consumption, environmental impact and more compact installation (Da Silva et al., 2012). Tsamos et al. performed an analysis between different CO_2 refrigeration systems in moderate and warm climates and proposed the CO_2 booster system with gas bypass compressor can provide best performance among other CO_2 refrigeration systems configurations in moderate and warm climates (Tsamos et al., 2017).

NH_3 is not among the best options due to its toxicity and flammability and HC presents restriction in charge that leads to lower capacity of the systems and refer mainly to stand-alone refrigeration applications. However, NH_3 has already successfully been used in grocery stores in the US (ASHRAE, 2015).

2.4 Energy Performance simulation

Building energy simulation has been widely used for the performance evaluation of new buildings and for energy retrofits and continuous commissioning in existing buildings, optimisation and cost effectiveness of solutions and energy conservation technologies.

In 2013 ASHRAE Handbook-Fundamentals, building modelling is divided into two basic categories; forward modelling and inverse modelling. The forward modelling included a general physical description of a building with details regarding to construction materials, lighting, equipment, occupancy levels and HVAC system. Forward simulation models, also known as law driven models, physical models or white box models are used for building load predictions. Data driven models or black box models which resulted from inverse modelling, work on the opposite approach by using system behaviour as a predictor for system properties. Many inverse models tend to have poor precision and weak robustness due to lack of high quality training data. Grey box models are getting advantages from both white and black box models as they use certain parameters identified from a physical model. They require less training and they are more robust (ASHRAE, 2013).

Many authors have reviewed existing thermal simulation tools for building simulation. Crawley et al. reviewed 20 building simulation software packages regarding their capabilities including EnergyPlus, ESP-r, IES-VE and TRNSYS and they pointed out that it should be more productive to use a suite of tools which will fulfil as much as possible requirements for the needs of each research (Crawley et al., 2008). Coakley et al. (2014) reviewed current approaches to model development and calibration after analysing in details various analytical tools employed by researchers to date. The authors noted the benefits of building model simulation on the energy performance at all stages of the building life-cycle and he pointed out the significance of the calibration process after which the model will represent as much as possible the real building. As there is no a unique solution for calibration, this review showed that the evidence based method according to source evidence, the short-term monitoring of the building and the uncertainty quantification of input parameters by are the most frequent methods used (Coakley et al., 2014).

Buildings energy performance is usually evaluated through Dynamic Simulation Modelling (DSM). DSM is an accurate and powerful tool for assessing the energy and environmental performance of buildings over a period of time by specific time step. DSM software tools can be used to compare alternative designs or energy saving solutions by creating a very detailed thermal model.

In order to evaluate the energy performance of the refrigeration system in the supermarket the simulation model should be capable of predicting the hourly total energy use of all the components of the refrigeration system (compressors, condensers' fan, and other electric consumptions) in addition to other subsystems such as HVAC, lighting, building envelope and heat gains.

2.4.1 Computational tools for supermarkets

As previously described, supermarkets are complex energy systems which consists of subsystems which interact with each otherNot all the tools can represent the entire supermarket including the interactions with the subsystemsThere are two categories of tools; (a) tools for modelling and simulation of the energy consumption of the supermarket as a whole (CyberMart, EnergyPlus, Matlab, SuperSim, Retscreen) and (b) modelling and simulation of subsystems (Coolpack, CoolTool, EES, IMST-ART, PackCalculationPro).

Models coupling HVAC, refrigeration and building have been can be divided into two categories:

1. Coupled Refrigeration/HVAC/building. Three models have been developed under IEA Annex 31 collaborative project (Annex 31, 2012): SuperSim (Ge & Tassou, 2000) EnergyPlus and CyberMart (Arias & Lundqvist, 2005). Parker et al. (2016) establish a heat exchange process within IES-VE which is associated with the sales area refrigeration system in order to simulate dynamically the energy performance of large food retail buildings (Parker et al., 2016). In addition, other models have been developed within TRANSYS investigating the potential of night ventilation and active cooling for cold climates (Wu et al., 2006) and ESP-r to investigate retrofit measures (Jenkings, 2008). A moisture balance equation was used by Bahman et al. (Bahman et al., 2012) to simulate energy use which was shown to correlate with internal air relative humidity.
2. Data driven models include spreadsheet based, regression and Artificial Neural Networks (ANN) models. A supermarket model was developed within RETScreen (Annex 31, 2012), which was shown to correlate well with the other

three more detailed models. An ANN model was developed by Datta et al. (Datta & Tassou, 1997) to predict the electrical energy use in supermarkets. A diagnostic tool (Mavromatidis et al., 2013) was developed base on ANN to evaluate and predict the energy consumption of the supermarket as a whole and of its individual energy systems separately. Regression analysis was used (Braun et al., 2014) to predict future energy consumption. However, these models are specific to the case-studies of data sources. Moreover, Spyrou et al. presented a regression model for the prediction of energy use in supermarkets based in parameters such as floor sales area, food and non-food ratio, volume of sales, year of construction, ceiling height, number of floors and the existence of CHP (Spyrou et al, 2014).

In UK, National Calculation Methods (NCM) can be used for modelling of the food retail stores. Hill et al. compared results from supermarket modelling with NCM and EnergyPlus. Results have shown that the heat exchanges between refrigeration cabinets and their surroundings on the supermarket retail floor have significant impact on the heat balance in the building (Hill et al., 2014). However, the same authors developed appropriate representation of refrigeration thermal "gains" for use in design and compliance model supermarket zone with NCM (Hill et al., 2014).

Of the available models we considered three in more detail. Parker et al. uses a dynamic thermal simulation tool which however does now allow for individual refrigeration units to be modelled discreetly and for that reason, proxy refrigerated units are used to simulate the impact of these units in the sales area. Although the baseline model was calibrated against real store performance data using annual measurements only, this was done for a large food retail store (Parker et al., 2016). CyberMart by J. Arias (Arias & Lundqvist, 2005) although tested and against field measurements, is for quasi-steady state models and lacks the incorporation of multiple zones simulations within the sales area something crucial as different conditions should be considered (i.e. display area, tills area). Ge et al.by using SuperSim, created a multi zone validated model through operation data to evaluate energy performance of various refrigeration technology heat recovery (Ge et al. 2016, 2016).

This project required dynamic simulation and for this reason CyberMart and Retscreen are not suitable as they enable quasi-steady state simulation. Supersim software (based on TRNSYS) although includes many characteristics for dynamic simulation of an entire supermarket, it does not cover several characteristics of the case studies systems which are important for the simulation of the supermarket buildings as close as possible to the reality. The first one is the HVAC systems; Supersim includes only CAV system while EnergyPlus includes wide range of HVAC options (CAV for CS1 and VRF for CS2). Regarding the refrigeration system, Supersim does not include walk-in coolers facing multiple zones in comparison with EnergyPlus. The case studies are frozen food supermarkets and require high volume of walk-in freezers and chillers to maintain the stock products (Annex 31, 2012).

2.4.2 EnergyPlus software

EnergyPlus is a "whole building energy simulation program". According to Engineering Reference Documentation of Energy Plus (Engineering Reference, 2015) it is free and open source and financed by the U.S. Department of Energy Building Technologies Office. It has its roots in both the BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 (Department of Energy) programs. The energy consumption modelling includes heating, cooling, ventilation lighting and process loads. The EnergyPlus program is a collection of many program modules that work together to calculate the energy required and the core of the simulation is a model of the building that is based on fundamental heat balance principles. It mainly uses conduction transfer functions transformation techniques although finite difference methods (based on BLAST) have been added to some elements. The simulation includes:

- integrated simulation tool and therefore all three of the major parts (building, system and plant) are solved simultaneously
- heat-balance based solution technique for building thermal loads (radiant and convective effects at both interior and exterior surface during each time step)
- sub-hourly and user defined time steps for the interactions between thermal zones and the environment
- combined heat and mass transfer model
- advanced fenestration calculations
- daylight controls and the effect of reduced artificial lighting on heating and cooling
- configurable HVAC systems
- ASCII text based weather, input and output files

EnergyPlus has not a user interface. Loads calculated by heat balance method at a user-specified time step and are passed to the building systems simulation module at the same time step. The building systems simulation module calculates heating and cooling system and plant and electrical system response.

It is a whole building simulation and able to simulate an entire supermarket. It includes components for refrigeration systems and heat rejection to a thermal zone or the building or outdoors. EnergyPlus is an integrated simulation tool in which the three major parts, building, system and plant must be solved simultaneously. These three parts have to be linked in a simultaneous solution in order to represent the building in a realistic way.

Therefore, EnergyPlus is a very powerful tool and one of the few tools that are able to simulate an entire supermarket because it includes a developed component for refrigeration systems.

2.4.3 Climatic data files

Climate is the most unpredictable driver that affects the behaviour of buildings. The influences of air temperature, solar radiation, wind speed and air humidity on heating and cooling energy demand of buildings is assessed by DSM by using hourly weather files data. There are several criteria for weather file according to the purposes of the DSM. For the purposes of this project the following weather files are used:

- Test Reference Year (TRY) is used for energy analysis and for compliance with the UK Building Regulations (Part L). It is composed of 12 months of historic weather data with extremely high or low mean temperatures and was progressively eliminated until a mild year created.
- Design Summer Year (DSY) is a continuous year rather than a composite of average months and it is used for overheating analysis.
- Weather data files available from the locations or geographically close location of the buildings. They represent data from specific years and are used for validation purposes of building models.

Chapter's summary

This chapter outlines the market trends regarding the food retail stores and its power in the preferences of the customers. It starts with an overview of the global food retail sector and narrows to the frozen food market. The retail stores format and the trends throughout the world food retail sector are analysed and parameters that influence the food retail market evolution showed that the fast way of living nowadays asks for short and easy shopping with ready meals without negotiating the reduction in the food quality. This lead to an increase in number of small supermarkets, discounters and convenient stores.

It continues with a supermarket energy use literature review throughout the world and then focuses on UK. It covers energy use intensity of supermarkets from projects in several countries and UK and outlines available benchmarks. It was shown that energy use is increasing while the store size is decreasing. Frozen food supermarkets are even more intensive buildings in comparison with conventional food retail stores as they contain more refrigeration load

An up-to-date research on the systems of the supermarkets is presented divided into building design, HVAC system and refrigeration system. The different philosophy of the two categories of the HVAC system (coupled and decoupled) is discussed. An overview for the pressure F-Gas European regulation poses for natural and low GWP refrigerants is included.

Finally, a review of tools available for building energy use predictions and benchmarking was presented which afterwards focused on the supermarket simulation. Gaps in the tools and previous researches were outlined which suggested that better analytical tools would enable better accuracy in the energy and environmental conditions modelling of supermarkets. According to these conclusions, the EnergyPlus software was chosen for this work as it incorporates heat exchanges of refrigeration and HVAC system, it includes a wide variety of HVAC and refrigeration systems and it is commercially free enabling wider use by researchers internationally.

Chapter 3

Description of Case Studies and field measurements

Introduction

This chapter is provided to add context to the results presented in chapters 4, 5 and 6. This includes an overview of:

- Description of building and equipment of the supermarket case-studies
- Energy use monitoring and metering of plugged-in lift up lid cabinets
- Environmental monitoring
- Customers' and transactions' data

3.1 Frozen food supermarket chain: Relevant information

The two case study stores selected belong to the same supermarket chain with many similarities but different HVAC systems. This is the main reason for their selection.

The supermarket chain which provided the two case study stores is a British food retailer with over 880 stores throughout UK. 80% of products retailed are food products (Figure 3-1) and approximately 80% of the refrigeration cabinets in their stores are frozen food cabinets. The majority of the stores are located within town centres and the building types vary from purposed built to refurbished buildings. In addition, these stores do not include bakers, delicatessen, meat and fish counters.

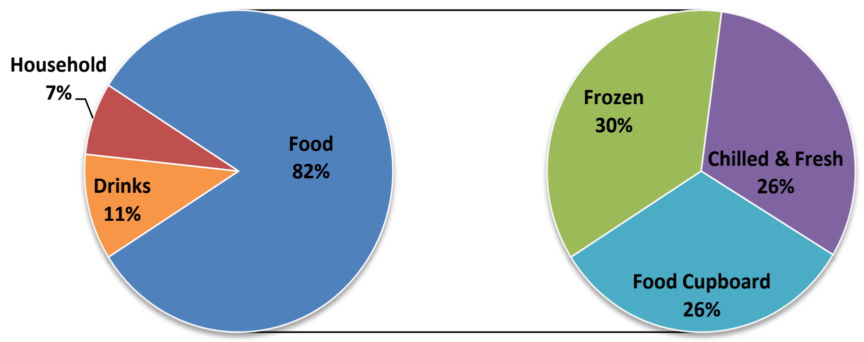


Figure 3-1: Share of typical products retailed in the case-studies

As presented in chapter 2, stores are categorised by sales area. The case study stores can be defined as small supermarkets as the sales area of both does not exceed 500 m^2 and is higher than 300 m^2.

The two case study stores were selected according the HVAC categorisation to coupled and decoupled systems (see section 2.2.2). The first is a refurbished two storey building located in central west London using all air constant air volume system which represents the **coupled air conditioning system with ventilation**. The second case study is a new purposed built store located in a commercial area in a southern London suburban area. The heating and cooling requirements are fulfilled by a variable refrigerant system with ceiling mounted cassettes in the sales area and this system represents the **decoupled air conditioning system from ventilation** as there is a separate ductwork for extract mechanical ventilation.

3.2 Case study 1: Coupled air conditioning with ventilation

The first supermarket store (CS1) is in Greenford, north-west of London. It is located in a central location and surrounded by commercial buildings. It is a refurbished two storey heavy-weight building (BS EN ISO 13790:2008) with the sales area (469 m^2) on the ground floor and storage on ground and the second floor.

The HVAC system for the sales area is roof mounted AHU with a DX cooling coil (88kW) and an electric heating coil (24kW). The set point temperatures have been set to 19.5^{o}C for heating and 20.5 ^{o}C for cooling. It is a Constant Air Volume (CAV) system which provides sales area with 6 m^3/s in trading hours through 11 four way diffusers, 1 three-way and 3 two way blow fixed blade diffusers. There is also an electric door heater rated at 18kW. Ventilation rates for the exhaust system during trading hours have been set to 6 ach for sales and 1 ach for the storage area. There are also supplemental extract ducts above the open front multi deck cabinets whose warm air is either exhausted directly to the atmosphere or used to heat the storage area on the ground floor when heating is required. The HVAC system is shown diagrammatically in Figure 3.2. The staff and rest rooms are heated by 1.5 kW electric heaters and an outdoor condensing unit serves as an inverter heat pump for the office area.

The lighting system comprises of T8 type fluorescent for the sales area. They consist of luminaires with 3 lamps; 21 in the tills area and 63 in the display area. LED strips are installed in the north-east and back sides of the sales area which operate 24hrs.

Table 3-1 and 3-2 present detailed data regarding construction of the building, lighting and electrical equipment loads.

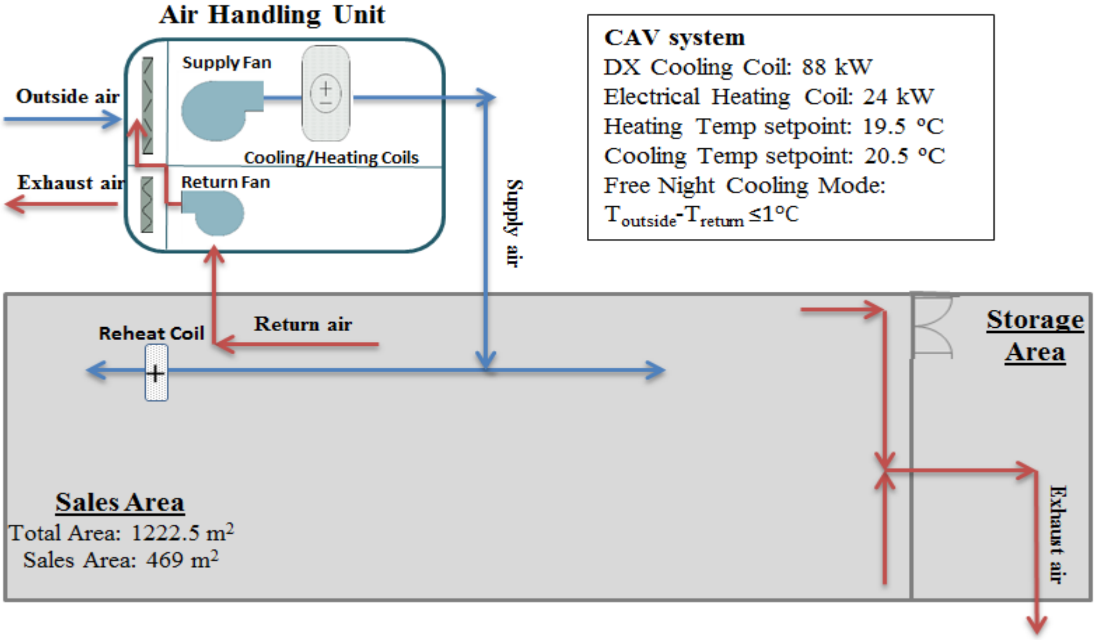


Figure 3-2: CS1, HVAC system

Table 3-1: Construction data, CS1

Construction	U-value (W/m^2K)
External Wall	1.6
Ground Floor	0.5
Internal celling	1
Internal floor	0.4
Roof	0.3
Internal partition	0.6
Windows (Single glazed)	5.7

Table 3-2: Customers' density, lighting and electric equipment data, CS1

Location/Thermal Zones	Customers' Density (m^2/person)	Lighting Load (W/m^2)	Electric Equipment (W/m^2)
Tills Area	4.7	19.1	6.73 (Tills equipment)
Display Area	28.2	23.01	n/a
Groundfloor Storage	27.2	4.26	n/a
Plenum	n/a	n/a	n/a
1st floor Storage	4.2	0.7	n/a
Training room	8	16.2	n/a
Equipment Storage	n/a	7.44	6.41 (PCs)
Corridor	n/a	13.83	n/a
Restrooms	n/a	7.04	64.7 (Heaters)
Main Office	n/a	10.68	18.41 (PCs, printers and control equipment)
Stairs	n/a	21.48	n/a
Kitchen	9.4	11.69	163.73 (Fridge, microwave, kettles, dishwasher)
Elevator	n/a	n/a	n/a
2nd Floor	n/a	n/a	n/a

The refrigeration system consists of three different stand-alone refrigeration cabinets; (a) chilled food open front multi-deck cabinets, (b) lift up lid and (c) open top case frozen food cabinets. One freezer ($60m^2$) and one chiller ($12m^2$) coldrooms are located in the storage areas; the freezer cold room has a high efficient split refrigerated system with 30 kW condenser outdoor unit. The chiller cold room with condenser capacity of 5.2 kW is a mono-bloc system of two single units containing the evaporator, compressor and condenser with the evaporator inside and the compressor/condenser outside the cold room. Table 3-3 presents the refrigeration loads of CS1.

Table 3-3: Display cabinets' and coldrooms refrigeration load, CS1

Display Cabinets	**MT**	**LT**
Refrigeration Load (kW)	20.3	30.7
Coldrooms	**MT**	**LT**
Dimensions (m^2)	12	60
Refrigeration Load (kW)	5.2	30
Temperature Setpoint (^oC)	0-2	-20
Refrigerant	R404A	R404A

3.3 Case Study 2: Decoupled air conditioning from ventilation

The second supermarket (CS2) is in south of London, in a typical small out-of-town retail centre. It is medium-weight (BS EN ISO 13790:2008) single storey newly built store with 315 m^2 sales area.

The HVAC system of the sales area is a VRF system for both heating and cooling. Two equally sized outdoor condensing units provide total heating output of 113 kW and cooling output 101 kW delivered to sales area through 7 ceiling cassettes and 1 door heater. The HVAC system is operated 24h with 20-21^oC set point temperature for both cooling and heating; the heat pump works either as a compressor or evaporator controlled by the BEM system. Extraction of the air from sales and staff area is by an extract fan which is in operation 24h hours. Ventilation rates for the exhaust system during trading hours have been set to 6 ach for staff areas and sales area, 10 ach for restrooms and cloaks and 1 ach for the storage area. During night time the exhaust fan is set to lower speed to extract 0.75 m^3/s. The staff and rest rooms are heated by 1.5 kW electric heaters and an outdoor condensing unit serves as an inverter heat pump for the office area.

The lighting luminaires are typically T8 type fluorescent for the sales area. They consist of luminaires with 3 lamps; 23 in the tills area and 30 in the display area. LED strips are installed in the north-east and back sides of the sales area which operate 24hrs.

Figure 3-3 shows diagrammatically the air conditions and ventilation system while tables 3.4 and 3.5 present detailed data regarding construction of the building, lighting and electrical equipment loads.

The refrigeration system consists of three different stand-alone refrigeration cabinets the same as CS1. One freezer (29m^2) and one chiller (6m^2) coldrooms are located in the storage areas; the freezer cold room has a high efficient split refrigerated system with one 8 kW condenser outdoor unit. The chiller cold room with condenser capacity of 2.3 kW is a mono-bloc system of one single unit containing the evaporator, compressor and condenser with the evaporator inside and the compressor/condenser outside the cold room. Table 3-6 presents the refrigeration loads of CS2.

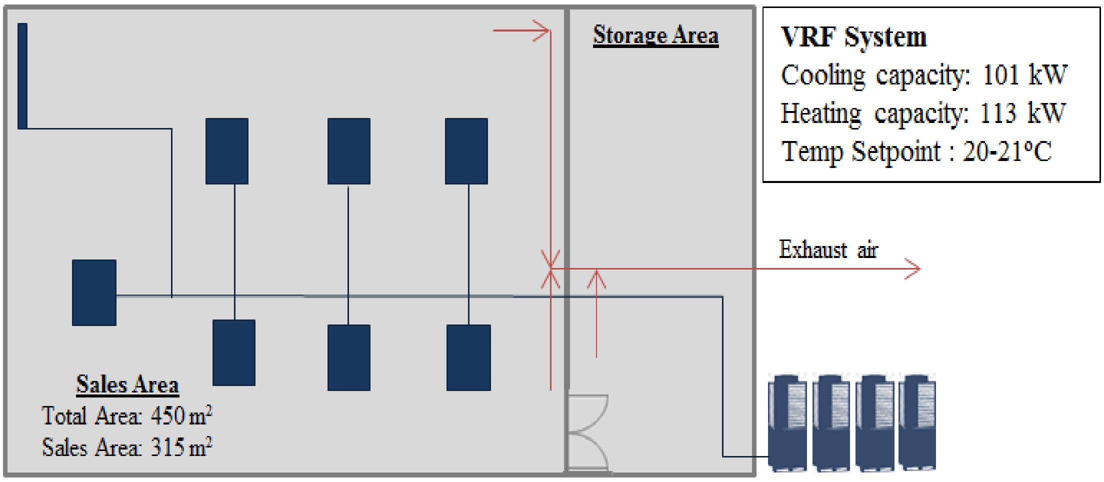


Figure 3-3: CS2, HVAC system

Table 3-4: Construction data, CS2

Construction	**U-value (W/m^{2}K)**
External Wall	0.35
Ground Floor	0.25
Roof	0.25
Windows (Single glazed)	5.7

Table 3-5: Customers' density, lighting and electric equipment data, CS2

Location/Thermal Zones	Customers' Density (m^2/person)	Lighting Load (W/m^2)	Electric Equipment (W/m^2)
Tills Area	7.6	32.9	15.9 (Tills equipment)
Display Area	16	16	n/a
Storage Area	31.6	1.9	n/a
Office-Control Room	5.9	9.9	30.6 (PCs, printers and control equipment)
Office	4.2	13.8	17.85 (PCs)
Kitchen	3.9	36.7	274.2 (Fridge, microwave, kettles, dishwasher)
Restrooms	n/a	10.6	137.4 (Heaters)
Storage Area (B&W)	n/a	18.8	n/a
Void Area	n/a	n/a	n/a

Table 3-6: Display cabinets' and coldrooms refrigeration load, CS2

Cabinets	**MT**	**LT**
Refrigeration Load (kW)	10.4	26.3
Coldrooms	**MT**	**LT**
Dimensions (m^2)	6	29
Refrigeration Load (kW)	2.3	16
Temperature Setpoint (^oC)	2	-20
Refrigerant	R404A	R404A

3.4 Monitoring plan

The monitoring of the case study stores included both energy use and indoor air environmental conditions as follows:

- Energy data for CS1 and CS2 were available for 5 and 3 years respectively. Moreover, sub systems energy data from similar stores were available for one months. Finally, a lift up lid frozen food cabinet was monitored regarding its energy, operating temperature and open/close statement.
- The indoor air environmental conditions monitoring included air temperature, relative humidity, light intensity and carbon dioxide concentration levels measurements. The indoor air environmental monitoring was carried out for a complete year.
- Daily transactions data for 2 years were available for both case study stores as well as hourly transactions and customers counts for one week. Supplementary spot observations for customers inside the sales area were conducted for 3 different days and times during July 2014 in order to evaluate the customers' location and activity inside the sales area.

3.4.1 Energy Use

Half hourly energy data use is available from both case study stores. CS2 opened in June 2013 and data were available since the opening of the store. Sub metering of the systems of the stores was not available and a plan to do this even for one store was not possible to be facilitated. However, metering of the sub systems of similar store of the same frozen food supermarket chain was available for May 2016. Table 3-7 presents the energy use monitoring period for both case studies.

Table 3-7: Duration of gathered energy use data

Case study	Energy Use data
CS1	From 1/7/2011 to 31/5/2016
CS2	From 1/6/2013 to 31/5/2016

The half hourly energy data were used firstly for the energy benchmarking of the case studies in comparison with previous research projects. There were also used for the validation of the EnergyPlus numerical models, validation with real data is highly recommended in the literature (see section 5.5) for confidence in the prediction of developed models.

3.4.2 Indoor Environmental Conditions

The indoor environmental conditions monitoring was carried out using HOBO loggers recording air temperature, relative humidity and CO_2 levels and located at different points as well as at different heights (knee level, head level and ceiling level) within the stores.

The majority of the sensors were located in the sales area as this is the area that the customers have access and the indoor environmental conditions are more vulnerable to change. Moreover, the monitoring of the indoor conditions of the storage area where the coldroom chiller and freezer are and the products are stored was needed as well as in the coldrooms.

The equipment used is indicated in the figures 3-4 and 3-5 and their technical characteristics are analysed as well in Table 3-8.

Figure 3-4: Monitoring equipment used for spot measurements

Figure 3-5: Monitoring equipment used for air temperature, relative humidity and CO_2 levels

Table 3-8: Technical characteristics of monitoring equipment

Monitoring Equipment	Accuracy	Resolution
Kestrel 4000 Pocket Weather Tracker	±1°C, ±3% RH,	0.1°C, 0.1% RH
Airflow TA 465	±3°C, ±3% RH, ±3% of reading for m/s	0.1°C, 0.1% RH, 0.01 m/s
HOBO U12-012	± 0.35ºC, ±2.5% RH, 1 to 3000 footcandles (lumens/ft^2)	0.03°C, 0.03% RH
HOBO UX100-003	± 0.21ºC, ±3.5% RH	0.024°C, 0.07% RH
TELAIRE 7001 connected with HOBO U12-012	±50 ppm	±1ppm
I-buttons DS1922L	±0.5°C	0. 5°C

The CO_2 sensor was located in an area not influenced by the outside air flow path of the main entrance or any ventilation inlet. According to ASHRAE (2015) and the guide for an advanced energy design for Grocery stores, when locating a CO_2 sensor directly in the flow path from an air diffuser would provide a misleading reading concerning actual CO_2 levels experienced by the customers. Moreover, it is mentioned that the best location for a CO_2 sensor to capture the entire impact of customers on the room airflow, is as near as possible to a return grille (ASHRAE, 2015). The CO_2 sensor was set in the middle point of the back area of the store. In order the sensor not to be affected at all by the diffusers, it was placed underneath a products' self.

Regarding to the walk-in cold rooms (chiller and freezer), sensors should be placed at height 1.5 m and at a place that they will not be heated by the fan motors.

In order to finalise the location of sensors spot measurements were carried out for air temperature, temperature of air by air inlets and air velocity. In this way differences between areas were firstly evaluated so that the final monitoring plan was designed.

The indoor environmental monitoring of the stores facilitated the understanding and evaluation of the temperature patterns in the sales area and where and how this is affected by the interactions between the refrigeration cabinets or the infiltration of the walls and the main entrance of the stores. Moreover, the control strategy of the HVAC systems was evaluated through these monitoring results and supplemented by separate monitoring of supply air temperature of the cassettes and diffusers. Comparison of the air temperature, RH, carbon dioxide and lighting levels of monitored data with standards (ASHRAE, CIBSE and literature).

CS1

Equipment used for initial monitoring are the Airflow TA 465 that measures air temperature, RH, air velocity and dew point temperature and the Kestrel 4000 Pocket Weather tracker (Figure 3-4) . The measurements took place during two days, on 6th and 17th of February 2014. The 17th of February was a colder day than the 6th of February. Figure 3-6 shows the measurements with the Kestrel 4000 Weather tracker only on the ground floor, while the figures 3-7 and 3-8 show the measurements for 17th of February with the Airflow TA 465 for both groundfloor and first floor.

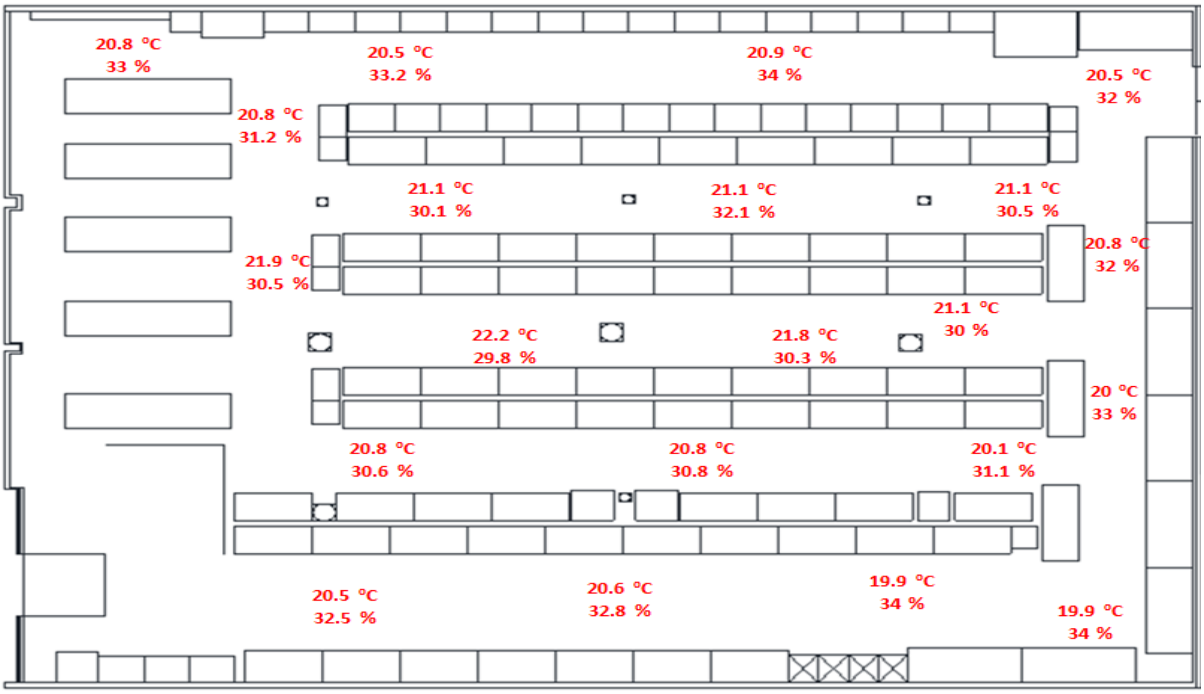


Figure 3-6: Temperature and RH spot measurements by Kestrel 4000 Weather tracker

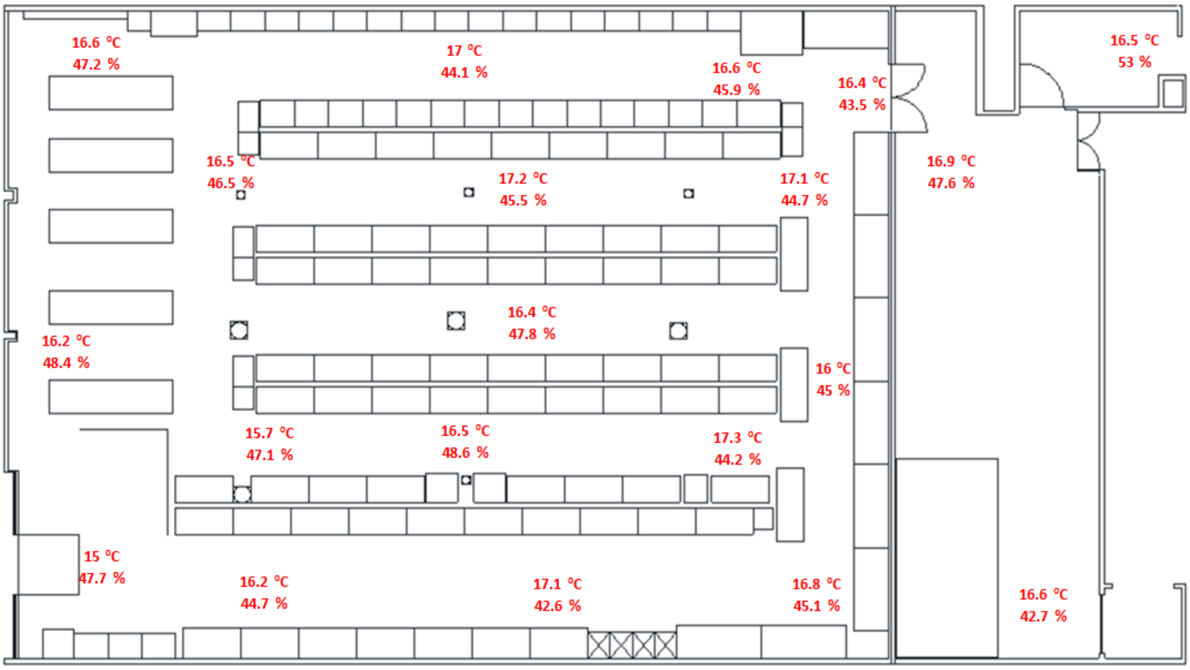


Figure 3-7: Temperature and RH spot measurements by Airflow TA 465, Groundfloor

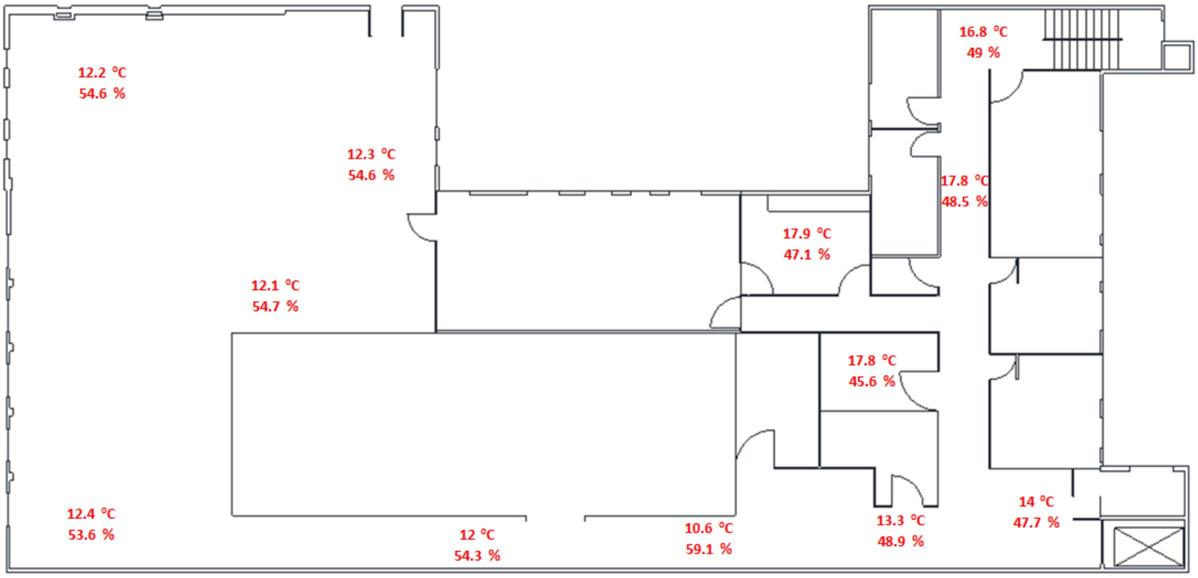


Figure 3-8: Temperature and RH spot measurements by Airflow TA 465, First floor

The cassettes' temperature and air velocity were also investigated for the better understanding of the HVAC system's control strategy and the final plan of the cassettes' monitoring. Figure 3-9 presents the location of the diffusers in the sales area.

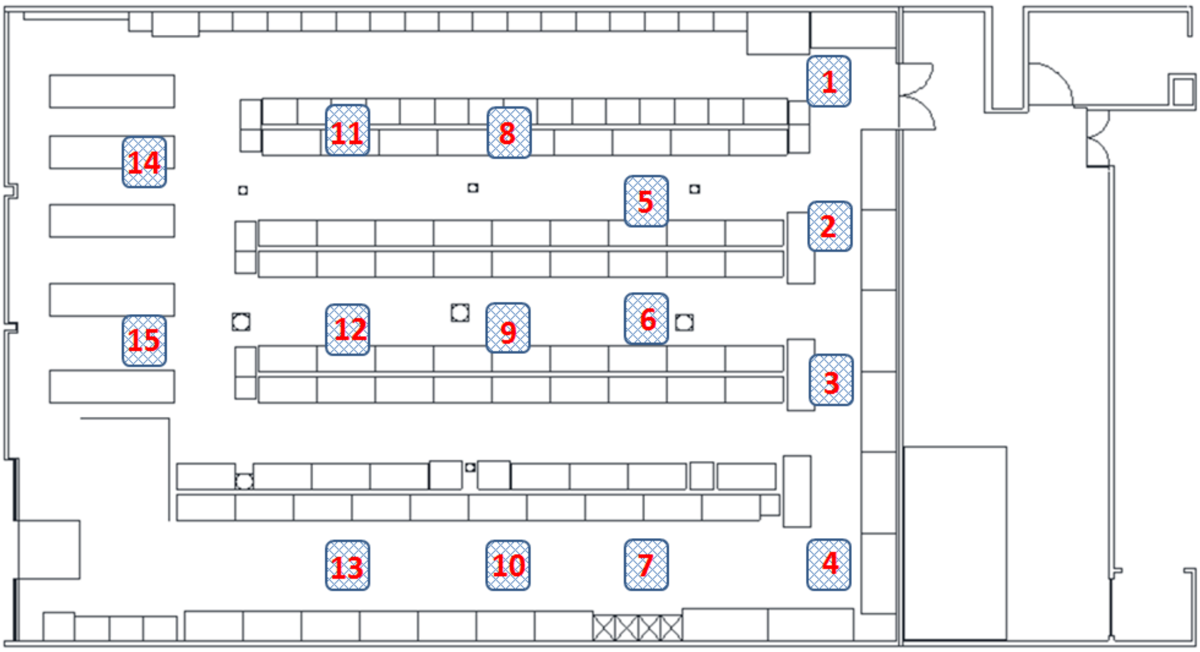


Figure 3-9: Diffusers' location in the sales area

According to these spot measurements the air temperatures of the diffusers remain the same and follow the control strategy set points but the air velocity presents significant changes between the cassettes. According to the mechanical design, the system is designed to serve with 6 m^3/s air flow rate. According to the design and the air flow rates that the diffusers should serve, the air flow rate of each one should be approximately 0.4 m^3/s. Figure 3-10 shows the spot measurements taken for 1 minute on the 17th of February 2014. The average air velocity shows that the system is quite well balanced and each diffuser serves with the expected air velocity. However, every diffuser has its one Volume Control Damper (VCD), and for this reason it cannot be concluded that the average air velocity of each diffuser is the expected one according to mechanical design. Nevertheless, the majority of the diffusers exhaust air with the average expected air velocity, 4 m/s. Only the diffuser #1 was found to exhaust air with the maximum speed of the fan while cassettes with numbers #2, #3, #4 and #13 seems to perform with the exhaust air with even less than the specified low speed of the control strategy of the HVAC system. This could be either due to the position of these diffusers on the plan and the possible losses that might occur or due to specified change in the VCD before these diffusers. The same implies for the diffusers #1. This could be explained by the fact that this area presents higher internal heat gains due to the open front multi deck cabinets' refrigeration load that could lead an on purpose increased air velocity in this area.

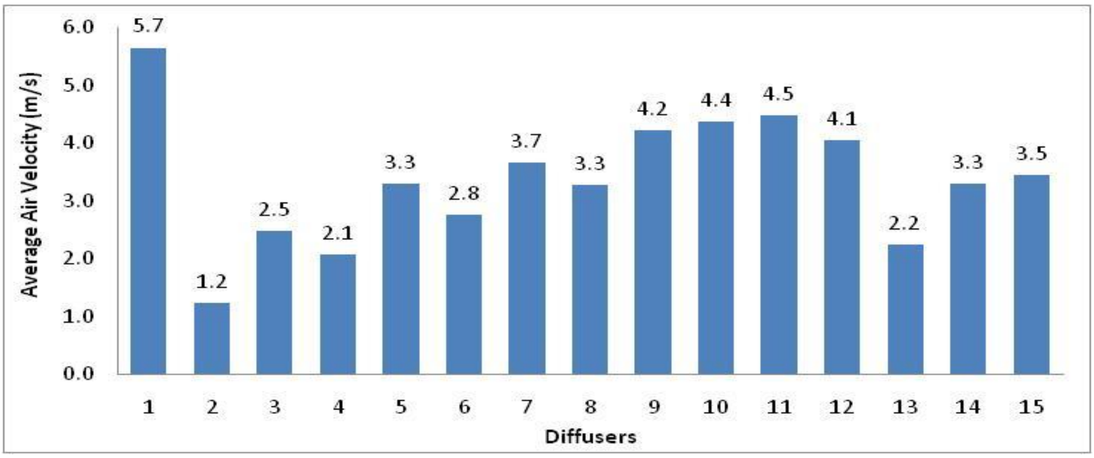


Figure 3-10: Air velocity measured in the outlet of the diffusers

Finally, the monitoring plan of the CS1 store included also monitoring of the diffusers of the HVAC system for 7 months in two different periods (March 2014- July 2014 & April 2015-June 2015). Five of them were selected for monitoring; two with the minimum average air velocity and three with the average expected air velocity. The diffusers that were selected are the diffusers with the indicated numbers 4, 6, 8, 12 and 15 in Figure 3-9.

After the evaluation of the spot measurements the first monitoring plan was designed and it included sensors in strategic places to give a range of environmental conditions. The spot measurements showed that there is not significant stratification in the store for the both days of the observations.

The first plan of the monitoring phase started on the 14th of March 2014 and was upgraded with a more detailed plan on the 21th of March 2014. The monitoring phase of the store ended on the 19th of June 2015. The CO_2 sensor was connected to sensor Gr10 and located in an area that is no influenced by the outside air flow path of the main entrance or diffuser's outlet air

Figures 3-11 and 3-12 present the final monitoring plan of the CS1 store. Figure 3-13 shows some examples of the monitoring equipment mounted in the locations.

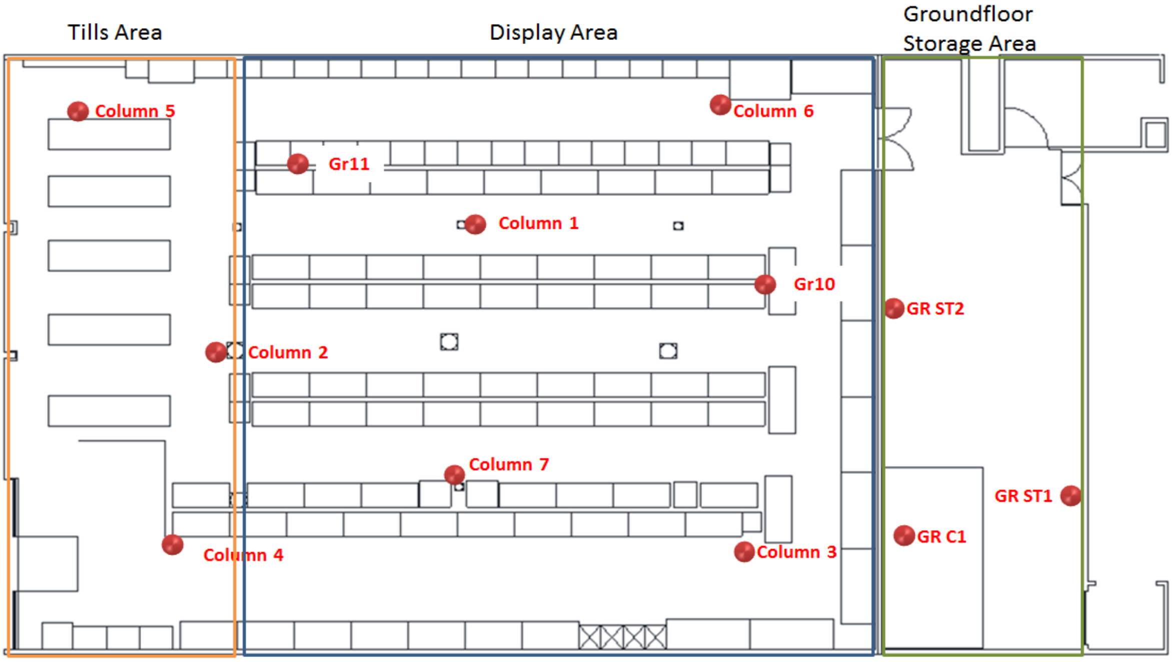


Figure 3-11: Final environmental monitoring plan, CS1, groundfloor

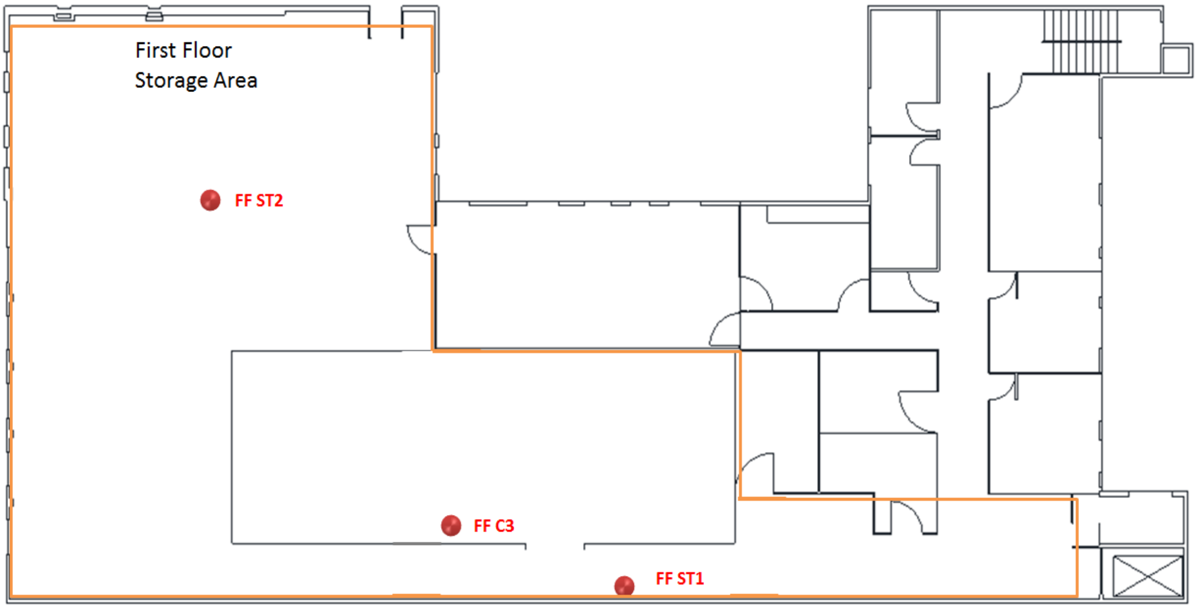


Figure 3-12: Final environmental monitoring plan, CS1, first floor

More detailed information for the environmental monitoring equipment (type of sensors, name and height of installation) used can be found in Appendix A together with details for the environmental monitoring period.

The plan to gather measured data for a whole year was successfully completed despite the fact that there were several missing monitoring periods of the HOBO data loggers due to lack of data loggers' memory and damaged or missed data loggers.

The diffusers' monitoring was separated in two phases. In the beginning HOBO U100-003 were used and recorded data for June and July 2014. However, these data loggers were big in size and difficult to be installed inside the cassettes. For this reason i-buttons were used for the winter monitoring period.

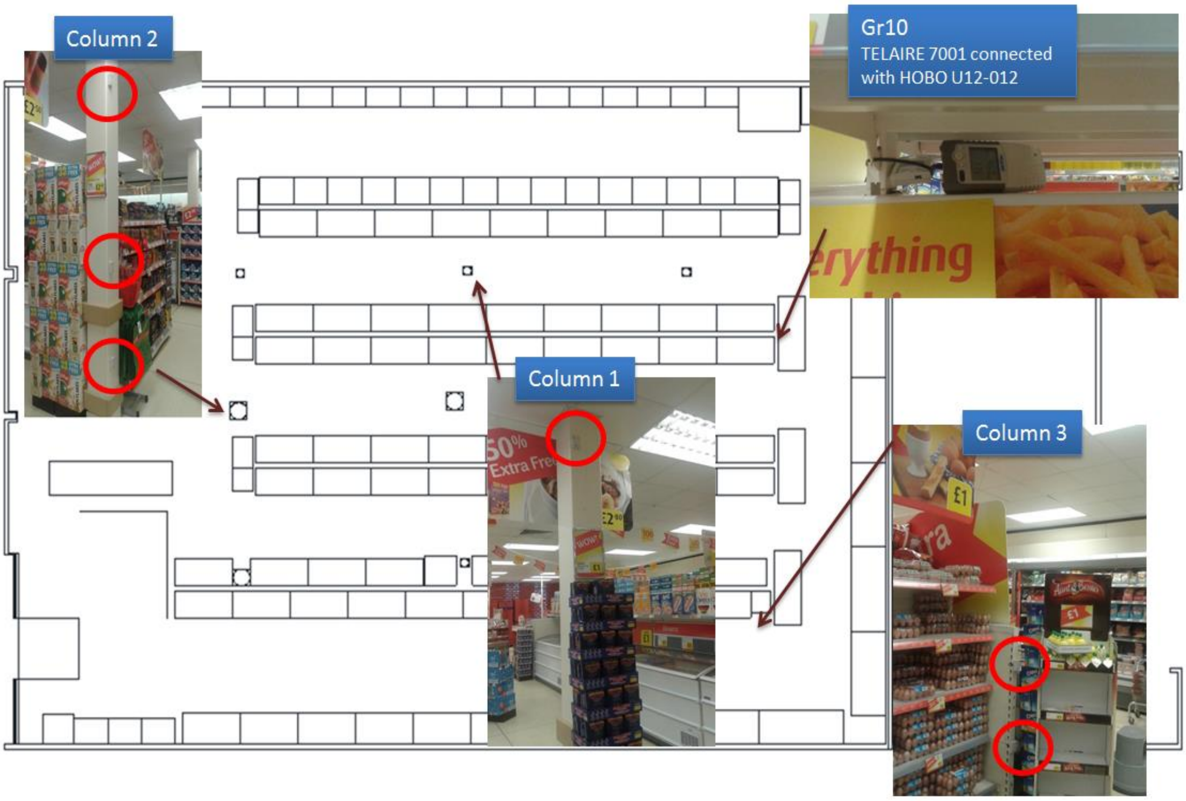


Figure 3-13: Installed monitoring equipment inside the sales area, CS1

CS2

As in CS1, for the first step of the monitoring, the Airflow TA 465 was used for air temperature, RH and air velocity measurements of the cassettes. In this way differences between areas was firstly evaluated and then the final monitoring plan was designed. Figure 3-14 presents the floor plan of the CS2 store as well as the location of the cassettes of the VRF system in the sales area. Figure 3-15 presents the spot temperature measurements of the cassettes which remain the same and follows the HVAC control strategy but the air velocity presents significant differences between the cassettes. Every cassette is controlled to operate on cooling or heating mode only when there is need for each area to be conditioned.

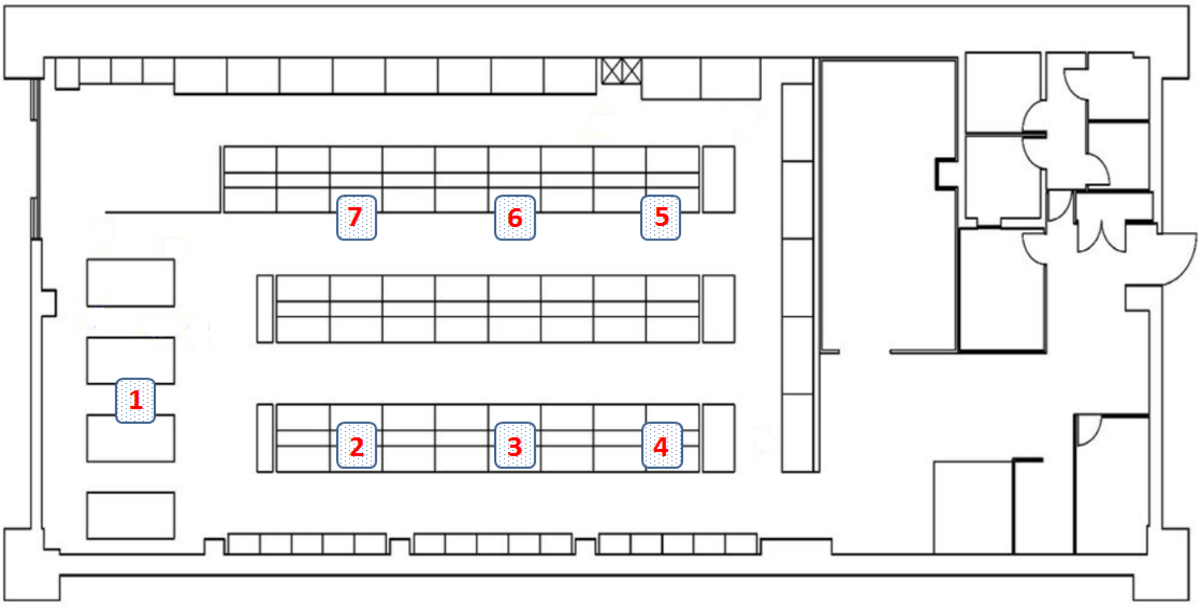


Figure 3-14: Cassettes' location in the sales area

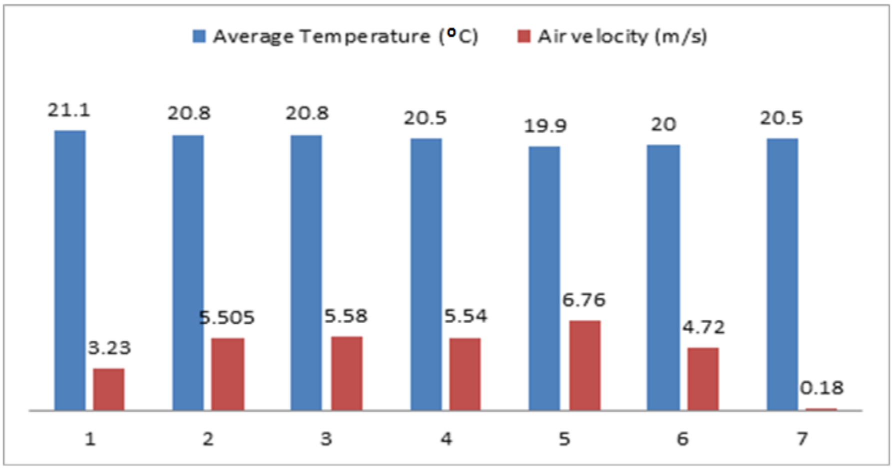


Figure 3-15: Air velocity and temperature measured in the outlet of the cassettes

The final monitoring plan of the store is indicated in Figure 3-16. The CO_2 sensor was connected to sensor SA1 and located in an area that is not influenced by the outside air flow path of the main entrance or a VRF cassette. Figure 3-17 shows the location of several data loggers in the sales area as they have indicated in figure 3-16.

More detailed information for the environmental monitoring equipment (type of sensors, name and height of installation) used can be found in Appendix A together with details for the environmental monitoring period.

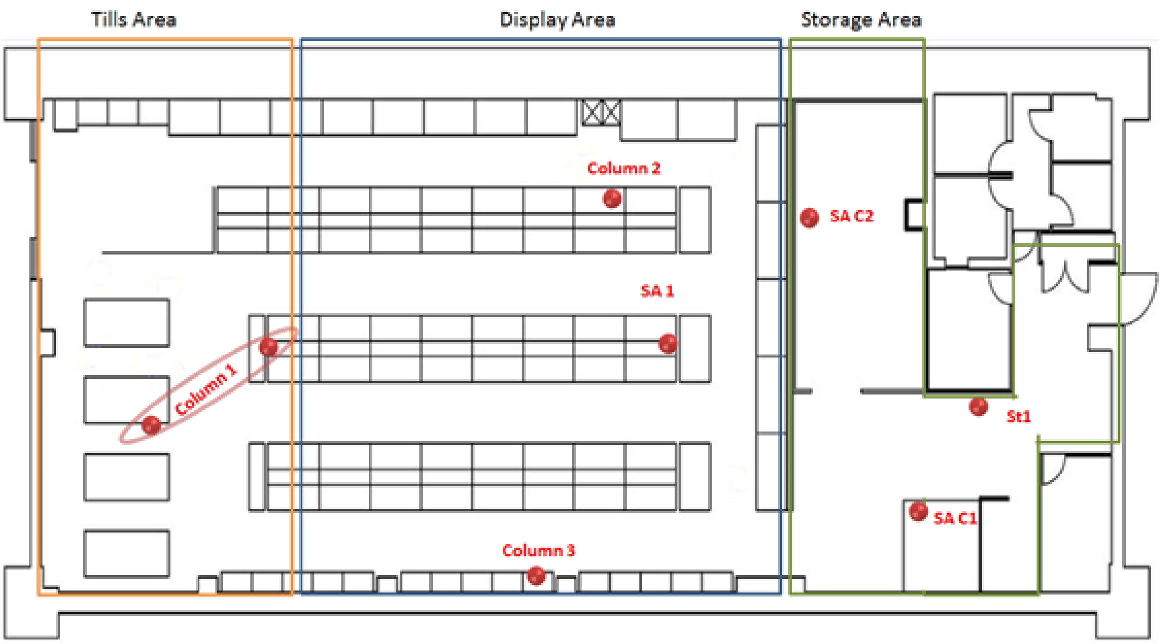


Figure 3-16: Final environmental monitoring plan, CS2

Figure 3-17: Installed monitoring equipment inside the sales area, CS2

The plan to gather measured data for a whole year was not successfully completed because there were several missing monitoring periods of the HOBO data loggers due to lack of data loggers' memory and damaged or missed data loggers. However, there are significant amount of data for the periods that all the sensors were working and they are representative to identify the profile of the environmental conditions in the store and to facilitate the EnergyPlus model validation.

As in CS1, the cassettes monitoring was separated in two phases. In the beginning HOBO U100-003 were used and recorded data for June and July 2014. However, these data loggers were big in size and difficult to be installed inside the cassettes. For this reason i-buttons were used for the winter monitoring period. The sensors were installed in the same side of cassettes (west side outlet of the cassettes).

3.5 Transactions and customers

Daily transaction data were provided by the managers of the stores for two years for both case study stores. Moreover, these data were supplemented by hourly transactions data and hourly customers' counts.

Spot observations took place during weekday and for several hours (12:00-13:00, 14:00-15:00, and 16:00-17:00 with 3 minutes interval) during the trading times in order to represent the customer's density at different trading hours.

Table 3-9: Transactions and customers data monitoring period

Case study	Daily Transactions period	Hourly transactions data & customers' counts	Customers Spot observations
CS1	6/3/2013-5/3/2014 28/3/15-25/3/2016	Thursday 22/5/2014 & Sunday 29/6/2014	15/7/2014
CS2	4/6/2013*-5/3/2014 28/3/15-25/3/2016	Wednesday 28/5/2014 & Monday 30/6/2014 -Friday 4/7/2014 & Sunday 12/7/2014	23/7/2014

*Official opening of the store

3.6 Refrigeration cabinet monitoring

3.6.1 In-store monitoring

One lift up lid frozen food cabinet was chosen to be monitored in terms of energy consumption, operating temperature and open/close statement of the lid. The energy consumption and operating temperature were monitored for the whole week but open/close statement counts took place for 19 days including 2 full weeks and supplementary weekdays.

Figure 3-18 shows the metering box created to facilitate the energy use monitoring of the cabinet as no energy meter could monitor the three phase cable of the cabinet. Figure 3-19 shows the open/close statement sensor use while figure 3-20 indicates the two temperature sensors for the operating temperature inside the cabinet. The characteristics of the monitoring equipment are summarised in the table 3-10.

Table 3-10: Technical characteristics of lift up lid frozen food cabinet monitoring equipment

Monitoring Equipment	Accuracy	Resolution
Fluke 345 Power Quality Clamp Meter	I >10A: ±3 % rdg ± 5 digits & I<10A: ±0.5A, V >1V: ±3 % rdg ± 5 digits & V<1V: ±0.03 V, W: 2.5 % rdg ± 5 digits, PF: ± 3°	0.025% A, 0.025% V, 0.025% W, 0.001 PF
HOBO State Data logger UX90-001M	±1 minute per month	State and Event: 1 State or Event
HOBO Temperature Waterproof Data logger	± 0.75°C at -20°C	0.2°C at -20°C

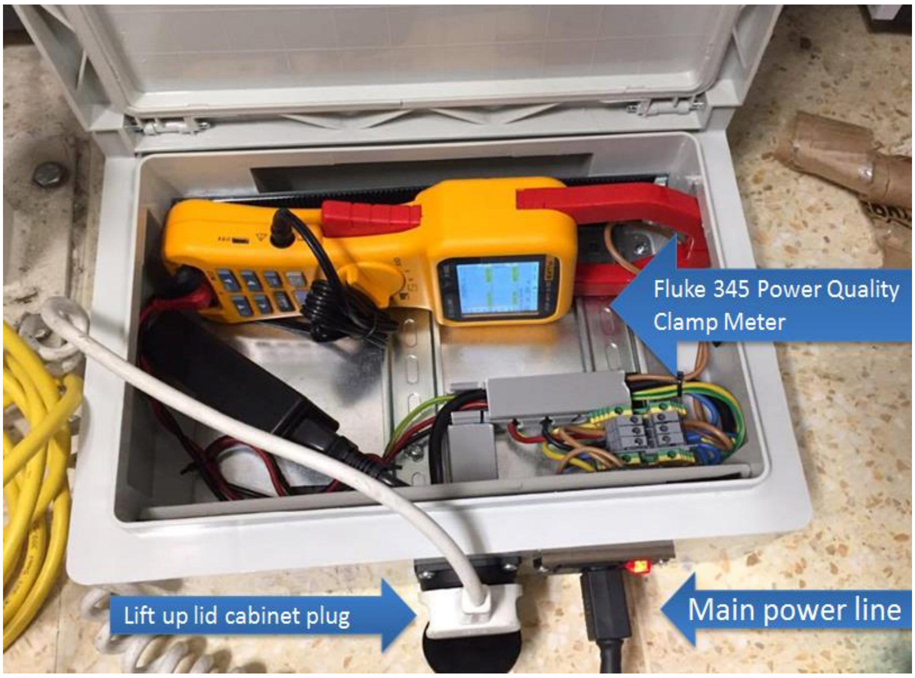


Figure 3-18: Energy consumption metering box

Figure 3-19: Hobo state data logger installed on the lift up lid frozen food cabinet

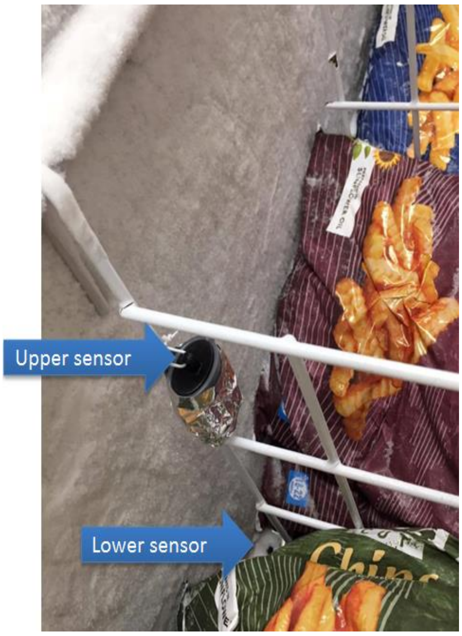


Figure 3-20: HOBO Temperature Waterproof Data logger

3.6.2 Laboratory monitoring

The same type of cabinet was monitored in the lab facilities of the CSEF centre in order to evaluate the energy consumption and the surface temperature ($T_{surface}$) of the glass lid of the cabinet. $T_{surface}$ plays an important role for the control strategy of night cooling which is analysed in section 6.6. Ambient temperature and relative humidity were set for an environmental test room and energy use, surface temperature of the glass lid (inside/outside) and temperature inside the cabinet were monitored for several hours. The equipment used is the same power meter as the one used at the store (Figure 3-18) and 8 thermocouples whose technical characteristics are indicated in table 3-11.

Table 3-11: Technical characteristics of lift up lid frozen food cabinet monitoring equipment

Self Adhesive Patch Thermocouple	
Description	Type K
Operation range	-50°C to 250°C
Patch size	25mm x 20mm

The test room was constructed in November 2014. Its construction is 100mm insulated interlocked and weather proof panels. The floor is made of concrete slap with insulation. On top of the insulation an additional 9mm of Hexa-Floor was added. Hexa-Floor is strong birch plywood overlaid with a non-slip finish. The room is fitted with a supply and return air plenum to facilitate laminar air distribution through it. The air flow is parallel piped through the room and is supplied and returned to the air handling plant via perforated fabric type technical walls located at both ends of the rooms. The system is also served by a steam humidifier unit operating using demineralised water. The test room has a supply side control philosophy. The return air (mixed condition) is returned and reconditioned by the air handling equipment and plant and supplied to the supply technical wall at the selected control conditions and at a mean air speed of 0.1 – 0.2 m/s.

Figure 3-21 shows the cabinet monitoring set up. The cabinet was loaded with M-type test packages which were used as food simulators in the unit, specified according to ISO

23953-2:2015 (BS EN ISO 23953-2, 2015). The location of the sensors is shown in figure 3-22.

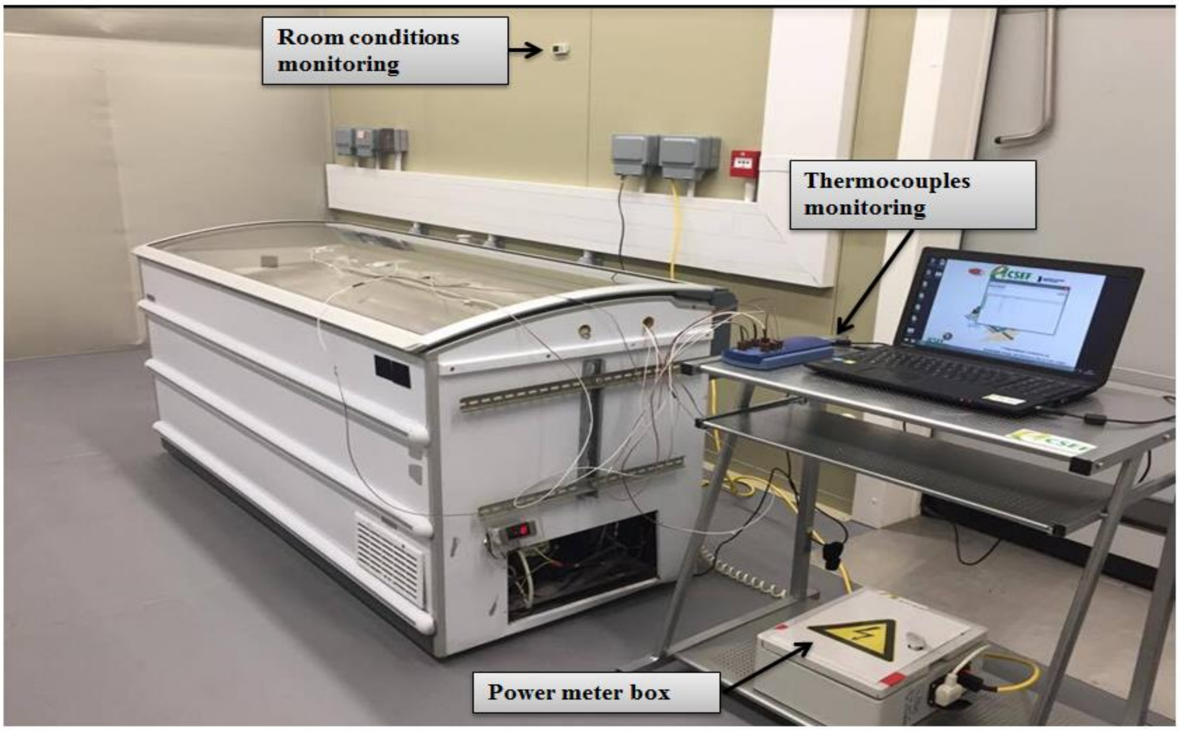


Figure 3-21: Lift up lid frozen food cabinet monitoring set up inside the test room

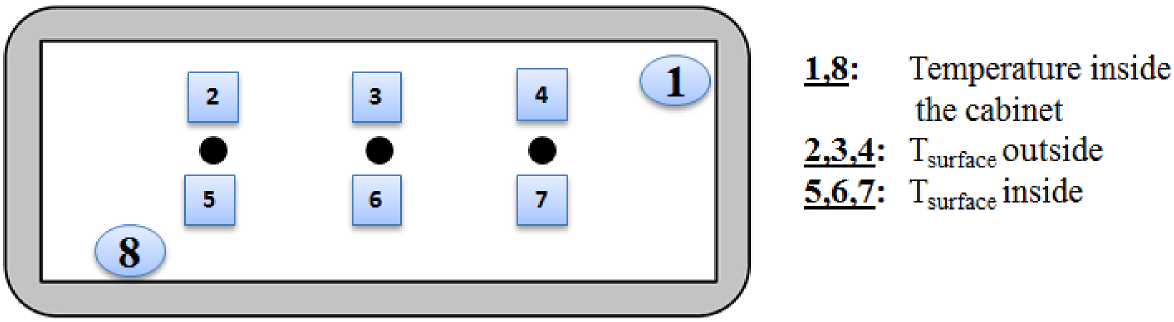


Figure 3-22: Location of the thermocouples inside the cabinets and attached on the glass surface

Chapter's Summary

This chapter provides a description of the frozen food store case study buildings and highlights the differences and similarities in their design (i.e. HVAC and refrigeration systems). It also describes the monitoring plan of the case studies and presents the equipment used. This is intended as a reference guide to provide context to the detailed results presented in the next chapters.

Chapter 4

Field Monitoring Results

Introduction

This chapter presents the results from the case-study stores monitoring plan presented in Chapter 3. The stores' information and plans are provided in sections 3.3 and 3.4.

First the total energy use analysis of both monitored stores and sub-systems energy breakdown from similar store from the same supermarket chain is presented. Characteristics from indoor air environmental conditions inside the stores derived from the monitoring are outlined. Monitoring results from the storage areas and the coldrooms are provided. The chapter continues with the analysis of transactions data for both case study stores. Finally, the results (energy use and statistics from opening/closing of the lid) from the lift up lid frozen food cabinet during in-store operation are presented. Energy use of the same cabinet as well as surface temperature of the glass lid of the cabinet are analysed.

The analysis presented in this chapter gives insights and significant results that are used for the model development presented in Chapter 5. Firstly, the temperature levels of the diffusers/cassettes supplemented the information of the HVAC control strategies. Secondly, the transaction data and the customers' spot observations are used for the creation of the hourly schedule of the customers' density in both sales and tills area. The in situ spot observations enabled the mapping of the customers inside the sales area from which the customers' density in both tills and display area derived. The surface temperature of the glass lid of the frozen food cabinet were used to evaluate the control strategy of the night cooling in order to avoid the risk of condensation on the glass lid.

Therefore, apart from the evaluation of the indoor air environmental conditions and the energy analysis, these results are used for the validation of the models in terms of energy use sales area temperature predictions.

4.1 Energy Use analysis

Figure 4-1 presents the annual energy use normalised per sales floor area of both monitored stores. The first year of operation CS2 appeared to have slightly lower energy use than CS1 but the following years higher by 4 % - 6 %.

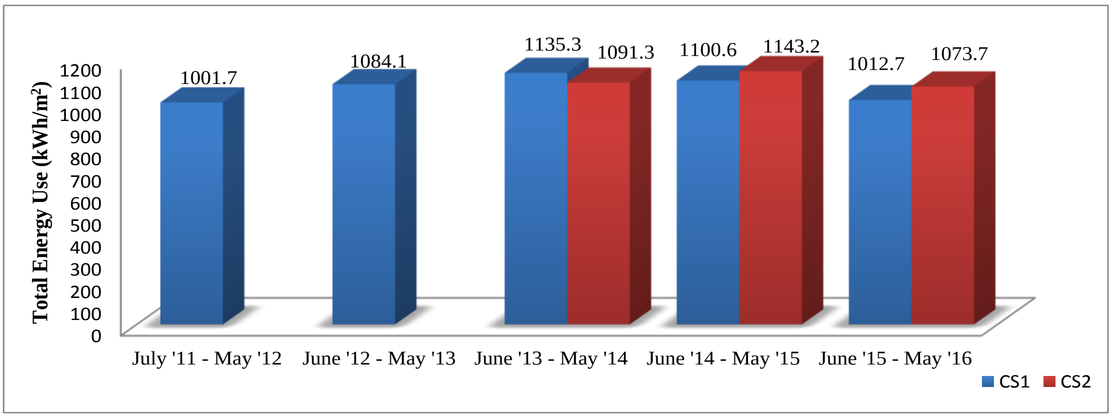


Figure 4-1: Measured annual energy use per sales area

According to data from literature (Chapter 2, Table 2.2) the case study stores are at the upper range of supermarkets and at the lower range of convenience stores. However, the high refrigeration load leads to higher energy use in comparison with a typical supermarket.

Figures 4-2 and 4-3 present an overview of hourly measure energy data using box whisker mean (BWM) plots. The mean hourly energy use of the months is presented based on hourly data. Figure 4-2 shows 5 years data for CS1 and figure 4-3 presents the 3 years data for CS2. Table 4-1 summarises the trading and non-trading times hourly energy use, the average hourly energy use and the highest measured trading times load.

Table 4-1: Hourly energy use during trading and non-trading hours

Hourly Energy Use (kWh/m^2) sa	CS1: Coupled heating/cooling with ventilation	CS2: Decoupled heating/cooling from ventilation
Trading times	0.15-0.18	0.14-0.18
Non-trading times	0.08 to 0.11	0.10-0.11
Average	0.11-0.16	0.12-0.15
Highest load	July ’13: 0.19	July ’14: 0.18

CS1 has a consistent energy demand during cold months with average trading hours (25th percentile) energy use to float at around 0.15 kWh/m^2 sa with peaks on warm months 0.18 kWh/m^2 sa before falling to the non-trading hours energy use (75th percentile). CS2 presented an average 0.14 kWh/m^2 sa (25th percentile) during trading time with peaks on warm months at around 0.18 kWh/m^2 sa. Due to the fact that the HVAC of the CS1 is not operating during night (in comparison with CS2 where HVAC is on 24h) and only free night cooling is in operation, there is a difference during the non-trading time energy use between the two stores. CS2 energy use during non-trading times observed to be around 0.10 kWh/m^2 sa. On the other hand, energy use of CS1 during non-trading hours ranged from 0.09 to 0.12 kWh/m^2 sa.

Figure 4-4 presents monthly energy use per sales area in correlation with Heating Degree Days (HDD) and Cooling Degree Days (CDD) for CS1. Winter 2013 was colder than the other winters; approximately 535 higher HDD. Therefore, energy use is higher during this winter. Summer 2015 was significantly warmer than the other summers of the monitoring period. However, the monthly and hourly energy use during this summer was not equally higher. Summer 2013 was warmer than the other summers and this also lead to higher energy use during this summer and consequently to total annual energy use.

Regarding CS2, the first year of operation (June 2013-May 2014) was more intense year in terms of heating and cooling requirements (Figure 4-5). Moreover, winter 2014 was colder than the other winters (approximately 103 higher HDD). Consequently, monthly and daily energy use measured to be higher during these months.

After October 2015 there was an upgrade in both stores regarding the lighting system. Typical T8 type florescent luminaires were replaced by LED lamps with 38% less power consumption. This change and the savings on the total energy use as well as the differences that occurred in the sub-systems are analysed in detail in Chapter 6.

According to the data, LED upgrade for CS1 resulted to an average monthly energy saving of up to 12 %. This percentage is lower during warm months due to the increase of the cooling demand which is more dominant in the energy use breakdown. For CS2 an average of 5 % reduction in the monthly energy use per sales area was recorded.

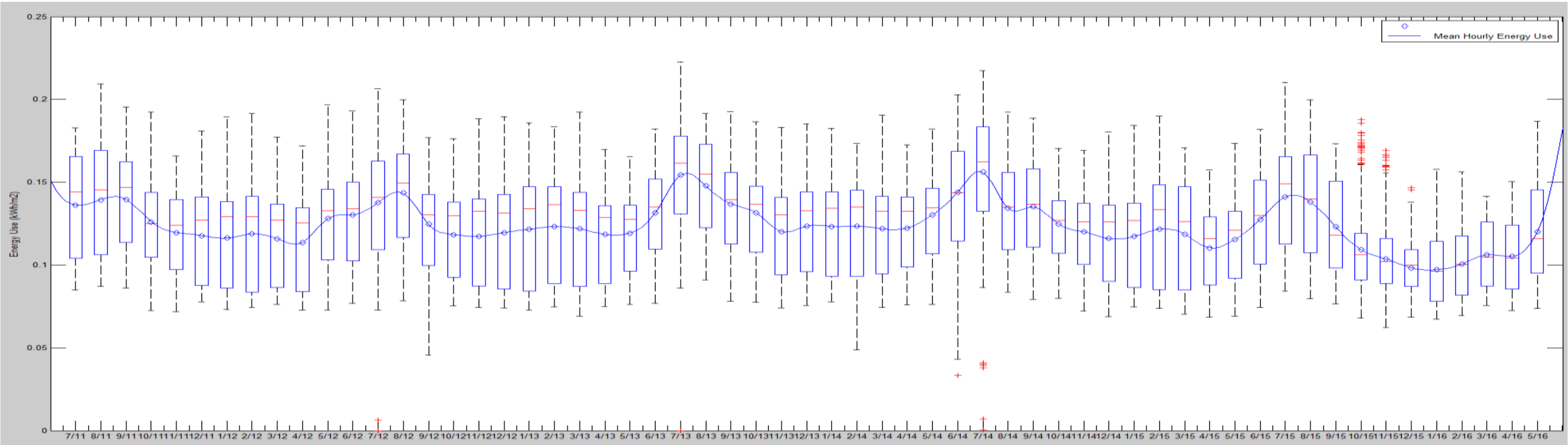


Figure 4-2: BWM plot of measured energy use per sales area based on hourly data, CS1

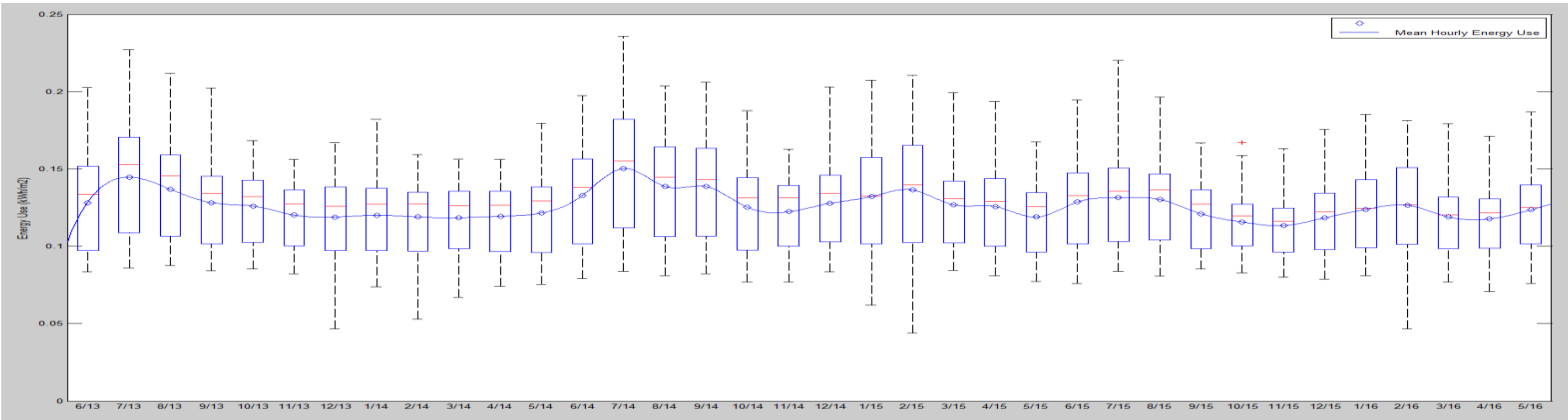


Figure 4-3: BWM plot of measured energy use per sales area based on hourly data, CS2

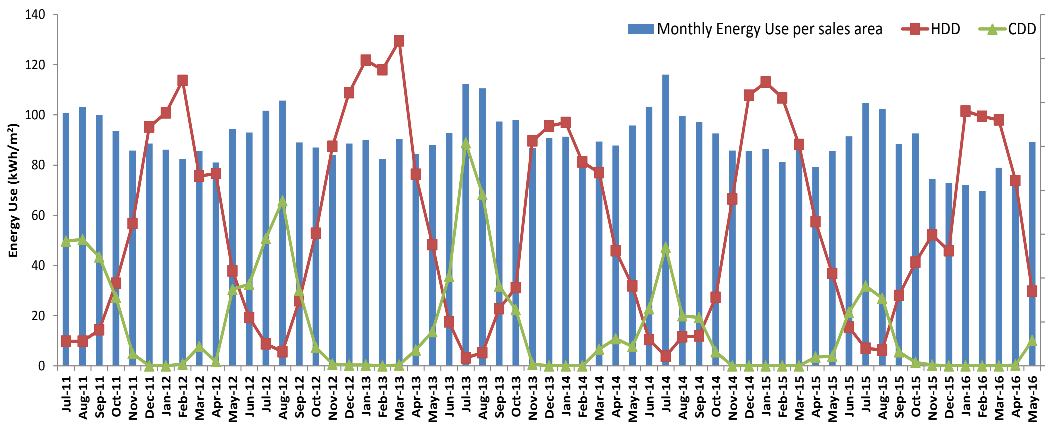


Figure 4-4: Monthly energy use per sales area in correlation with HDD and CDD, CS1

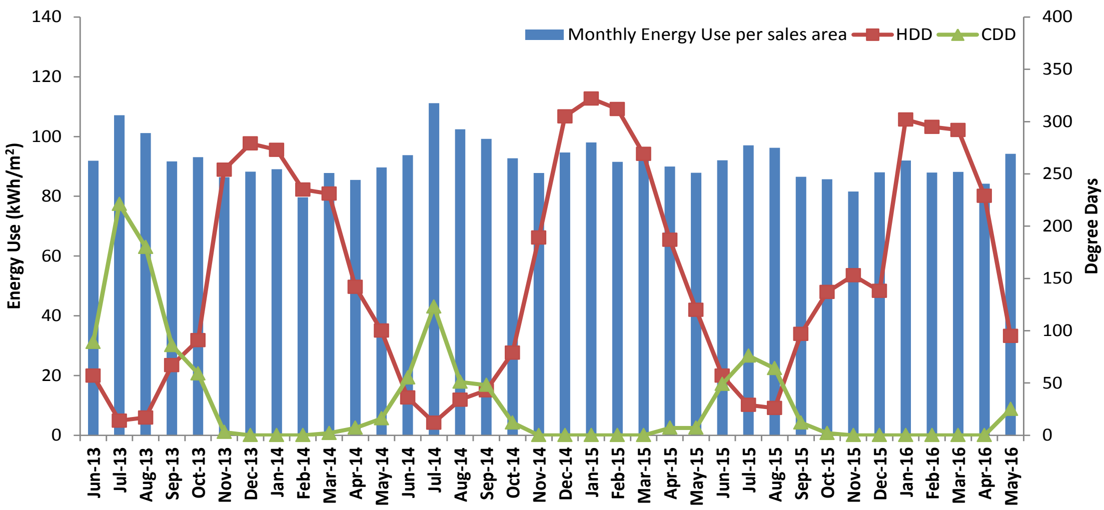


Figure 4-5: Monthly energy use per sales area in correlation with HDD and CDD, CS2

Figure 4-6 presents the correlation of the daily energy use of the stores with the outdoor temperature. It is observed that for both case study stores there is an outdoor temperature where the daily energy use found to be at its lowest levels. This is around 9^{o}C for CS1 and between 8^{o}C to 12^{o}C for CS2. Above these temperature the cooling requirements of the buildings increases and consequently the daily energy use from 25%-50% for CS1 and from 19% to 42%. The maximum daily energy use that monitored for warm days is almost the same for both stores but slightly higher for CS1.

However, a different pattern is followed for cold days and this is due to the difference of the control strategy of the HVAC systems. CS1 with the free cooling during night and non 24h HVAC system, presented lower daily energy use during cold days. The 24h

HVAC system in CS2 resulted in higher heating requirements and this higher daily energy use during cold days.

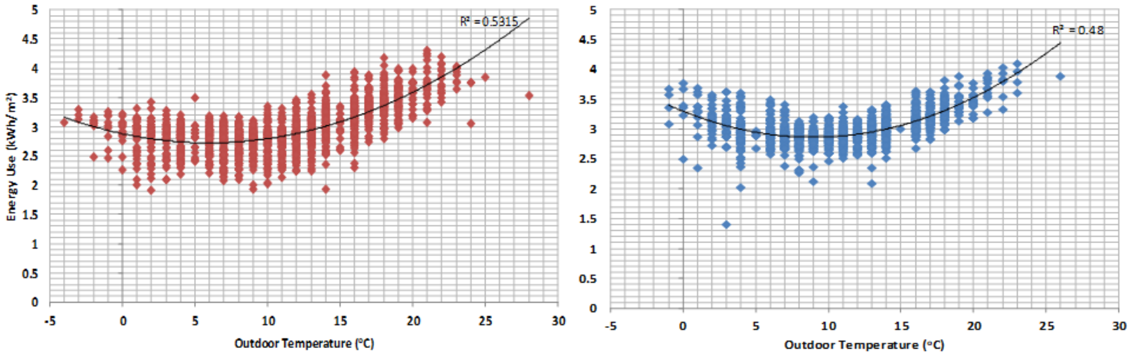


Figure 4-6: Daily energy use per sales area in correlation with outdoor temperatures, CS1 (left) and CS2 (right)

Figures 4-7 and 4-8 present the weekly pattern of the energy use and the external air temperature during the same weeks in July and January for CS1. The base load energy use is affected by the external temperature; from 0.1 kWh/m^2 to 0.11 kWh/m^2. The higher the external temperature during non-trading times, the less effective is the night cooling and fan energy use is increased without any effect on the temperature of the sales area but only in the total energy use. For January the base load is lower; 0.08 kWh/m^2 to 0.11 kWh/m^2. External temperature is important during the non-trading times as night cooling depends on the external temperature. External temperatures around 0-5 ^{o}C lead to lowest base load while higher temperatures make night cooling not so effective. For trading times external temperature is highly correlated with energy use which is between 0.15-0.18 for both July and January days. Moreover, in the beginning of the operation times there is a peak at around 6:00 when the HVAC and lighting systems are turned on according to control strategy for weekdays and Saturdays and at around 8:00 for Sundays. However, this peak does not appear during summer period (figure 4-7) because the temperature inside the store is not significantly low. At around 8:00 the energy use begins and remains stable until 20:30 when the reduction to the base load starts. It is worth noting that LED upgrade in October 2015 resulted to a daily energy use on January 2016 significantly lower than previous years.

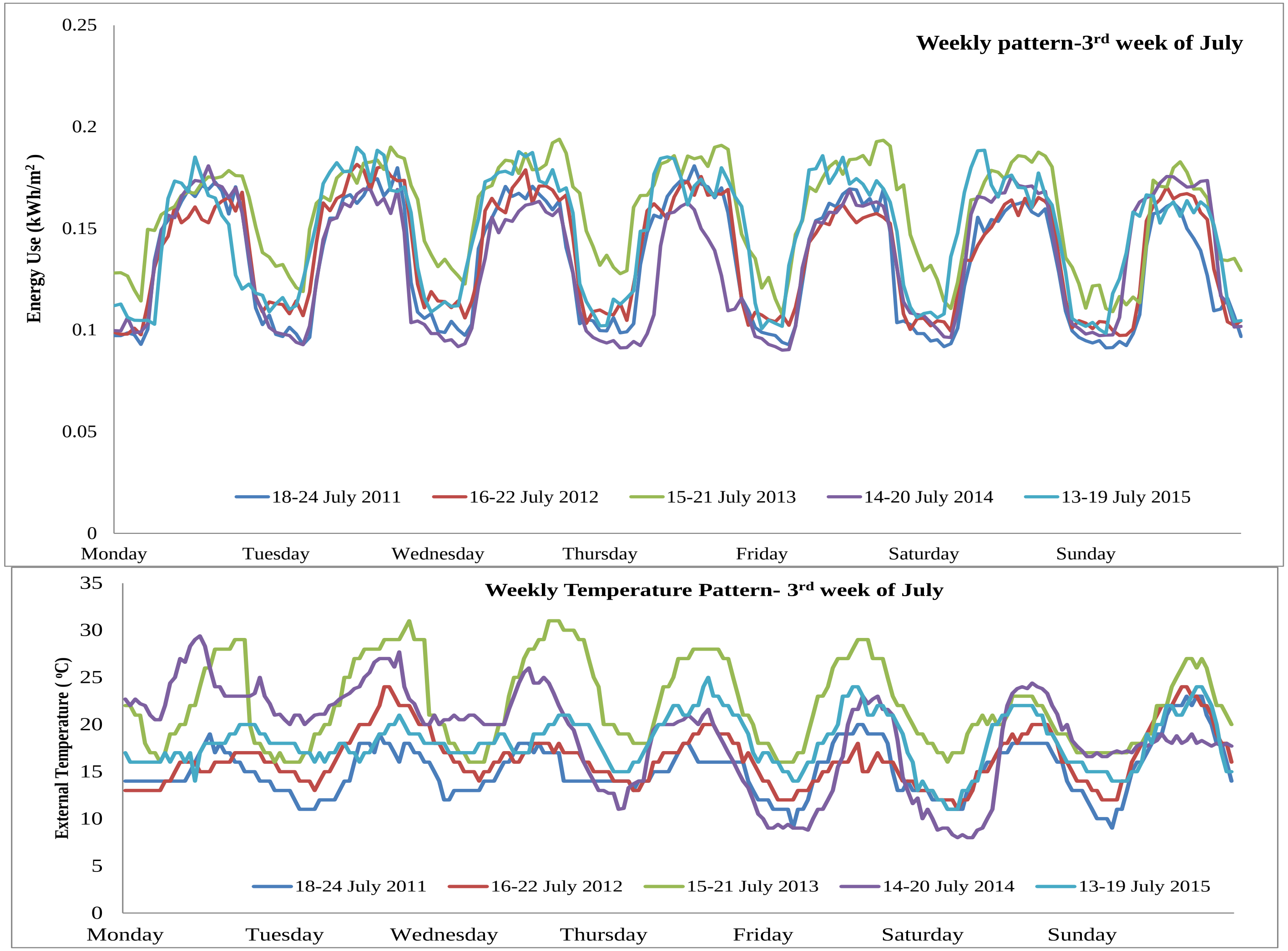
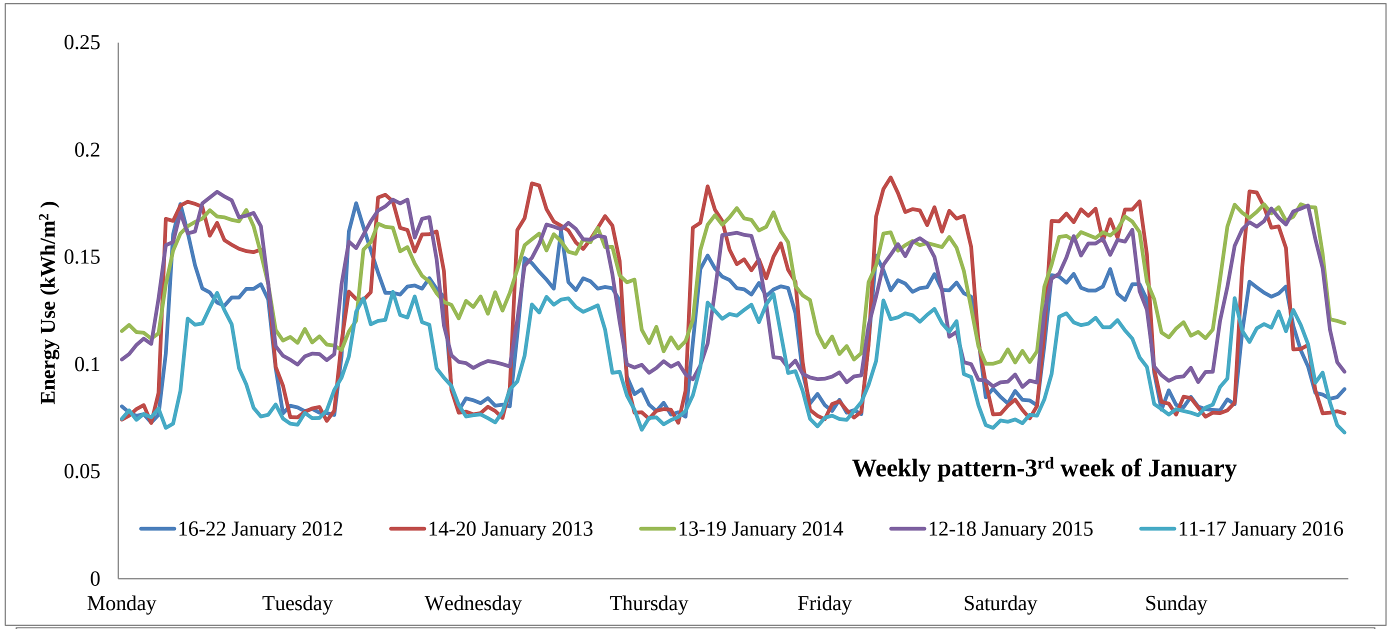


Figure 4-7: Weekly pattern of the energy use in correlation with the external air temperature during 3rd week of July, CS1



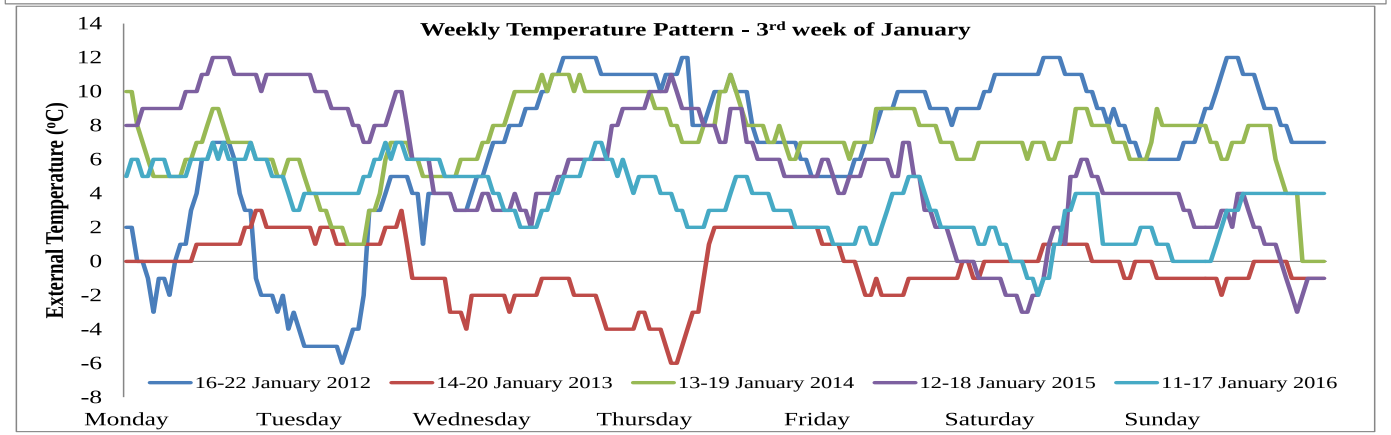


Figure 4-8: Weekly pattern of the energy use in correlation with the external air temperature during 3rd week of January, CS1

Figures 4-9 and 4-10 present the weekly pattern of the energy use in correlation with the external air temperature during the same weeks in July and January for CS2. External temperature is highly correlated with the energy use during warm months. July 2015 was cooler than in the previous years, and energy use during trading times was lower. Non-trading hours' external temperatures are similar; hence the energy use during night time differs insignificantly and was around 0.1 kWh/m^2.

Figure 4-10 presents the hourly energy use pattern during January (cold months). It shows that during trading times' energy use varies between 0.12-0.17 kWh/m^2 which is slightly lower than during the warm months (0.18 kWh/m^2). Extreme external temperature during January leads to higher energy use during trading hours (i.e. Saturday). It can be observed that when the external temperature remains almost at the same levels (8-10 ^oC), the energy use recorded during the trading times is the lowest recorded during the trading times (0.14 kWh/m^2). Moreover, and in comparison with CS1, no peak was recorded in the energy use at the start-up of the store because the HVAC system is in operation 24h and the temperature inside the store remains almost the same during the whole day.

Sub metering did not take place in both stores due to managers' hesitance for the measuring equipment and the inconvenient that these could create to customers. However, sub metering data from a store similar to CS2 in terms of HVAC system and similar to all the stores that belong to the same supermarket chain in terms of refrigeration cabinets were provided for one month (May 2016). Figure 4-11 present the sub systems hourly energy use breakdown for three days of the week (Tuesday 17/5/2016, Saturday 21/5/2016 and Sunday 22/5/2016) to depict the differences that occurred during week days and weekends. The highest percentage of the energy use metered is due to the refrigeration system which during trading times reached up to 60% while during night does not fall less than 43%. The second biggest energy consuming systems is the HVAC which is in operation 24h and during the night is as much as refrigeration energy consuming while during the day does not exceed the 20%. Lighting and electrical equipment energy use during the night that the stores is closed is less than 6% for all the indicative days but reaches during the trading times the maximum percentage of 28% of the hourly energy use.

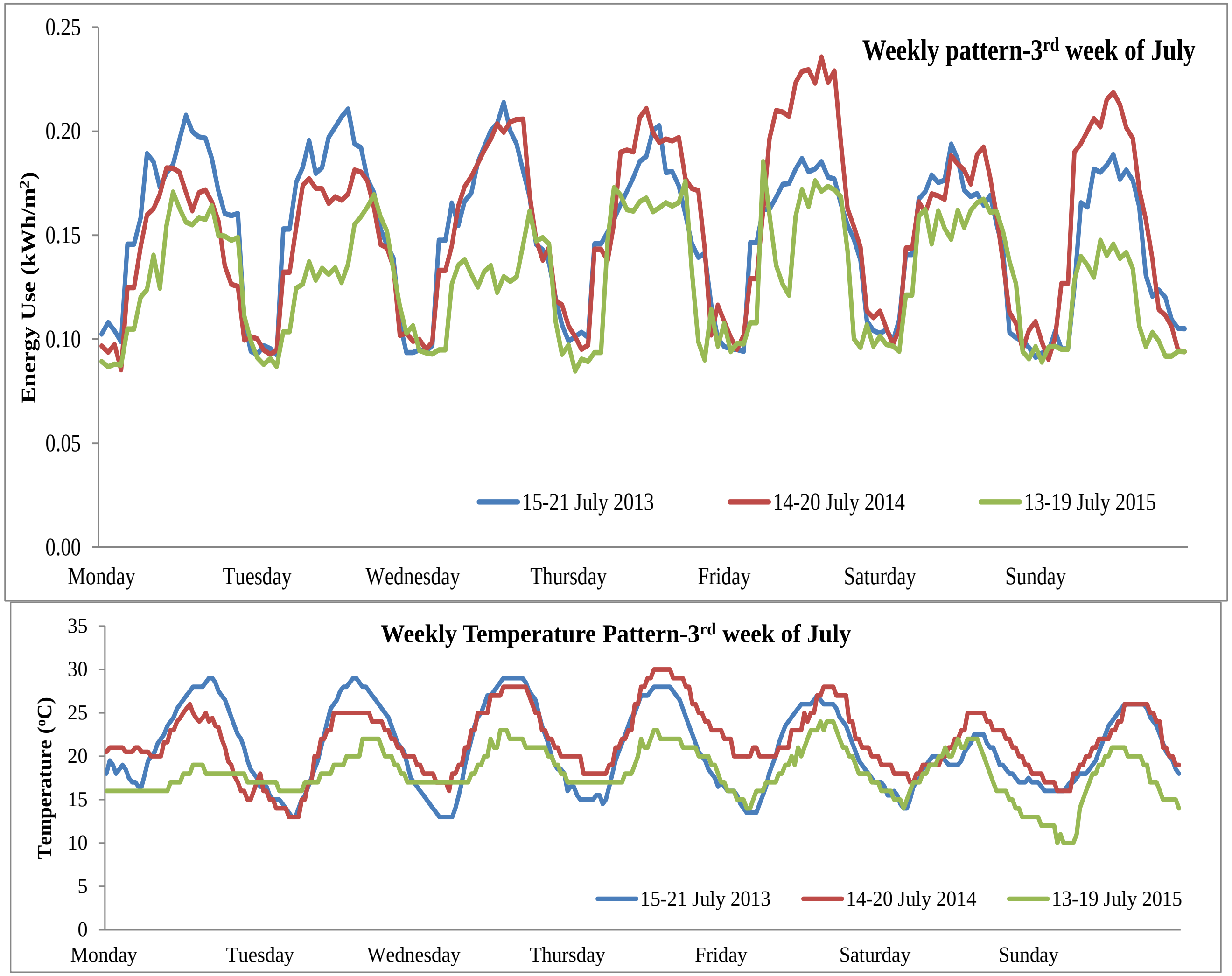
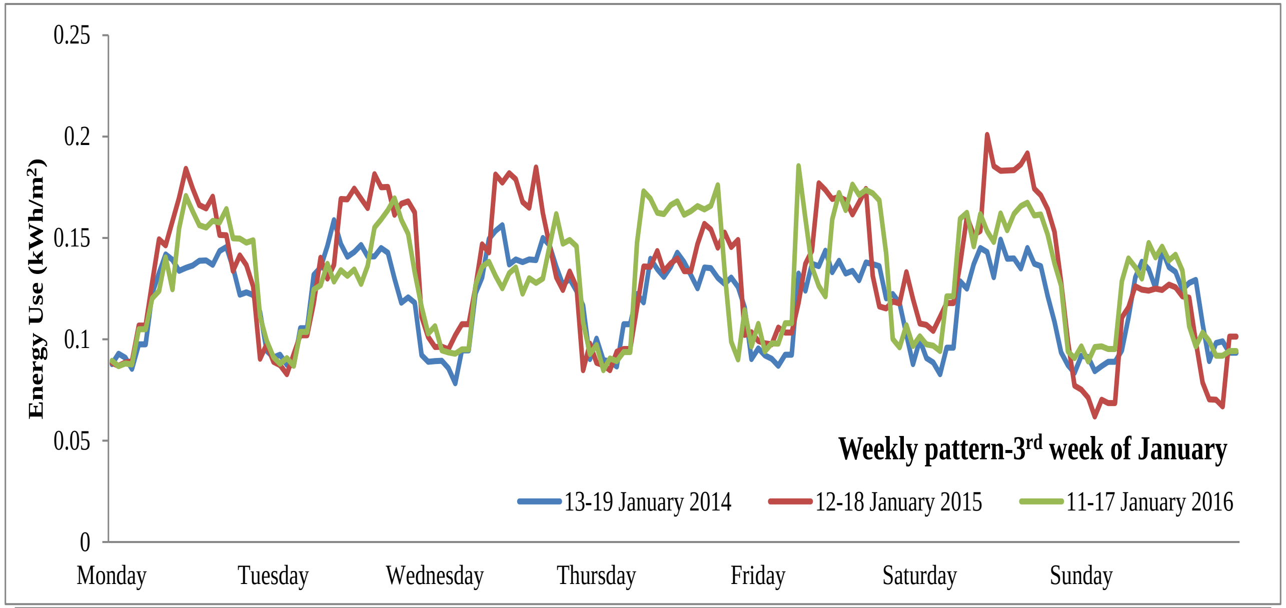


Figure 4-9: Weekly pattern of the energy use in correlation with the external air temperature during 3rd week of July, CS2



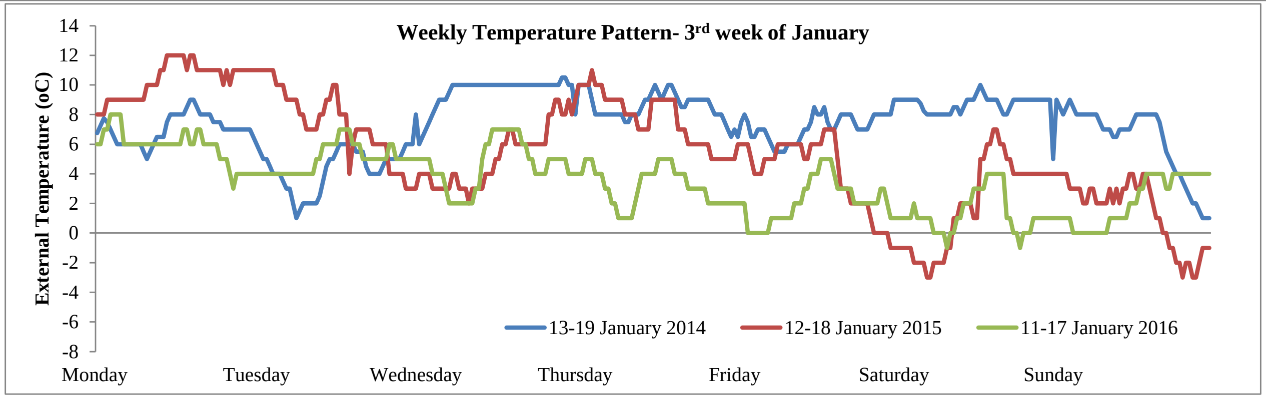


Figure 4-10: Weekly pattern of the energy use in correlation with the external air temperature during 3rd week of January, CS2

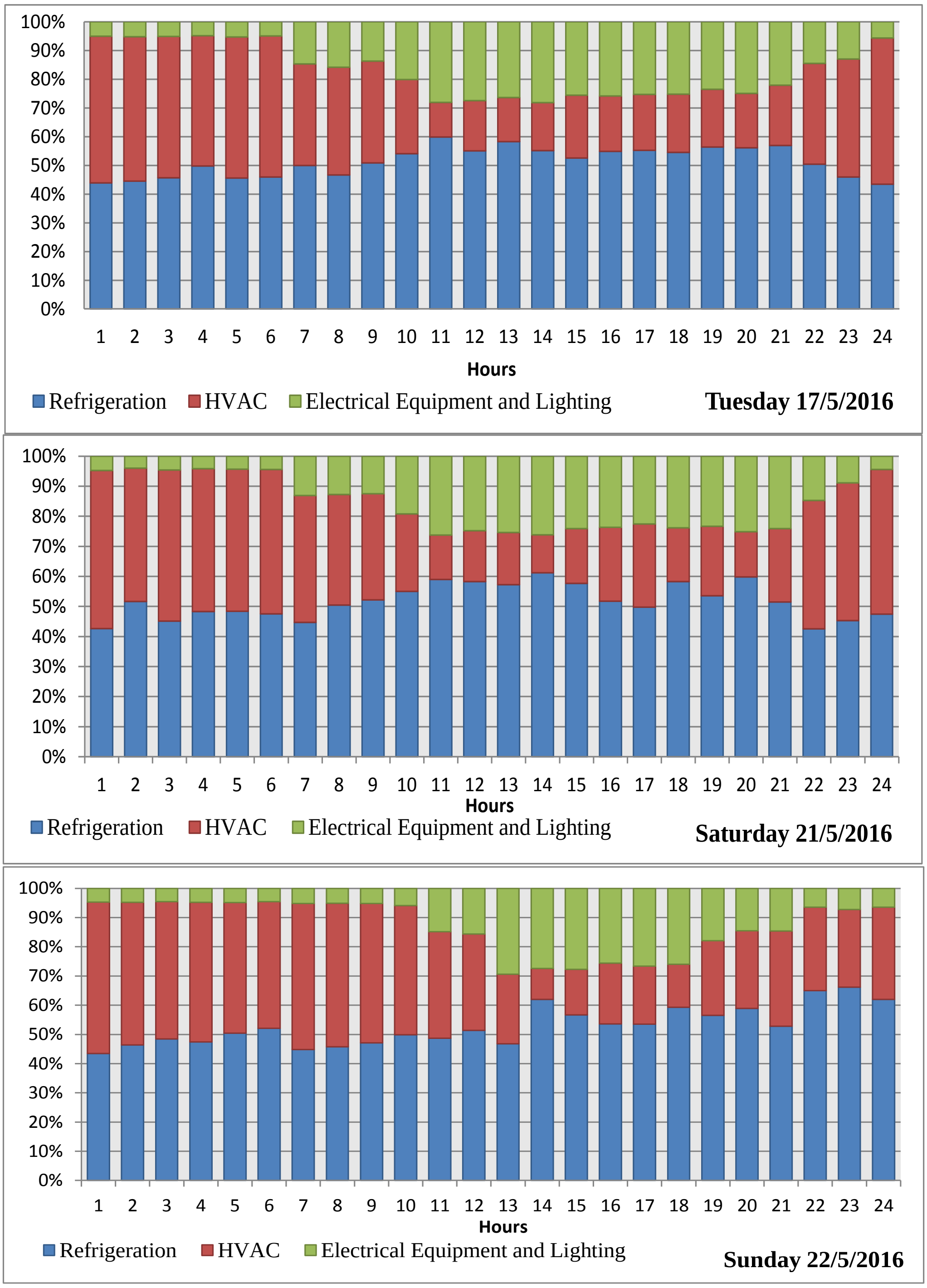


Figure 4-11: Sub systems hourly energy use breakdown for three days of the week (Tuesday 17/5/2016, Saturday 21/5/2016 and Sunday 22/5/2016)

4.2 Indoor air conditions analysis

This section presents the monitoring data of indoor air conditions of the stores. The data are evaluated and compared to standards and guidelines for thermal comfort in supermarkets and to lead to conclusions for the environmental conditions in the sales area.

CIBSE Guide A (2015) recommends for supermarkets the range of 19 ^{o}C to 21 ^{o}C for winter temperatures and the range of 21 to 25 ^{o}C for summer temperatures. RH 30% or below may be acceptable but precautions should be taken as sensory irritation (eyes, nose, throat, and skin), fatigue, headaches and difficulty in breathing problems will be increased (CIBSE, 2015). However, CS1 has implemented night free cooling in the HVAC control strategy which might require RH control in order to prevent condensation on the glass doors of the frozen food cabinets.

Light intensity is an important parameter in supermarkets; both in terms of energy use and illumination of displayed products. CIBSE Guide A (2015) recommends light intensity levels between 750 and 1000 lux for supermarkets and 500 lux for convenient stores (CIBSE, 2015) . A supermarket chain specifies near the upper range (Acha et al., 2012) while surveys indicate levels lower than the minimum range (Ticleanu et al., 2013).

Carbon dioxide level is an indicator of indoor air quality. Levels less than 1000 ppm are most typically specified as an indicator of Indoor Air Quality (IAQ). It can provide indication of the number of occupants and the effectiveness of the ventilation rate of the monitoring area (CIBSE, 2011). CIBSE Guide A recommends comfort criteria for supermarkets that point out a suggested supply air rate at minimum 10 L s^{-1} per person that leads to maximum 900 ppm CO_2 concentrations with an outdoor concentration of 400 ppm (CIBSE, 2015). According to ASHRAE, a recommended minimum ventilation rate for supermarket is 7.5 L s^{-1} per person results to an 1100 ppm CO_2 concentration with an outdoor concentration of 400 (ASHRAE, 2013).

4.2.1 CS1

Figure 4-12 summarises the location of the data loggers and the cassettes in the floor plan of the sales area. The sales area has been divided into three sub areas according to similar ambient conditions and parameters that influence their indoor air conditions:

a. Expose to outdoor conditions
b. Internal heat gains
c. Customers' density

As indicated in Chapter 3, diffusers monitoring plan showed that the diffusers presented similar temperature pattern for both trading and non-trading hours as was expected due to CAV HVAC system of the store. Only diffuser #15 has minor periods with significantly higher temperature than the set point and this is because of the additional heating battery of this branch. All the other diffusers followed the control strategy of the HVAC system and provided air with same temperature into the store.

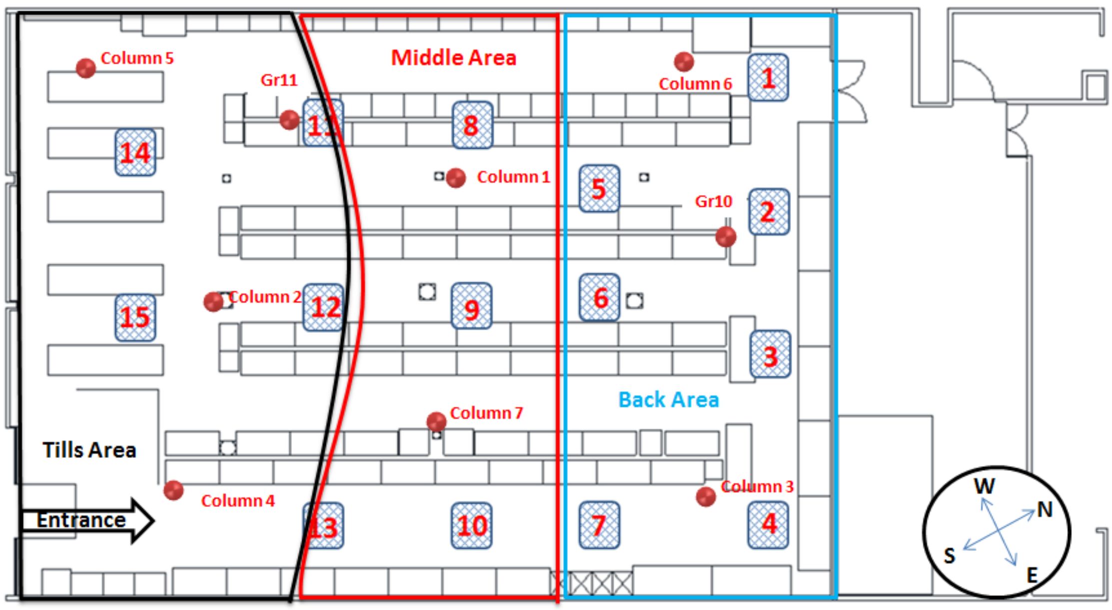


Figure 4-12: CS1 floorplan separated in areas with sensors location indicated

According to data, unremarkable stratification was observed between the data loggers in different heights (Appendix B). Temperature data in different heights have strong positive correlation (r) (0.75-0.97); the temperature of the loggers moves simultaneously at the same direction presenting almost the same increase/decrease. Moreover, all the sensors present a strong positive correlation with the external temperature. The highest value of this positive liner correlation is observed for columns in the tills area due the position of the sensors, near the front single glazes windows of the store. However, despite the location of the sensors in the back area of the stores (Column 6, Column 3 and Gr 10), a remarkable correlation (~0.75) with the external temperatures was found.

Figures 4-13 present in BWM all the measured data of the data loggers (based on 15 minutes intervals) of the tills, middle and back area as they are separated in figure 4-12. According to measured temperatures, the average temperature during the whole monitoring period is approximately 19-20^{o}C which agrees with the set point temperature of the HVAC system of the store. However, during warmer periods (June-September) the temperature average during the day is increased up to 22^{o}C. Moreover, during these significant high temperatures were measured (red-cross outliers) and reached up to 30^{o}C in the back area of the store. During non-trading times a high percentage of the recorder temperature inside the store is maintained between 16^{o}C and 20^{o}C. Night cooling has as minimum set point temperature 16^{o}C. (Section 5.4.3, Table 5-5). The decrease of the inside temperature due to the free night cooling is more obvious during winter months where the difference between inside and outside temperature is higher and the cold air brought in is more effective. After 20.5 ^{o}C the HVAC system is set to cooling mode and below 16^{o}C to heating mode.

Regarding the RH (figure 4-14) of the sales area, insignificant stratification was observed for the different areas of the stores and it varies from approximately 35% during cold months and approximately 60% during warm months of the monitoring period.

Light intensity (figure 4-15) varies significantly between the tills area and the sales area. Data from middle and back area are merged as the light intensity data from the back area was recorded only for several days and agrees with the data of the middle area. According to the measurements average light intensity on the tills area is 400-450 lx with the smallest measured during winter months and significant outliers (red-cross) are observed and this is due to the orientation of the building and the glazed front façade. Display area presented significant lower light intensity (50-100 lux).

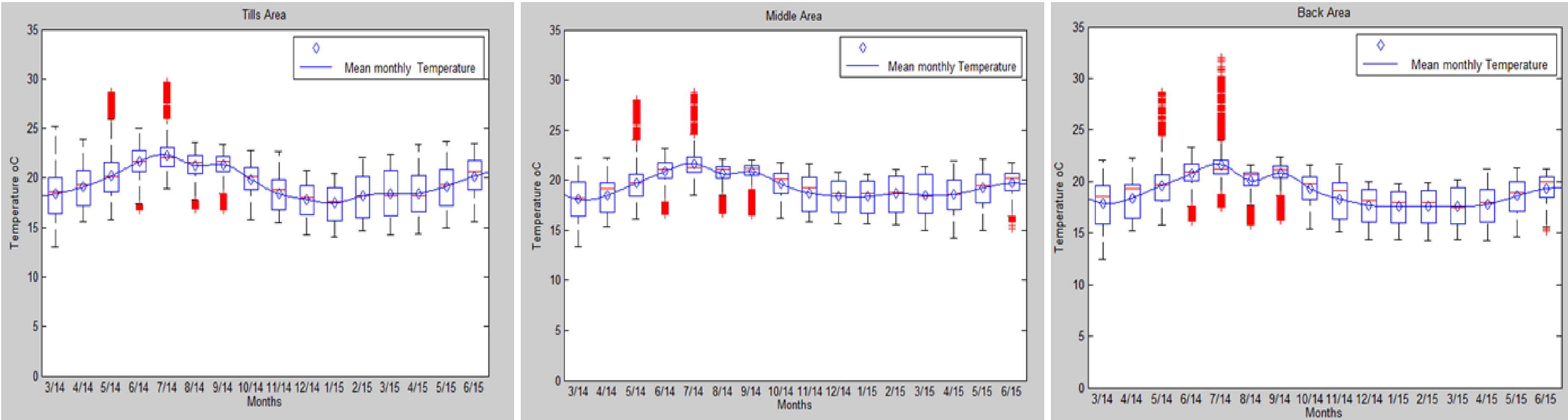


Figure 4-13: BWM plot of measured temperature data, CS1

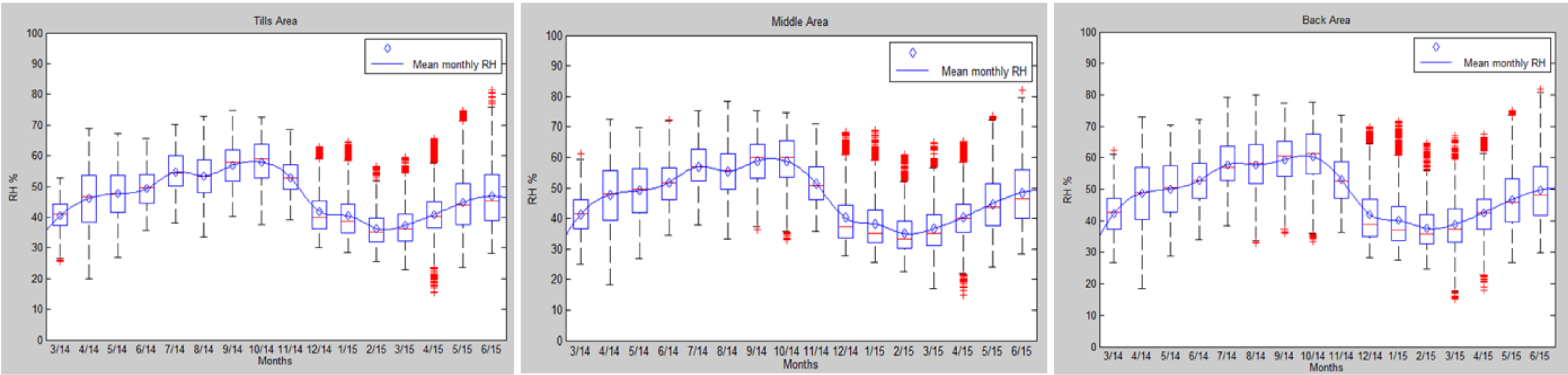


Figure 4-14: BWM plot of measured RH data, CS1

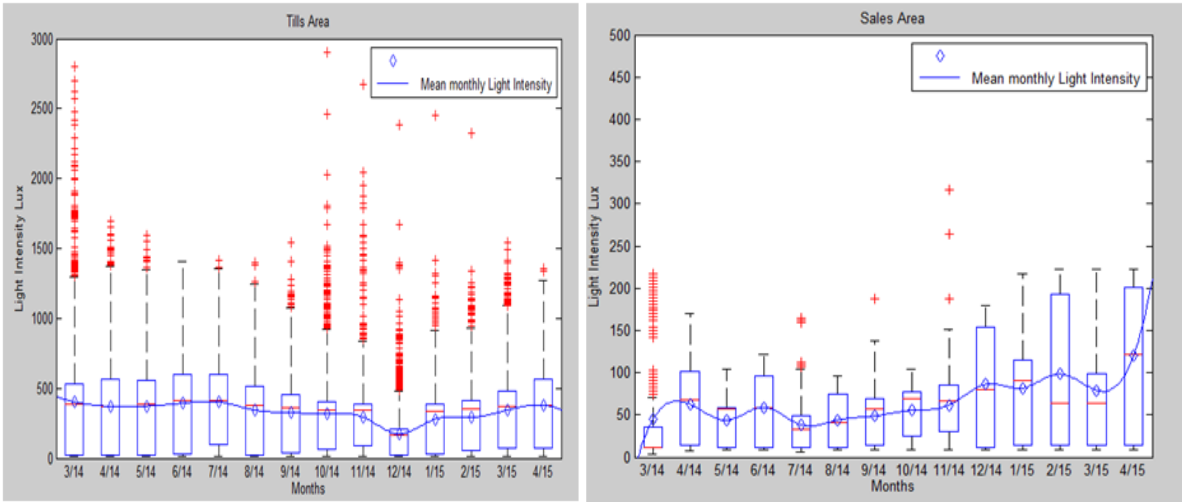


Figure 4-15: BWM plot of measured light intensity data, CS1

Figures 4-16 and 4-17 visualise the temperature results and the stratification of the temperatures inside the sales area for two extreme conditions (warmest and coldest time) and on a moderate day of March 2014 (figures 4-18 and 4-19). The 3-axis figure describes the floorplan of the sales area (x-axis: distance of the front side from the entrance, y-axis: distance of the sides from the entrance) and the temperature measured from the sensors (z-axis). The location of the sensors can be found in figure 4-12 and the average of the sensors in different heights has been used as there was not significant stratification between them. Moreover, temperatures areas that are not represented by a column or sensor are interpolated temperatures derived from nearest neighbour-sensors.

The areas with higher temperature during the warmest day were the one in the east back side and the west front side. This is due to the single glazed front side of the store which increases significantly the internal heat gains of the area and the accumulated heat gains from the refrigerated cabinets. Although the chilled open front multi deck cabinets and the frozen open up case cabinets are located in the back area, the infiltration exchange from the cabinets' air does not affect the ambient air and the exhaust heat of the cabinets lead to higher temperatures. According to measurements taken in the pre-monitoring period from the HVAC diffusers temperature and air velocity (Section 3.4.2, figure 3-10) , the diffusers in the back area (#2, #3, #4) had the lowest air flow air velocities indicating less control by the HVAC. This is something that can also be observed during in the coldest day measurements (figure 4-17). The middle area presents the lowest temperature in the store as it is not affected from the outdoor conditions (front side), internal heat gains from customers standing in the tills, heat gains from the chilled open front multi deck cabinets and the lowest airflow rates of the HVAC. During the night when the night cooling is in operation the infiltration through the sliding entrance door observed to reduce slightly the temperature (figure 4-17). Higher temperatures recorded as well for the back area which has the highest refrigeration load (0.3 kW/m^2) but due to closed curtains of the open cabinets the air exchanges are reduced significantly.

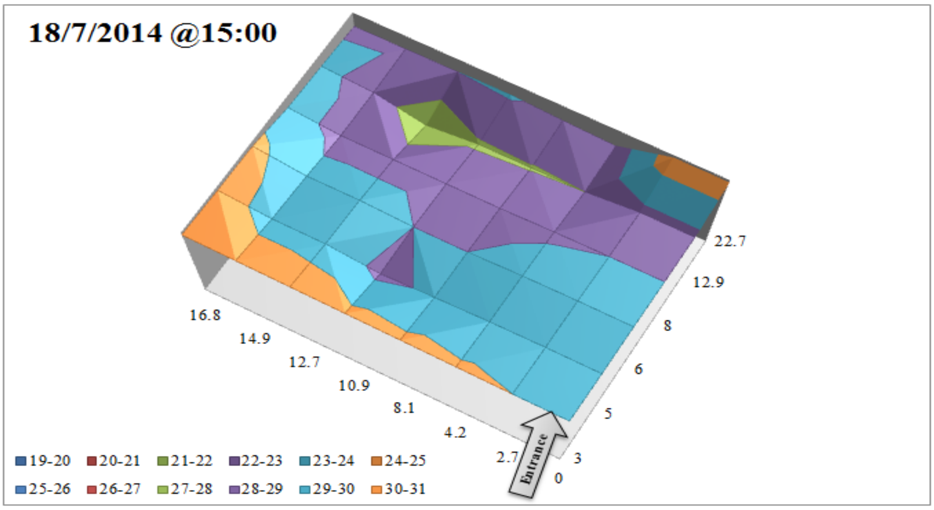


Figure 4-16: Temperature stratification in the sales area during warmest time of the monitoring period, CS1

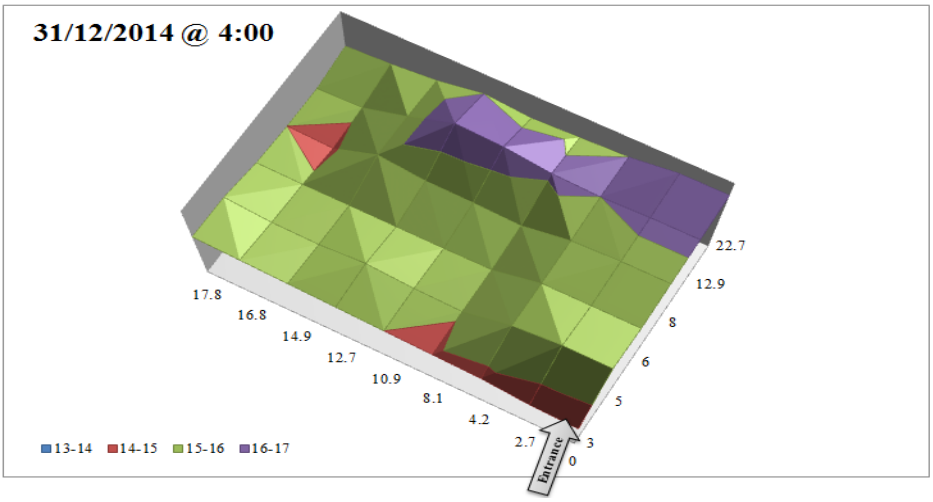


Figure 4-17: Temperature stratification in the sales area during coldest time of the monitoring period, CS1

During a day with typical mild UK weather conditions (11^{o}C average outdoor temperature) the west side of the tills area has the highest temperature during trading hours (22 – 24^{o}C) while the middle area is maintained at set point (~21 ^{o}C). Air infiltration from the open cabinets in the back area affects the air temperature which measured to be approximately 1^{o}C lower from the middle area. During non-trading times, middle area has the lowest measured temperature while both tills and back area has 1-2 ^{o}C higher temperature. During night time the open cabinets are closed using curtains to reduce the air exchanges with the back area and this leads to similar measured temperatures with the tills area which is due to the lower air velocity of the diffusers above this area and the accumulated heat gains from the cabinets.

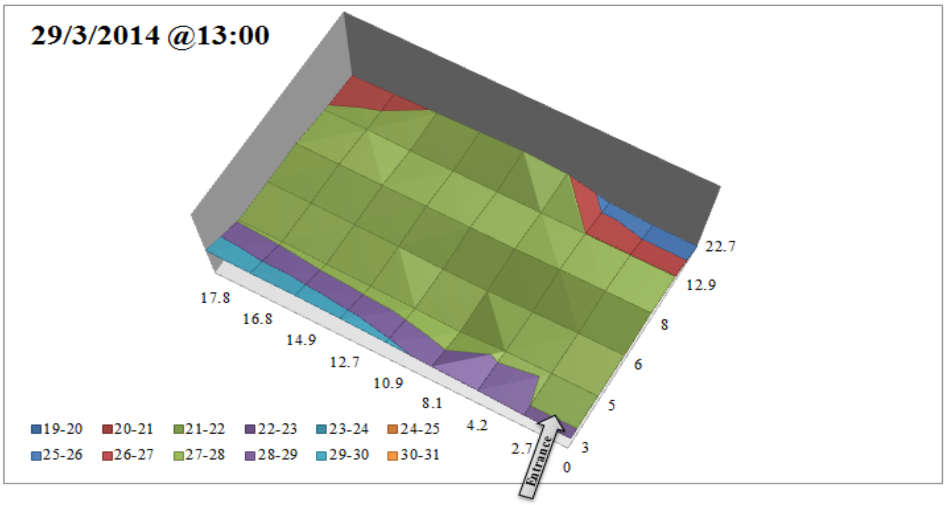


Figure 4-18: Temperature stratification in the sales area during a moderate outdoor temperature of the monitoring period, trading hour, CS1

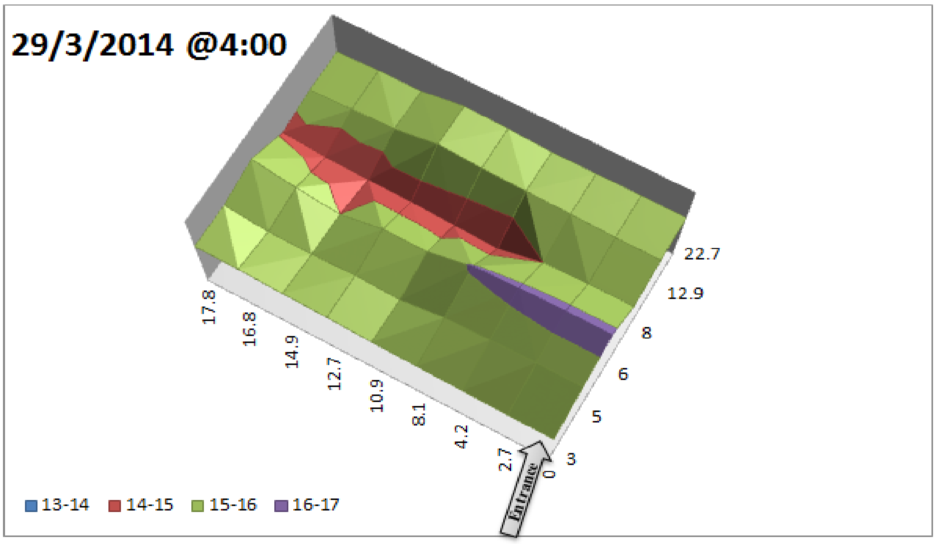


Figure 4-19: Temperature stratification in the sales area during a moderate outdoor temperature of the monitoring period, non-trading hour, CS1

Figure 4-20 presents internal air temperature daily pattern of the data loggers in the sales area on two indicative days with different external conditions (3rd and 19th of May 2014) correlated with the daily energy use per sales area and the external air temperatures. During non-trading times the back area presented higher temperatures in comparison with the other areas as it was analysed in previous graphs and tills is the one with the higher temperatures during trading times. The same applies for both days. During trading times, both days' back area's temperatures reduces while the tills area is highly affected form the heat gains of the single glazed front side windows and has higher temperatures. External temperatures plays important role for both trading and not trading times temperatures and the energy use of the store. The 3rd of May was coldest day than the 19th of May and average internal temperature of the store was approximately 5°C less. This is observed as well during night time where the night cooling is in operation. Night cooling takes the advantage of the low external temperatures (less than 5°C) and the set point of the night cooling (16°C) according to HVAC control strategy is achieved while on the 19th of May when the external temperature is quite high the night cooling does not manage to achieve the sales area temperature reduction. This is obvious as well on the measured energy use of both days; higher external temperature leads to insignificant results on the sales area temperature and the continuous fan energy use, hence, higher total energy use. External temperature also is highly correlated with the trading times energy use; more HVAC energy use is required to achieve the set point temperature.

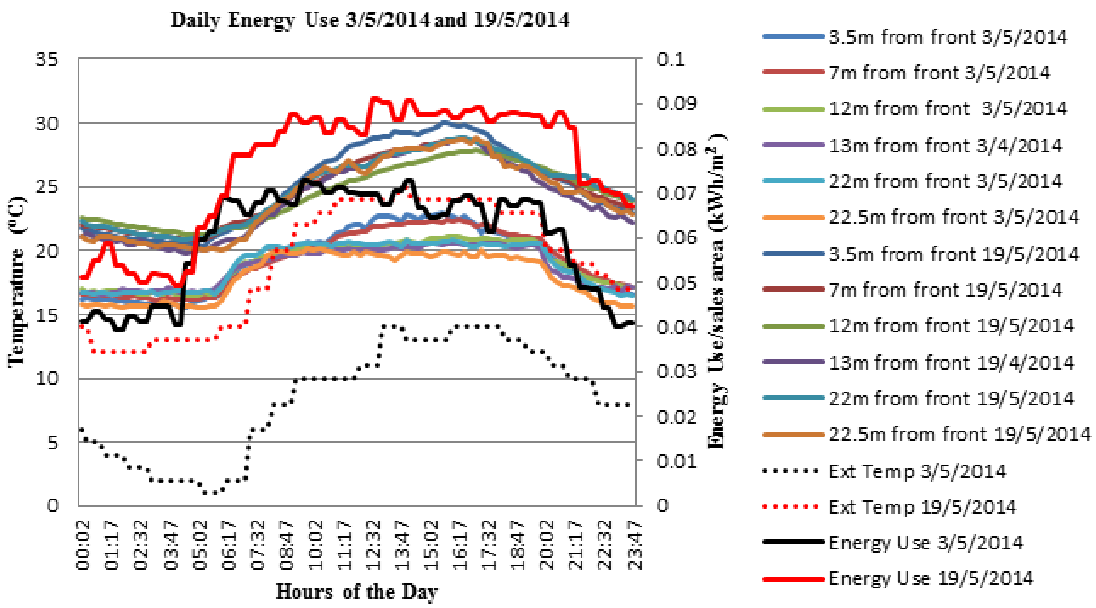


Figure 4-20: Daily pattern of sensors' measured temperature in correlation with external temperature and energy use, CS1

4.2.2 CS2

Figure 4-21 summarises the location of the data loggers as well as the cassettes location on the floorplan of the sales area. The sales area is separated into three areas; (a) tills, (b) middle and (c) back area according to internal heat gains, exposure to outdoor conditions and costumers' density. Cassettes D1, D2 and D7 are included in the tills area as they are affected more by the air flow rates of the main entrance and the heat gains of single glazed façades (north-west and south west). The middle area includes cassettes D3 and D6 while cassettes D4 and D5 are in the back area of the store. Moreover, according to the cassettes monitoring data D1, D2 and D7 presented similar temperature pattern which indicates the cooling and heating mode while D3, D4, D5 and D6 had different one and they are mostly in cooling mode.

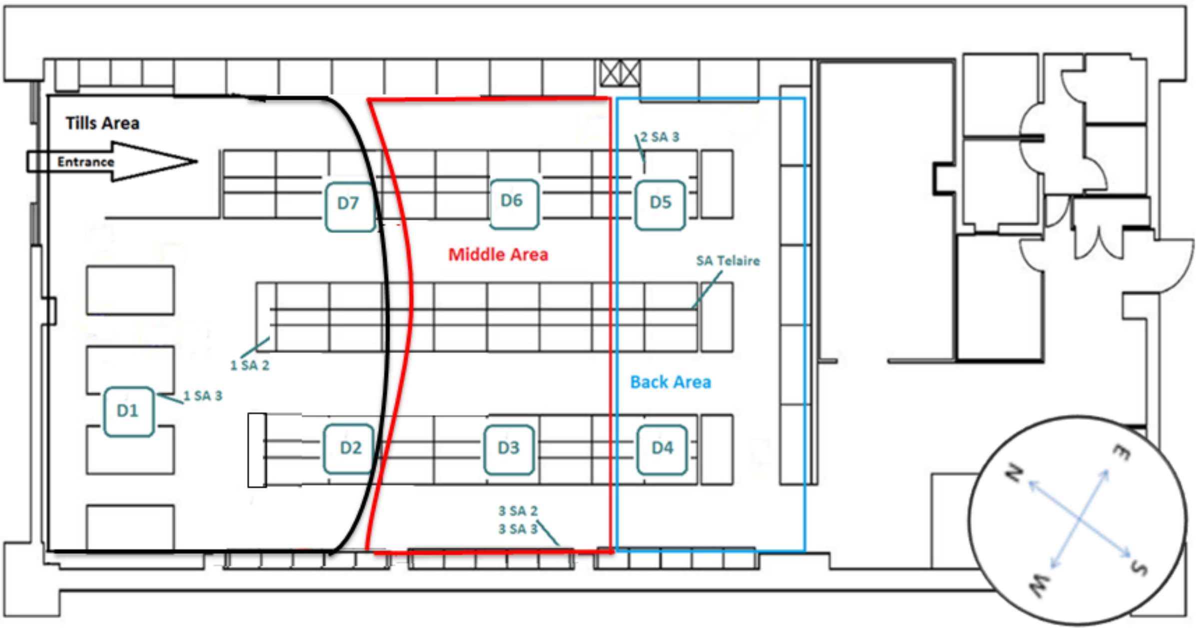


Figure 4-21: CS2 floorplan separated in areas with sensors location indicated

According to data (Appendix B), small stratification between sensors on different heights was observed and the sensors' data were positively correlated ($r > 0.5$). The smallest correlation observed for Column 2 and Column 3 between the sensors on the knee and head level and this is due to the position of the highest sensors which is closer to the air stream from the cassettes (Column 2) and closer to the heat gain/losses of single glazed south-west façade (Column 3). Higher correlation with the external temperature is observed for Column 1 while the rest of the sensors presented a moderate correlation with the external temperature.

Figure 4-22, 4-23 and 4-24 present in BWM plots the measured temperatures, relative humidity and light intensity of the three areas.

Tills area presents the higher variation from the set point temperature (21^{o}C) set by the control strategy of the HVAC. The average temperature of the tills area is between 18-22^{o}C and is significantly correlated with the external temperature (r > 0.7). During trading hours (upper quartile) the tills' temperature measured 18^{o}C and 21^{o}C for colder and warmer months respectively. During non-trading times temperature raised up to 22^{o}C during the warmer months of the monitoring period and at set point temperature during colder moths. Average temperature in the middle and the back area of the sales area didn't present remarkable stratification from the set point temperature during the monitoring period and the same applies for both trading and non-trading times. Moreover, the temperature data measured in the middle and back area of the sales area presented a smaller interquartile length in comparison with the ones of the tills area. That means that the variation of the measured temperature from the average temperature is not big. There are only two months (January and February) when this variation is bigger and an explanation could be the manual set point upgrade to higher temperatures by stores' staff.

Regarding the RH of the sales area, no stratification between different areas in the sales area was mentioned with the average to be from 40% for colder months and 50% for warmer months.

Figure 4-24 present the light intensity levels inside the sales area. Data from January 2015 were missing. Light intensity of the tills and middle area was observed to vary between the same values; approximately 500lux. Significant outliers (red-cross) measured in the middle area, especially in the evening times and this is due to the orientation of the building and the glazed south–west façade. Two single glazed window facades improved the lighting levels inside the sales area. Light levels at the back area did not exceed 150 lux.

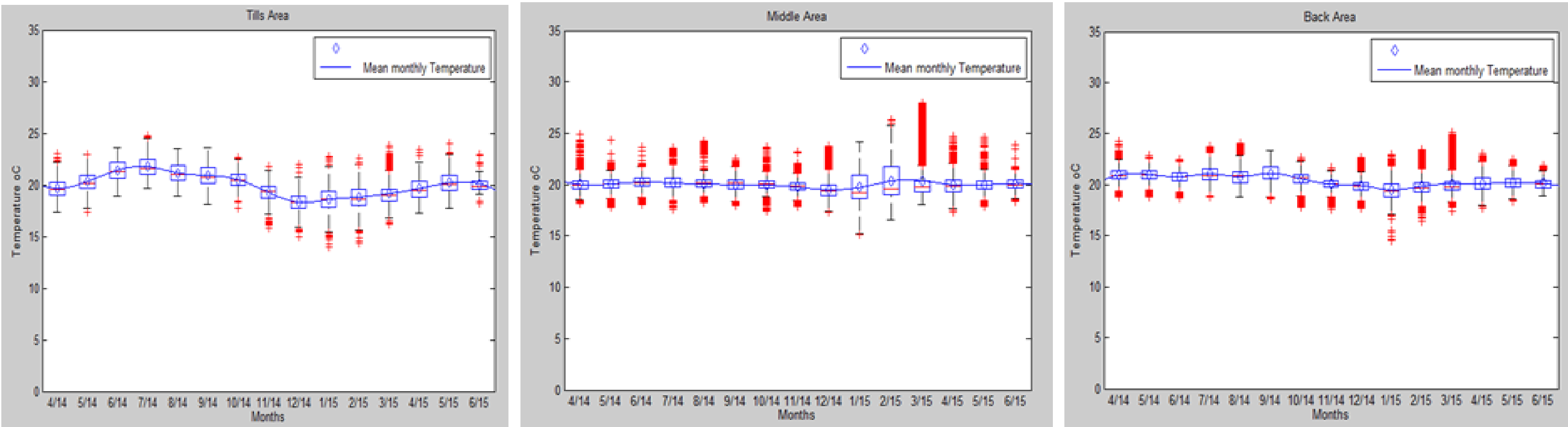


Figure 4-22: BWM plot of measured temperature data, CS2

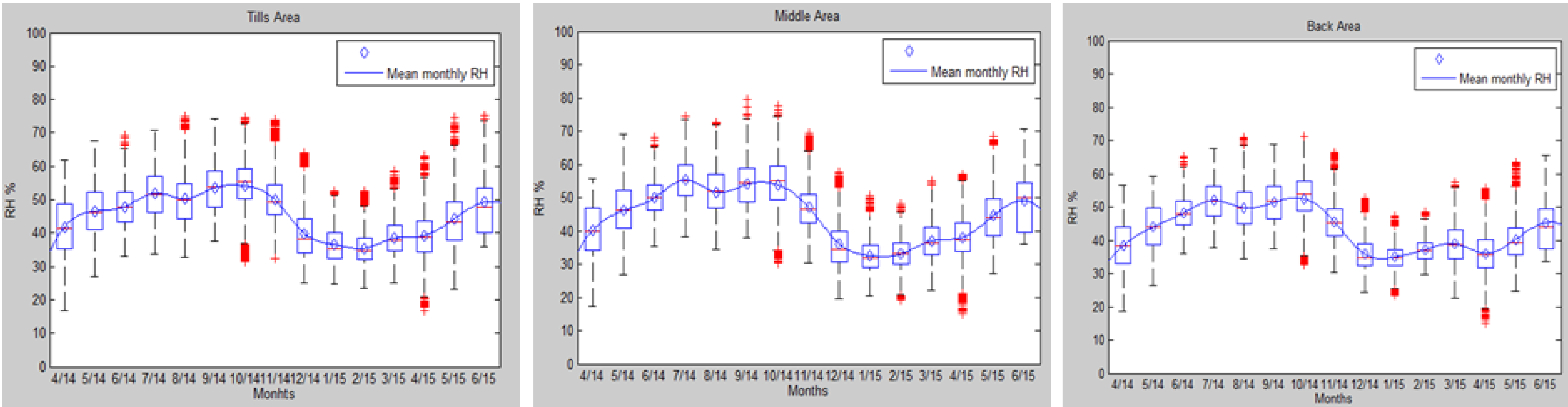


Figure 4-23: BWM plot of measured RH data, CS2

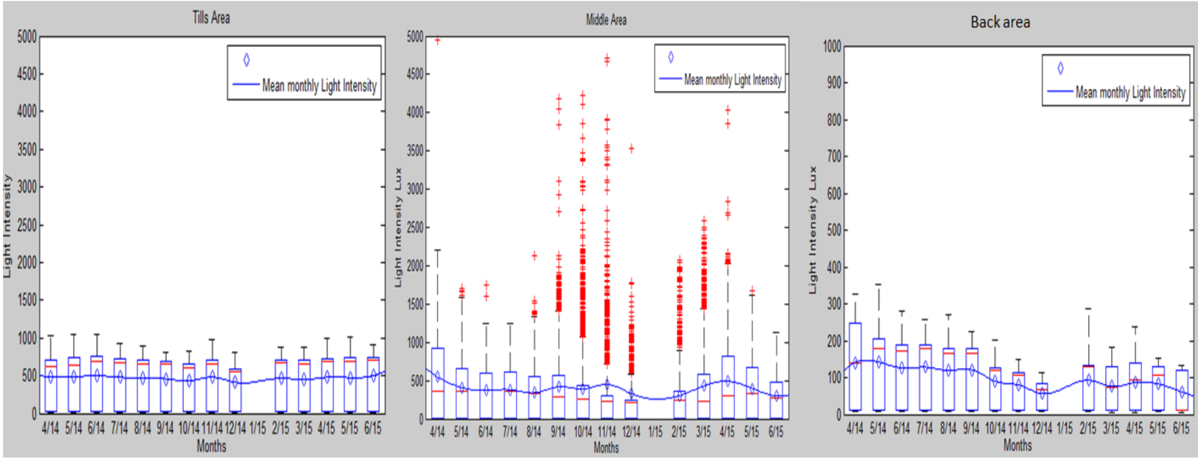


Figure 4-24: BWM plot of measured light intensity data, CS1

Figures 4-25 and 4-26 visualise the results and the stratification of the temperatures inside the sales area for two extreme conditions (warmest and coldest day) and on a moderate day of March 2014 (figure 4-27 and 4-28). The 3 axis figure describes the floorplan of the sales area (x-axis: distance of the front side from the entrance, y-axis: distance of the sides from the entrance) and the temperature measured from the sensors (z-axis). The average of the sensors in different heights has been used as there was not significant stratification between them. Moreover, temperatures areas that are not represented by a column or sensor are interpolated temperature derived from the nearest neighbour sensors.

During the warmest time, the tills area and the south-west side are the warmest areas in the sales area (23-25^{o}C). 1^{o}C above the set point temperature was the central point of the sales area and the back area. This is due to the accumulated refrigeration load of the area which is approximately 0.5 kWh/m^2. The north-east side of the middle area was the one that was around the set point temperature even at the warmest time of the monitoring period.

During the coldest time of the monitoring period (non-trading time) only the tills area observed with 2-3^{o}C lower than the set point temperature while the rest of the sales area was around 20^{o}C. Heat losses from the single glazed facades affect significantly the inside temperature and as the HVAC is in operation 24h, the HVAC energy use and consequently the total energy use.

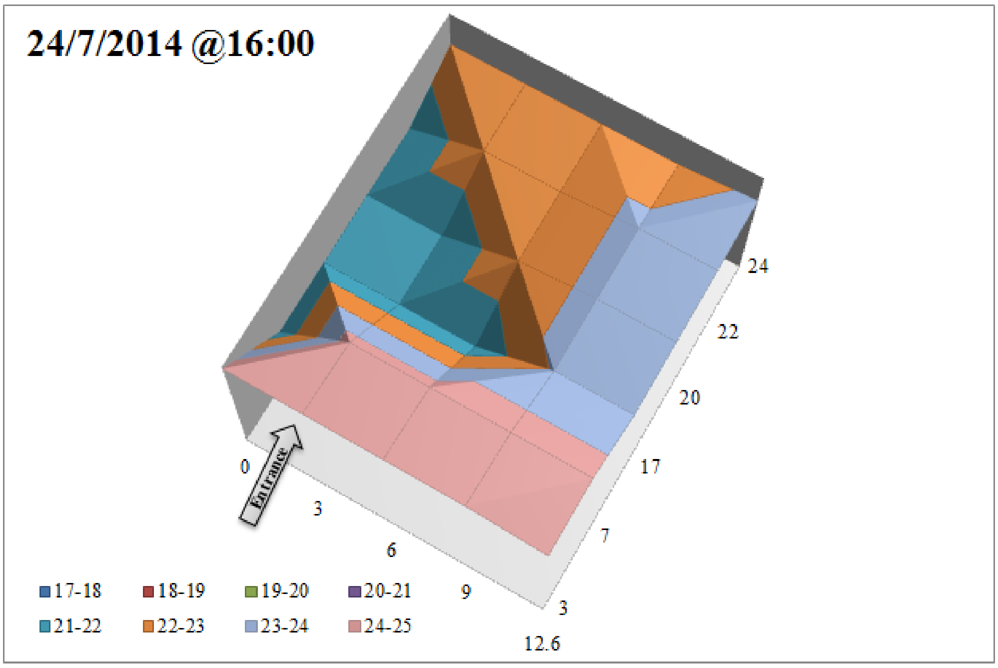


Figure 4-25: Temperature stratification in the sales area during warmest time of the monitoring period, CS2

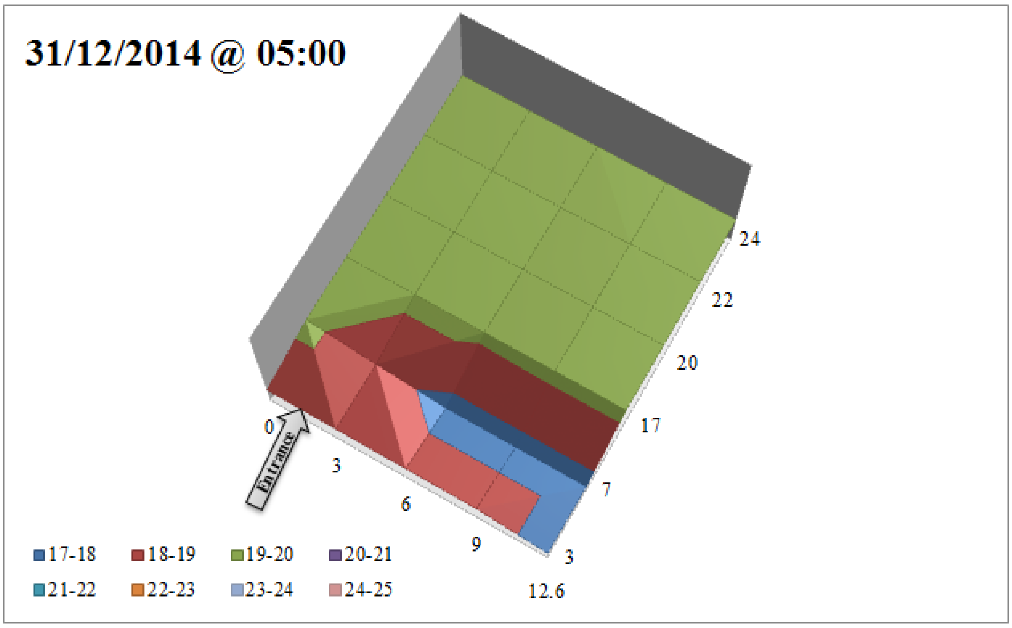


Figure 4-26: Temperature stratification in the sales area during coldest time of the monitoring period, CS2

For a mild day in UK (average temperature 11^{o}C) the conditions inside the store during trading times are quite stable with the tills and the back area to present slightly higher temperatures (21-22^{o}C) while the middle area temperature balances around the set point temperature (figure 4-27 and 4-28). During non-trading times there is bigger stratification inside the sales area with the back area to have the highest temperatures due to high refrigeration load in this area and the tills area to have the lowest recorded temperature; 1-2^{o}C less than the set point. As it was observed in the trading hours as well, middle area's recorded temperature was around 20-21^{o}C.

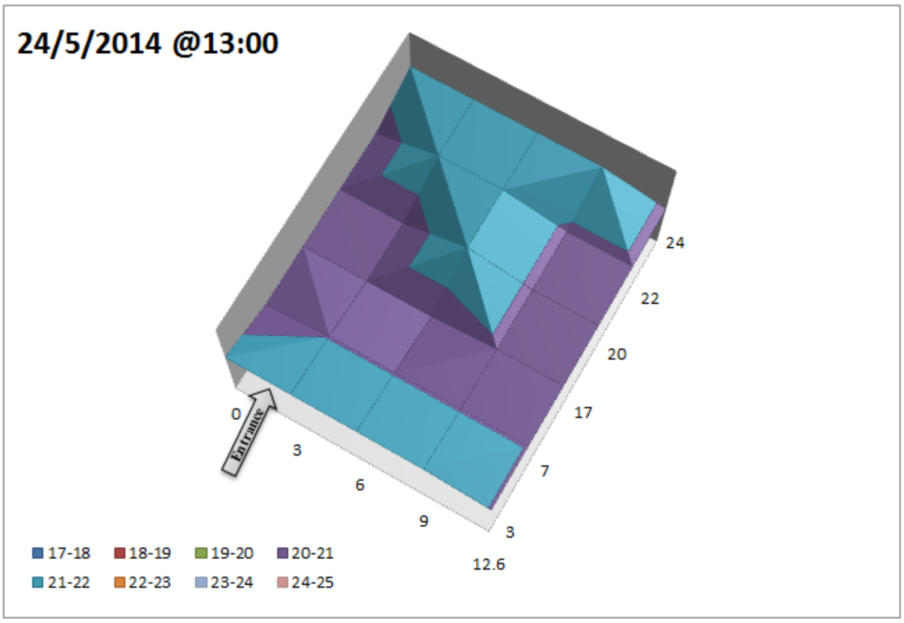


Figure 4-27: Temperature stratification in the sales area during a moderate outdoor temperature of the monitoring period, trading hour, CS2

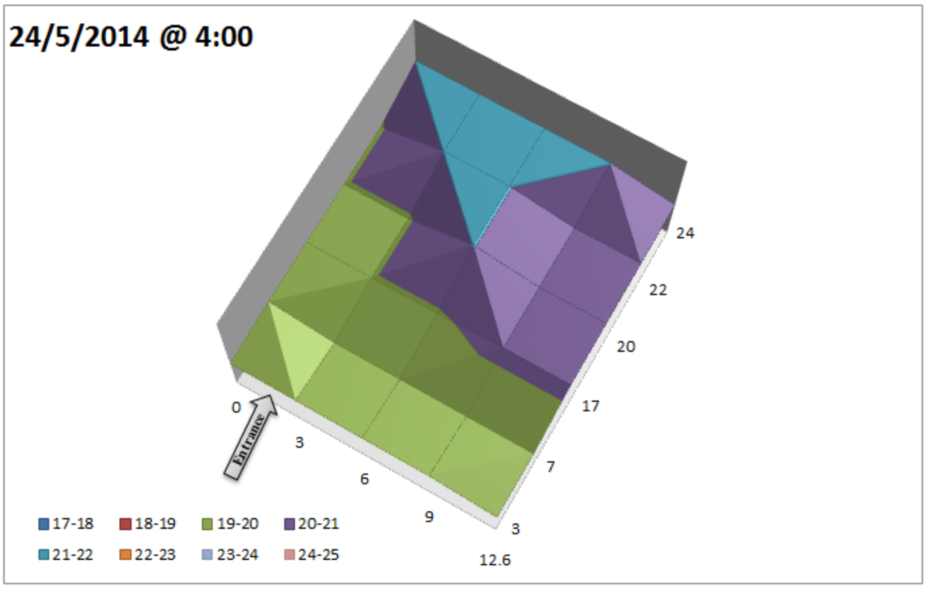


Figure 4-28: Temperature stratification in the sales area during a moderate outdoor temperature of the monitoring period, non-trading hour, CS2

Figure 4-29 presents internal air temperature daily pattern of the data loggers in the sales area on two indicative days with different external conditions (3rd and 19th of May 2014) correlated with the daily energy use per sales area and the external air temperatures. In comparison with the results from the CS1 and due to the 24h HVAC operation, the temperature inside the store during trading and non-trading times is similar. During the warmer day (19/5/2014) slightly higher temperatures recorded during the day with the tills area to have the higher temperatures which agrees with the previous figure (4-25). Air infiltration through the open cabinets in the back area keeps the temperature of the back area slightly lower (1°C) than the other areas of the store during trading times. For a coldest day (3/5/2014) the temperature inside the store was by 1-2 °C lower with the tills area to be the coldest part during the night and the back area during the day. Heat gains/losses from the single glazed front façade affect the temperature of the tills area while during the day when the infiltration from the open cabinets of the back area takes place, temperature in the back area is the lowest recorded one. It can be also observed that during night and despite the outside temperature difference of the two indicative days, the total recorded energy use is similar. During trading times total energy use is almost 29% higher than the total energy use of the colder day.

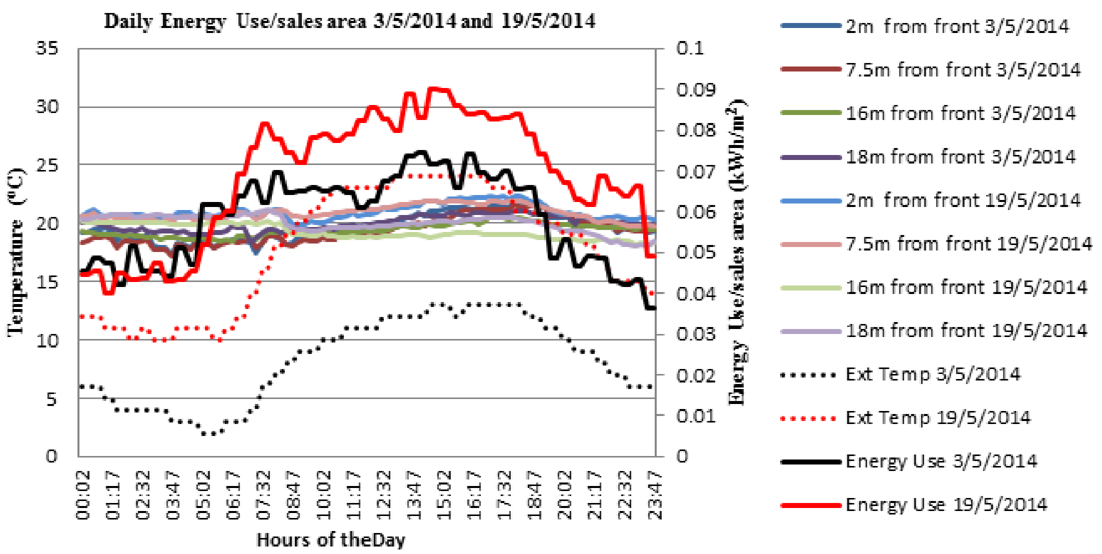


Figure 4-29: Daily pattern of sensors' measured temperature in correlation with external temperature and energy use, CS2

4.2.3 Storage areas

Products and especially food products must be kept at safe temperature during storage as well as during display. According to Handbook for Refrigeration by ASHRAE (2014), the dry storage temperature determines the life period of the products. If the temperature exceeds 21°C at 60% relative humidity then, the storage period of a significant amount of products decreases (ASHRAE, 2014).

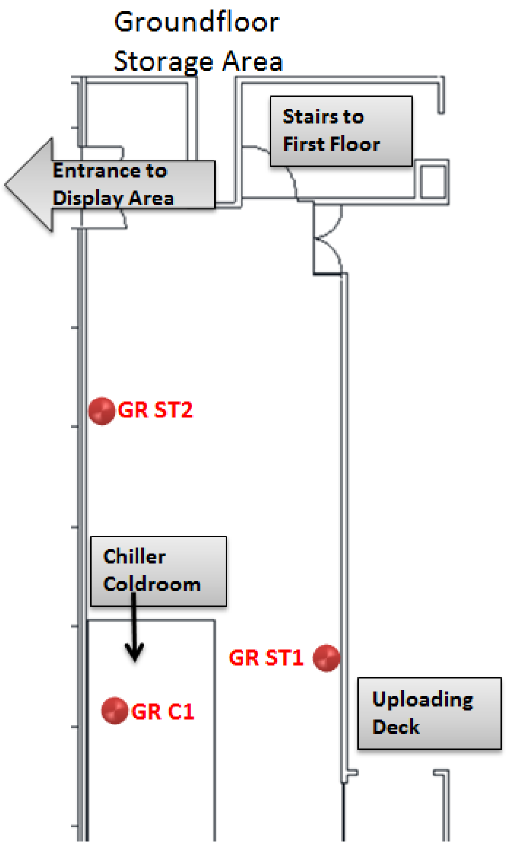


Figure 4-30: Groundfloor storage area and sensors locator, CS1

CS1 has two different areas for dry storage of products; one in groundfloor back area of the sales area where the chiller coldroom is located and one in first floor where the Freezer coldroom is located. Three different data loggers were used to monitor their environmental conditions in terms of temperature and relative humidity and Figures 4-31 presents in BWM plots all the temperature recorded data with 15min intervals. According to them the storage area present a variation of temperatures; GR ST1 measured higher temperatures (2-3 °C) than GR ST2 during the monitoring period and this is mainly due to the location of the data logger which is opposite to the coldroom's refrigeration system which heat is exhausted in the storage area. The average temperature of this area during the monitoring period varies between 16 °C to 26 °C and for GR ST2 was 19°C to 22.5°C. The difference temperature during day and night for both sensors is approximately 2 °C for all the monitoring months. The highest values for both sensors recorded for July 2014 which was the months with the warmest days of the year.

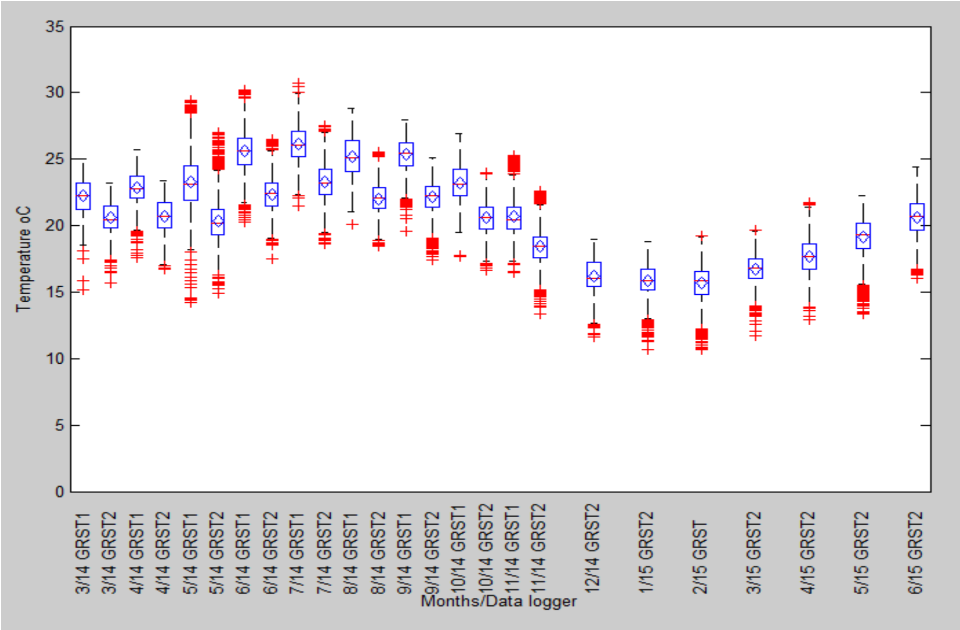


Figure 4-31: BWM plot of measured temperature data, groundfloor storage area, CS1

Regarding the first floor storage area (figure 4-32), two data loggers were used; one just opposite the freezer coldroom door and one in the centre of the main storage room. The average temperature during the monitoring period was 12°C to 24°C. There is no heating/cooling inside the first floor storage and the front side has single glazed windows and this is the reasons why the temperature inside the store are highly correlated with the external temperature. Temperature in the groundfloor storage was higher due to the internal heat gains from the mounted mono-block refrigeration system of the chiller coldroom.

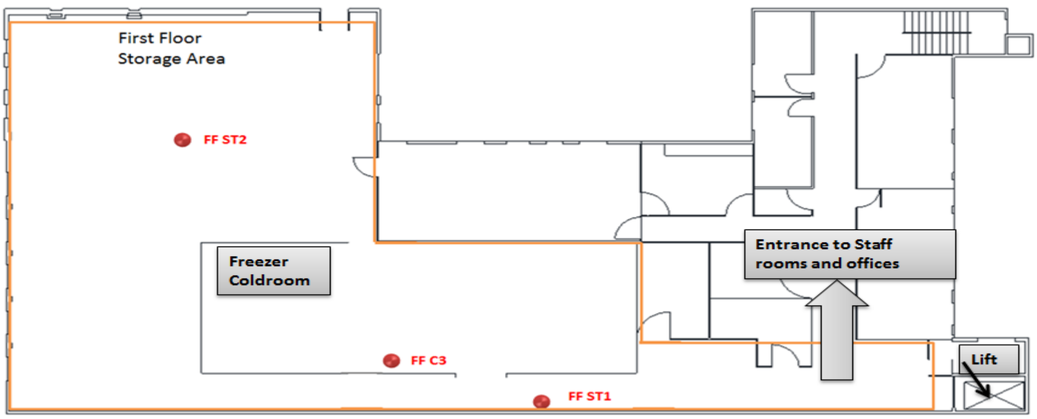


Figure 4-32: First floor storage area and sensors locator, CS1

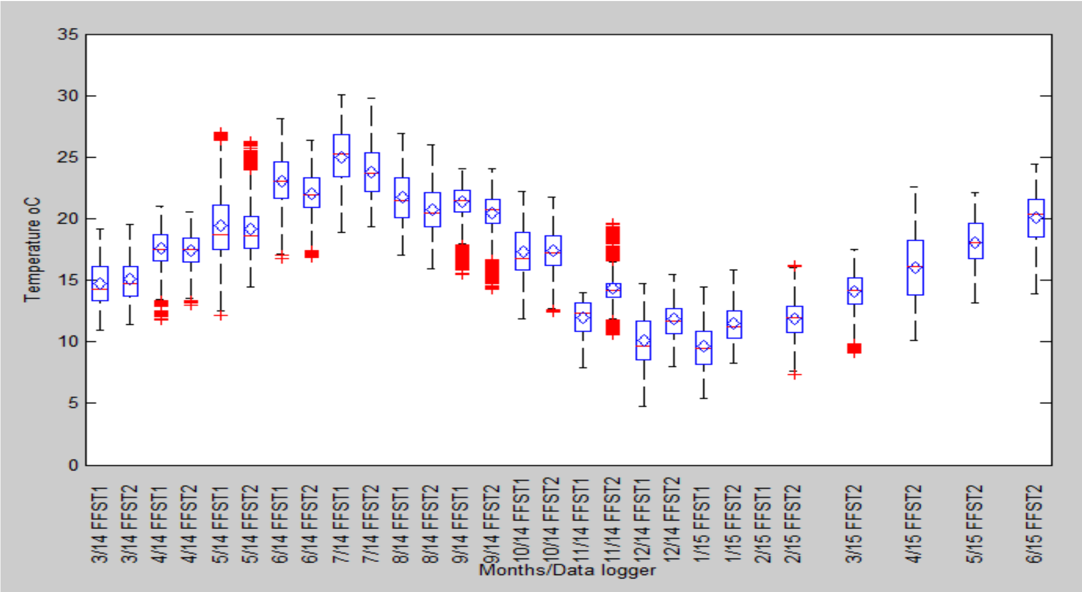


Figure 4-33: BWM plot of measured temperature data, first floor storage area, CS1

Regarding the RH, both groundfloor and first floor storage area did not have values more than 60%; 20-60%. Above 21^{o}C the RH remain below 60% which means no actions should be taken in order to prolong the storage period of products according to ASHRAE (ASHRAE, 2014).

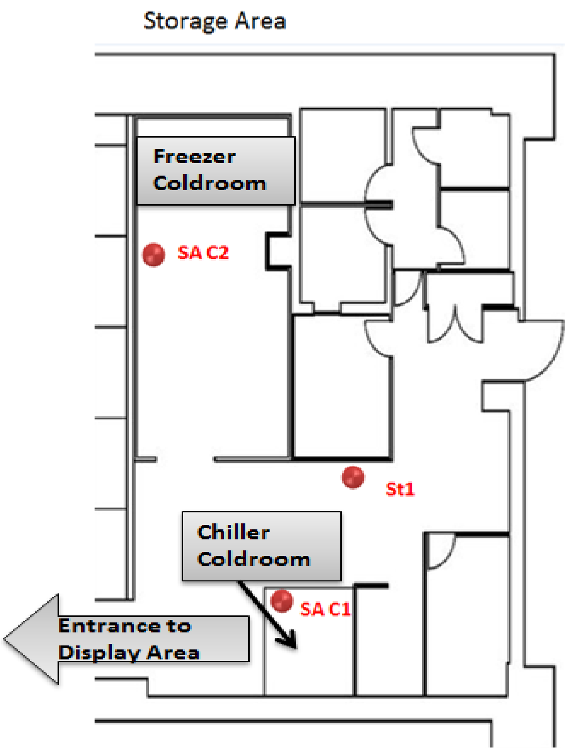


Figure 4-34: Storage area and sensors locator, CS2

CS2 storage area was monitored with one data logger which results are show in figure 4-35. There is no heating/cooling in the storage area as similar to CS1. The only heat gains are from the heat exhaust from the mono-block mounted chillers coldroom refrigeration system and heat losses from the open/close of the coldrooms doors. The average temperature of the area varied from 16^{o}C to 22^{o}C. Moreover, during colder months it can be seen that there is insignificant variation between day and night temperatures while during warm periods there is a different 2-3 ^{o}C.

RH of the CS2 storage area measured from 30-70 %. The percentage of the RH which measured higher than 60% was 5.5%. This should be taken into account for the storage period of the products according to ASHRAE (ASHRAE, 2014).

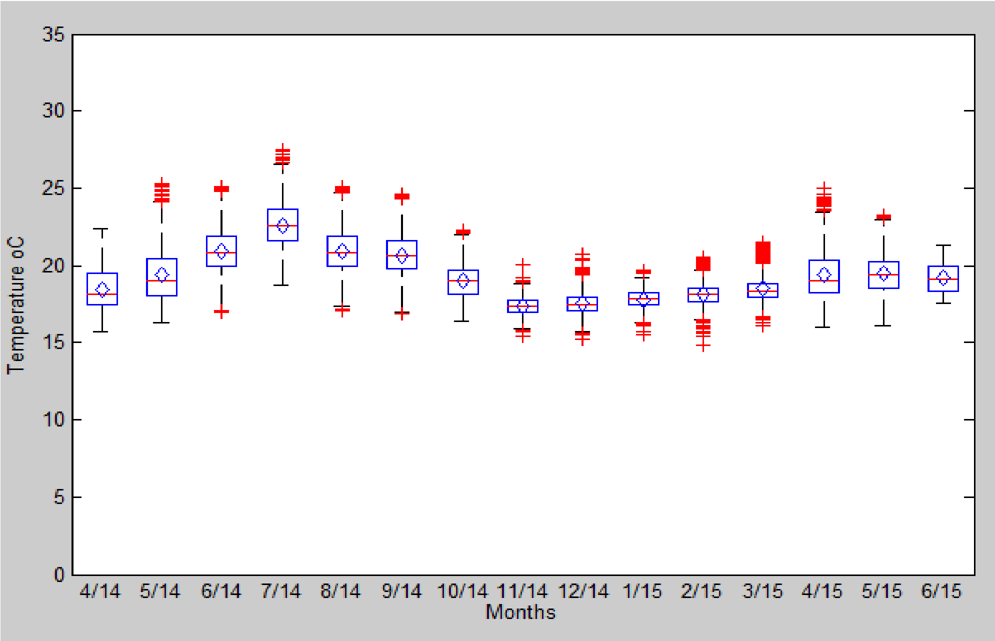


Figure 4-35: BWM plot of measured temperature data, groundfloor storage area, CS2

4.3 Refrigeration equipment data analysis

4.3.1 Coldrooms

Cold rooms are refrigerated spaces large enough for the users to walk in these spaces when loading and unloading the shelves with products. According to ASHRAE the retail stores require walk in coolers and freezers for food products. Walk in coolers are required to maintain temperature between -2 ^{o}C and 4 ^{o}C. Moisture conditions must also be confined to a relative narrow range because excessive humidity encourages bacteria and mould growth, whereas too little moisture leads to excessive dehydration (ASHRAE, 2014). Moreover, according to EPA, high relative humidity in cold rooms is a particular problem and leads to black mould build-up on walls and ceilings and the humidity should stay less than 60% to prevent mould growth which starts appearing at higher than 70% relative humidity (EPA, 2012).

Both case study stores have 2 walk in coldrooms within the storage areas and details about the equipment can be found on Chapter 3, section 3.3 and 3.4. The chiller cold room has plastic strip curtains at the door that lead to the minimum increase of the cold room temperature (~ 3-5 ^{o}C) when the door is open.

Chiller coldrooms monitoring data (figure 4-36 and 4-37) show that temperature vary -2 to 5 ^{o}C for CS1 while for CS2 temperatures measured between 2-3 ^{o}C.

Average relative humidity of the chiller coldroom of CS1 varied from 60-65% while there are significant periods that the RH reached up to 70%. Similarly to temperatures, CS2 average RH of chiller coldroom did not present big variations and measured around 72%. According to ASHRAE, caution should be given if the RH exceeds 70% for significant period.

Figure 4-38 presents a typical week for both chiller coldrooms. CS1 had significant fluctuations during the days while only Sunday appears to be more stable due to the fewer trading times and less transactions (Section 4.5). In CS2 chiller coldroom there are not significant variations of the temperature inside the chiller coldroom and the peaks occurs mainly during the start-up/close of the store when the stocking of the products takes place.

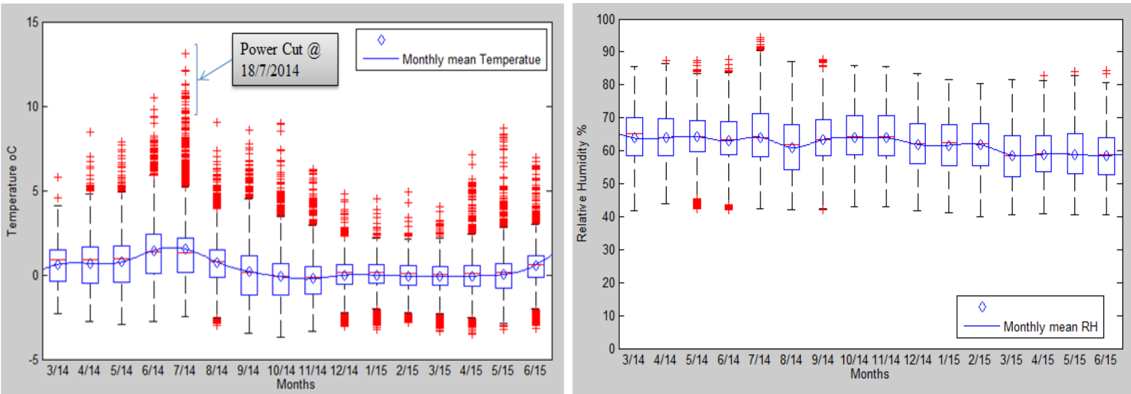


Figure 4-36: BWM plot of measured temperature and RH data for chiller coldroom, CS1

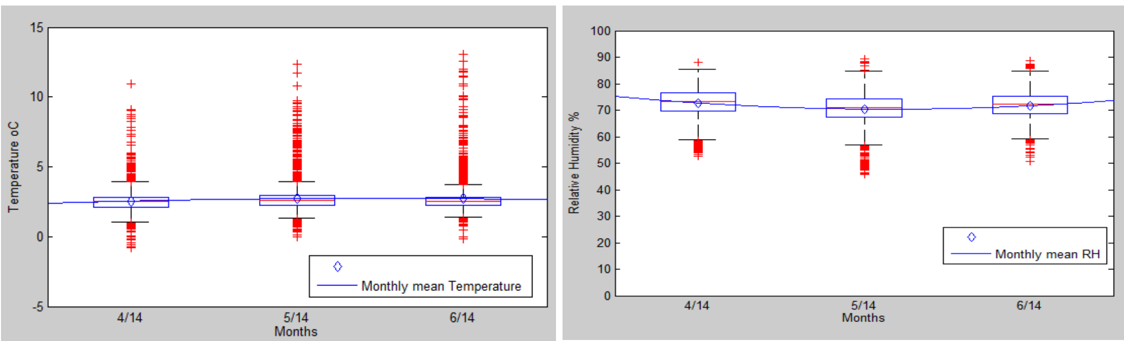


Figure 4-37: BWM plot of measured temperature and RH data for chiller coldroom, CS2

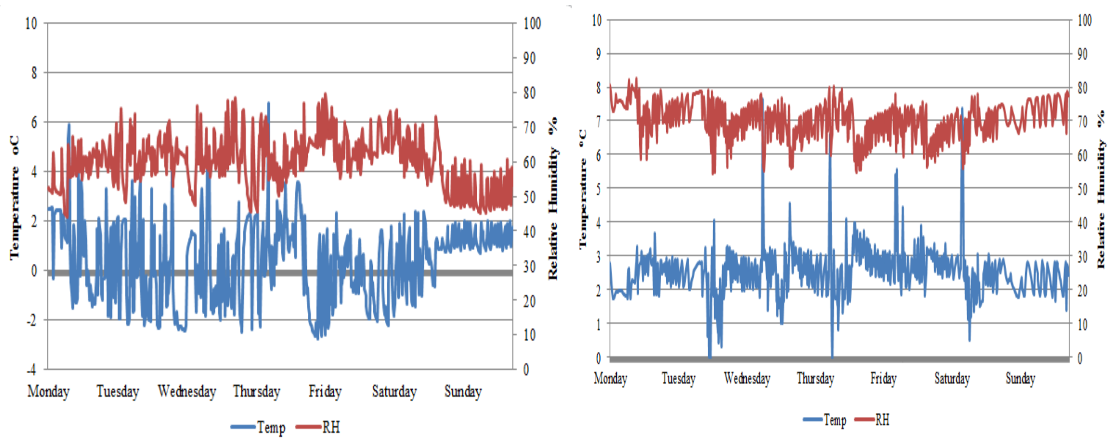


Figure 4-38: Temperature and RH data during a typical week for chiller coldrooms, CS1 (left) and CS2 (right)

Freezer coldroom of CS1 has an average temperature of -23^{o}C during the monitoring period which slightly increases during summer months. Average relative humidity remained stable during the months, approximately 65%. A 7.7% of RH measurements were above 70%. During months with higher external temperatures, hence storage temperatures where the cold room is located, higher temperatures inside the coldroom were measured (red-cross outliers).

Similar temperatures and RH results (figures 4-39 and 4-40) were measured for CS2 freezer coldroom. Due to missing loggers, only two months data are available for this case study. However, average temperature measurements were -23^{o}C and approximately 70%. Only 5.5% of the RH measurements were above 70% RH.

Figure 4-41 present a typical week for both freezer coldrooms. Temperatures during the day slightly varies between -20^{o}C and -23^{o}C and slightly lower for CS2. The peaks occur before and after the trading times when the staff is dealing with the restocking of the products from the display cabinets. Similar weekly pattern is observed for CS2. Relative humidity during the days is approximately 60-70%.

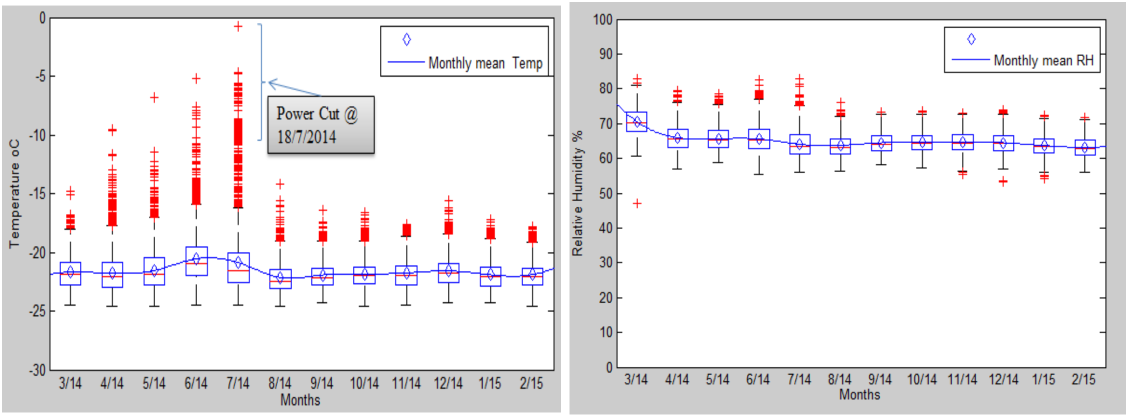


Figure 4-39: BWM plot of measured temperature and RH data for freezer coldroom, CS1

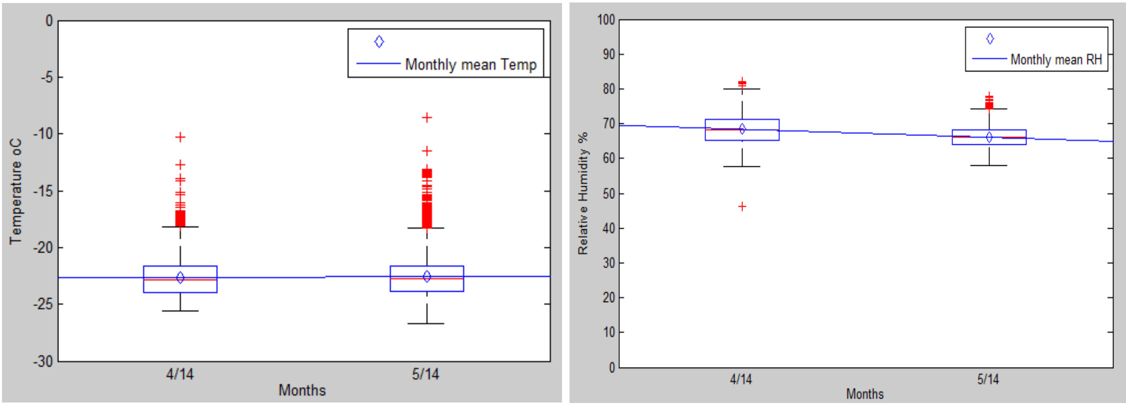


Figure 4-40 BWM plot of measured temperature and RH data for freezer coldroom, CS2

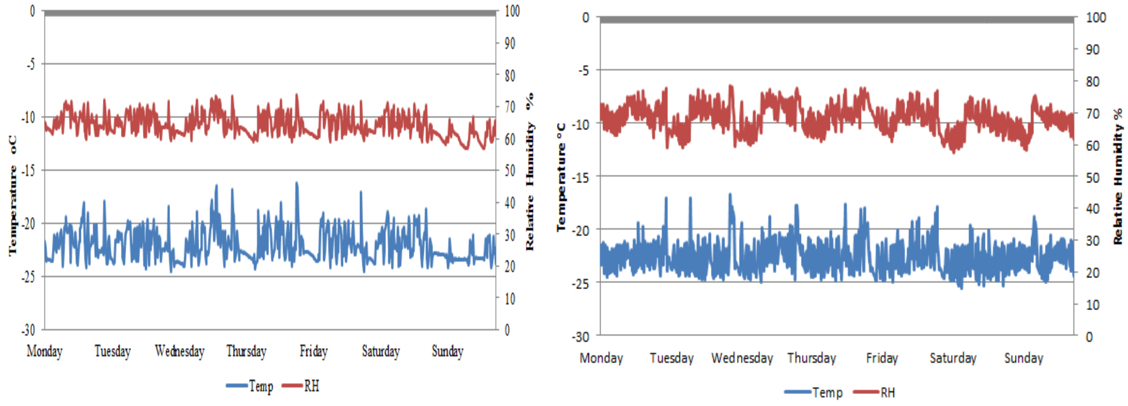


Figure 4-41: Temperature and RH data during a typical week for freezer coldrooms, CS1 (left) and CS2 (right)

4.3.2 Lift up lid cabinet monitoring

4.3.2.1 Lid's opening/closing state

During 19 days of monitoring period, a total 1077 lid openings were logged. The mean lid opening duration was 14.1 seconds including the staff restocking action. The longest lid opening duration was 339 seconds while the shortest lid opening duration was 1 second. Figure 4-42 presents BWM plot with the lid openings' duration during the monitoring period. Durations above 100 seconds are not presented in this figure as they occurred before and after the trading hours and they represent periods of products restocking in the cabinet from the staff. The majority of the lid openings did not exceed the 28 seconds but several biggest durations occurred (red-cross).

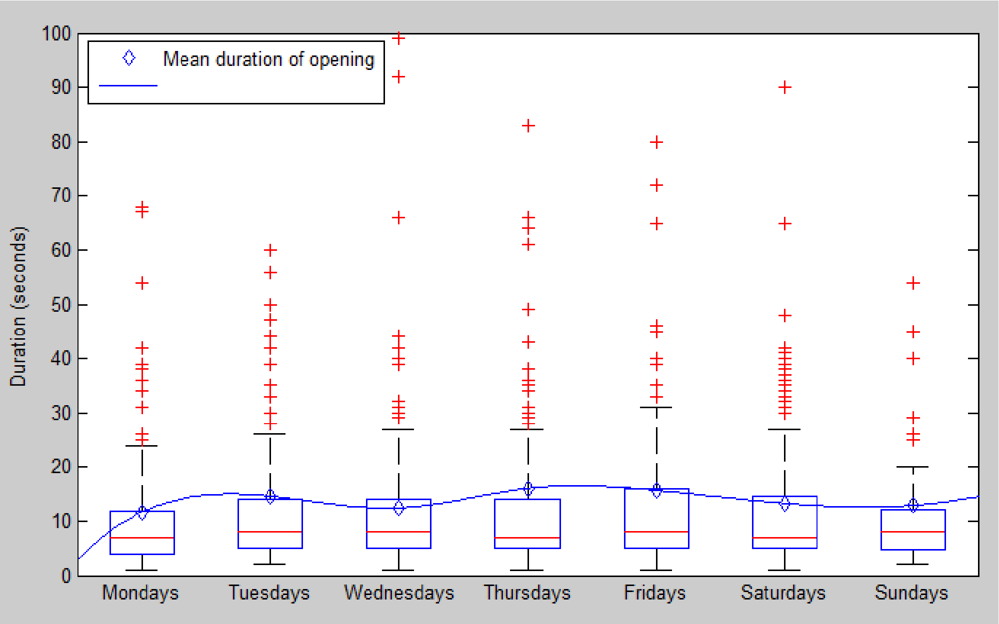


Figure 4-42: BWM plot of lid opening's duration for a week

From figure 4-43 it can be seen that the vast majority, or the 90% of the lid opening durations were less than 28 seconds. The mean of all lid openings with duration of less than 28 seconds was found to be 8.8 seconds with a standard deviation of 6 seconds. Moreover, it can be seen that the mode of the lid opening (the duration that occurs the most frequently) was 4 seconds.

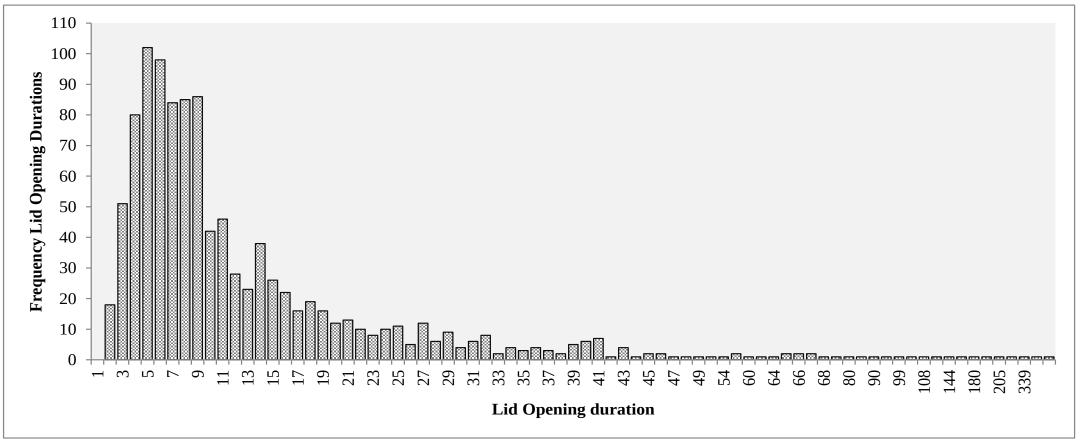


Figure 4-43: Frequency of lid openings' duration

It was also found that the mean lid opening frequency per hours was 4-8 times (figure 4-44). The highest frequency occurred on Saturdays which is considered the busiest day and the day that the biggest number of daily transactions have been recorded.

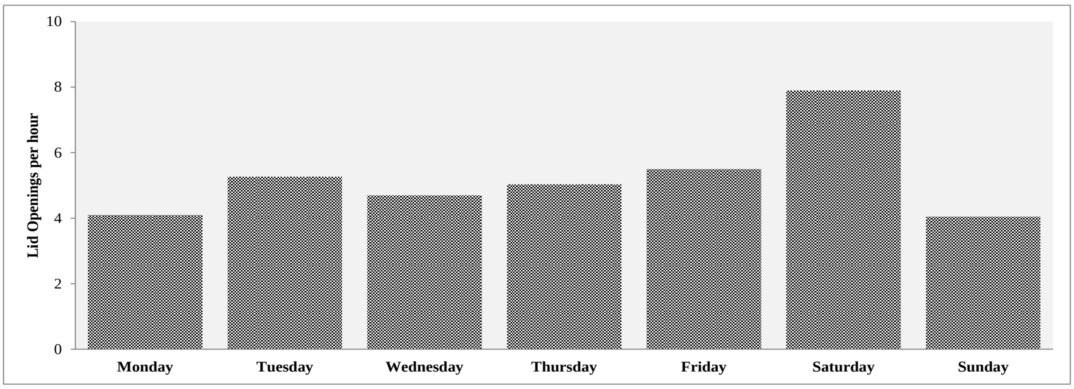


Figure 4-44: Lid openings per hour during a week

4.3.2.2 Cabinets' energy Use

This section presents the power monitoring results of a lift up lid cabinet as it was held in store during 7 operational days. These results were used not only for evaluation of the cabinet energy use regarding the opening/closing of the lid, but for model validation purposes as well as it will be analysed in chapter 5.

Figure 4-46 presents all energy data as they were recorded in correlation with the temperature data inside the cabinet in two different heights and the temperature 0.5m above the cabinet. The temperature inside the store was similar in both heights during all the days and the temperature 0.5m above cabinet was approximately 15^{o}C both during days and nights. Moreover, due to its location is not affected from the HVAC system and thus is only affected from the heat exchanged from the glass lid of the cabinet.

According to store's manager, there was a manual cut off of the refrigeration system for defrosting purposes. It started on Wednesday after the closing of the store until 2 hours before the start-up of the next day. This is something due several Wednesdays over a month.

The average daily energy use of the cabinet measured 2.4 kWh.

Figure 4-45: Temperature data logger above the monitored lift up lid cabinet

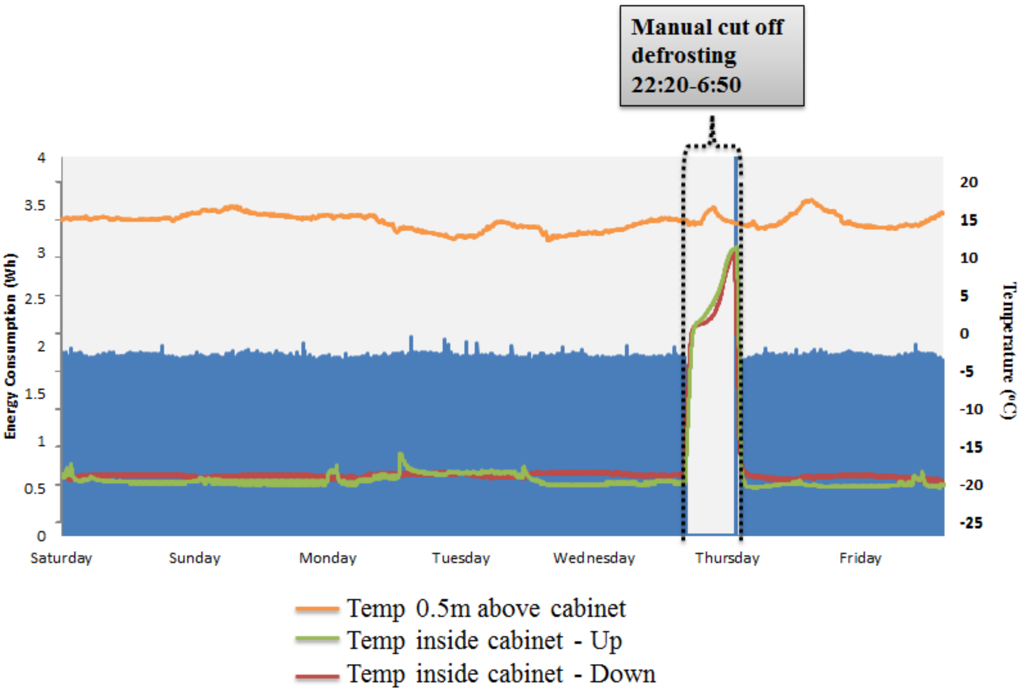


Figure 4-46: Cabinets hourly energy use in correlation with the temperature inside the cabinet and the ambient temperature 0.5 above the cabinet

Figure 4-47 presents the pattern of the energy data of the cabinet during the trading times of a day in correlation with the opening/closing of the lid. The average off cycle periods were around 9 min (Table 4-2) and the average period that the compressor is ON to achieve the setpoint temperature were 12.5min. It can be observed that after bigger duration of continuous opening of the glass lid, the compressor is on for bigger period of time.

Table 4-2: Compressor's operation duration

	Duration (min)
Compressor operation: OFF	
Average Off-cycle	9
Compressor operation: ON	
Average	12.5
Biggest	18
After defrost	68.5

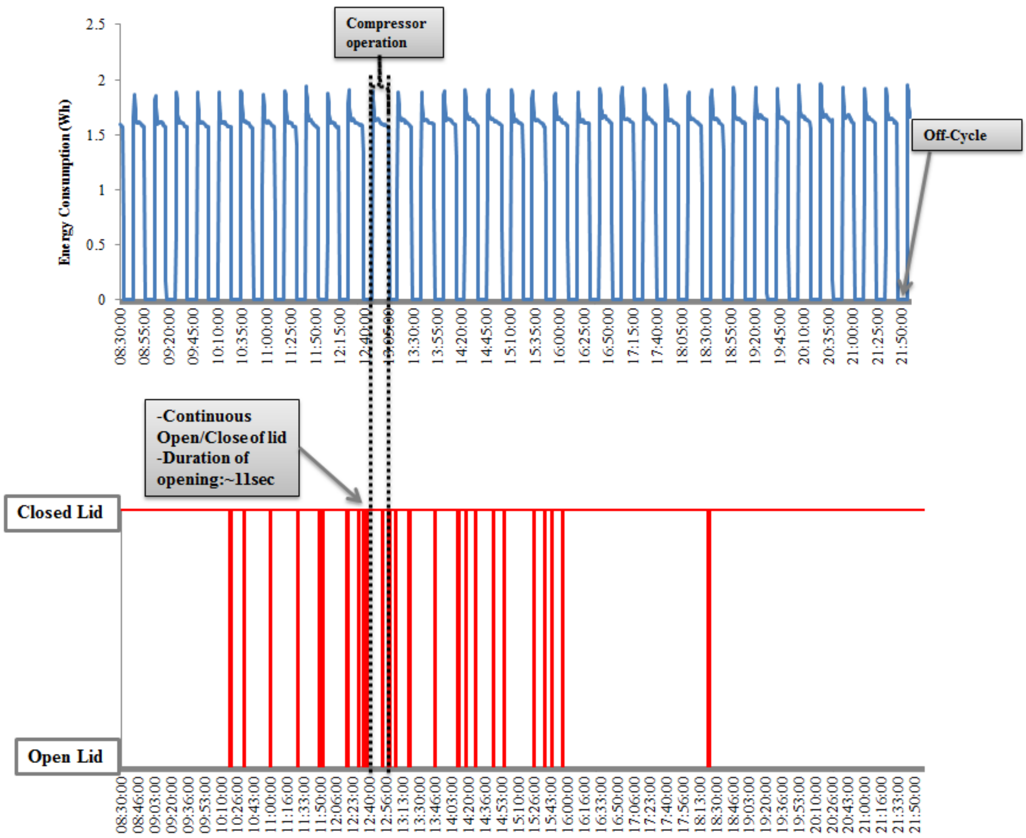


Figure 4-47: Cabinet's energy use during trading times in correlation with opening/closing of the lid

4.3.2.3 Lift up lid cabinet laboratory measurements

The same frozen food lift up lid cabinet was monitored in an environmental chamber room in the lab facilities of the CSEF centre. The purpose of this monitoring was to evaluate the cabinet's energy use and the surface temperature of the glass lid in correlation of different ambient conditions.

Figure 4-48 presents the monitoring results of the surface temperature; inside and outside of the glass lid and the temperature inside the cabinet as well. The monitoring results are for 48 hours. Surface temperature, which remains stable during the monitoring period increases when the ambient temperature is higher. During the test with the lowest ambient temperature (10^{o}C) the surface temperature did not fall lower than 7^{o}C. The same applies for the inside surface temperature of the glass lid (dashed lines). Results shows that the inside surface temperature is similar to the outside ones and that the temperature inside the cabinet does not affect this temperature. The temperature inside the cabinet differs approximately 1^{o}C in correlation to different ambient conditions although the set point operating temperature was the same for these conditions.

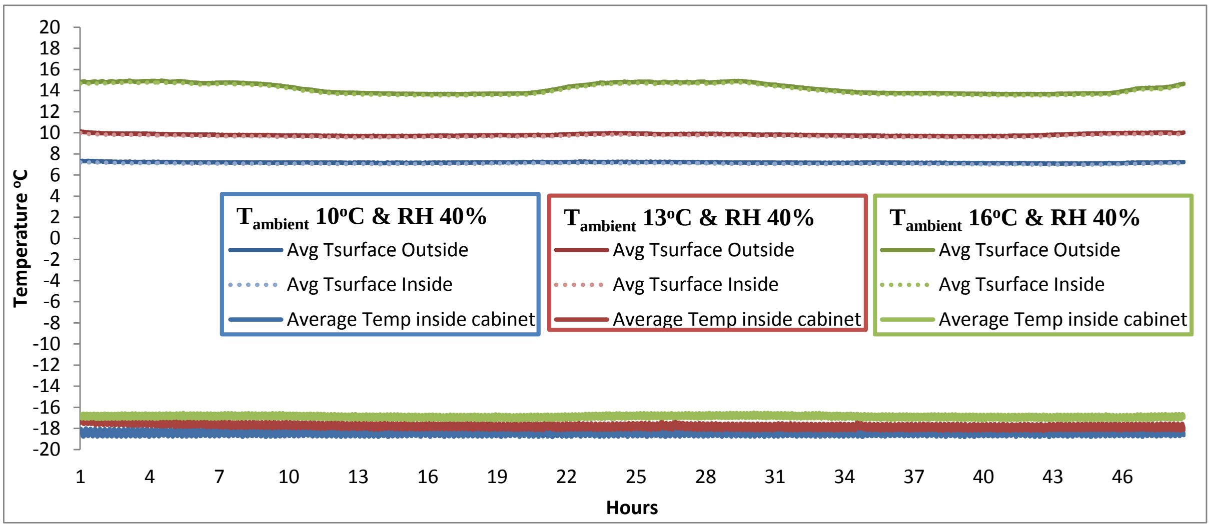


Figure 4-48: $T_{surface}$ of the glass lid and temperature inside the cabinet

Figure 4-49 presents the average daily energy use of the cabinet in different ambient conditions. Lower ambient temperatures lead to lower daily average energy use.

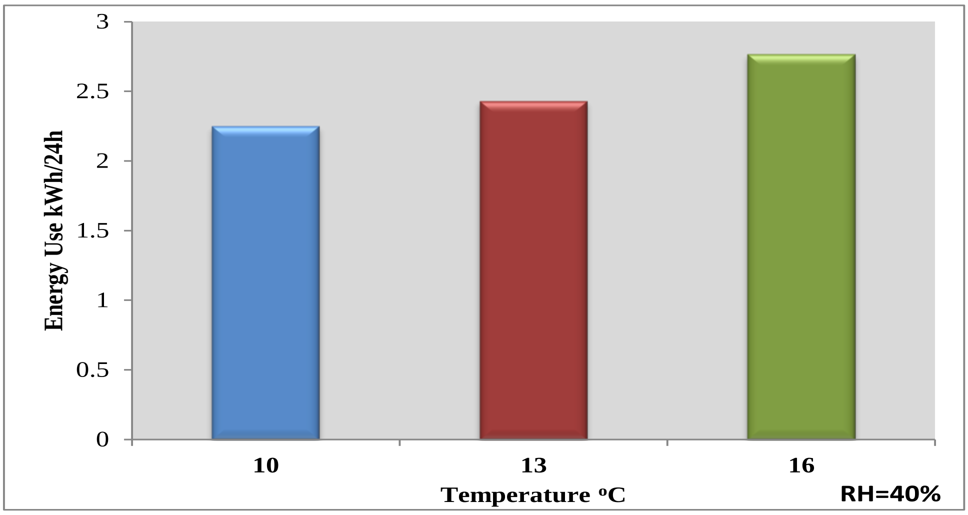


Figure 4-49: Daily average energy use of the cabinet in different ambient conditions

These measurements play important role for the control strategy of the night free cooling inside the case study stores when the goal is to reduce the temperature inside the store as low as possible in order to reduce the cooling demand of the stores. The ambient conditions inside the stores effect the refrigeration cabinets operation in terms of energy use and display conditions (condensation of the glass lids). According to monitoring results, the surface temperature of the cabinet's glass lid is not affected significantly from the temperature inside the frozen food cabinet but from ambient conditions and does not fall to low enough temperatures where the high relative humidity could create condensation problems. Taken into account that at 10°C ambient conditions the surface temperature of the glass lid is around 7°C, RH should not exceed 85%.

4.4 Transactions and customers data

Figure 4-50 presents in box plots of the daily transactions data that were available for both case study stores. Higher numbers of transactions are taken place in CS1; almost double the number of CS2 for all the days of the week. The average daily transactions during weekdays and Saturdays is approximately 1650 and 750 for CS1 and CS2 respectively. A peak is observed on Saturdays due to the customers' preference of shopping during non-working days. The lowest daily transaction on Sundays is due to lower operating hours of the stores. The highest transaction for both stores was observed during Christmas Eve and the lowest during boxing and New Year's Eve.

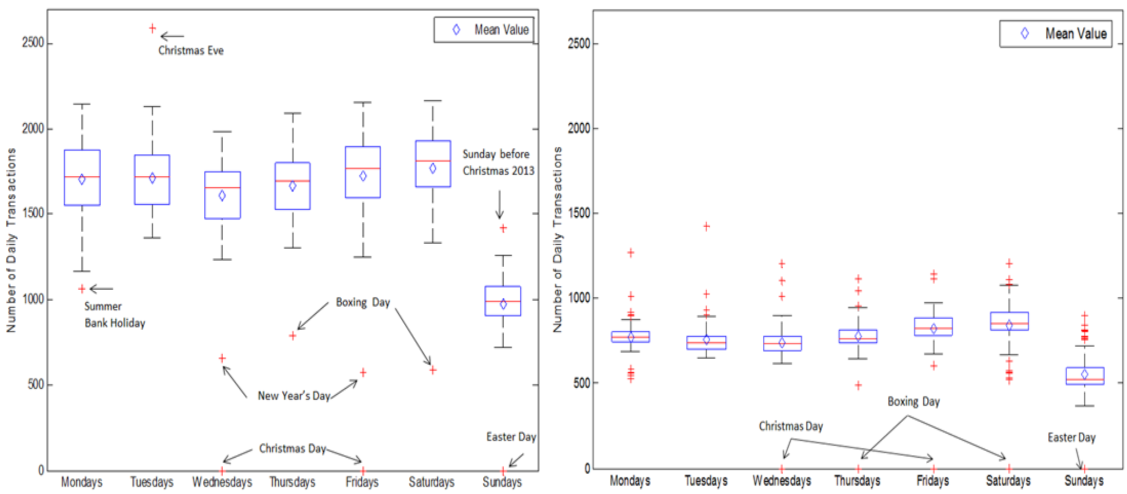


Figure 4-50: BWM plots of daily transaction data, CS1 (left) and CS2 (right)

Table 4-3 presents the data from the spot observations of the customers in the sales area. Significantly higher is the average number of the customers observed both in tills and display area in CS1. It is a bigger store and in a central commercial area and customers results agreed with the high transaction data (figure 4-50). The location of the CS2 which is located in an out of town retail centre and detached to a discounter supermarket store is the reason why the spot observations of customers inside the store resulted in remarkably lower numbers of customers in comparison with CS1.

Table 4-3: Customers density data from spot observations

	CS1: Coupled heating/cooling with ventilation		**CS2: Decoupled heating/cooling from ventilation**	
	Tills Area	Sales Area	Tills Area	Sales Area
Average	27	23	6	9
Maximum	40	35	10	17
Minimum	17	12	0	2

Spot observations for customers in the tills and sales area are presented in the Appendix C.

Chapter's Summary

This chapter described the monitoring carried out in the two case studies. Measurements indicate a relationship between outdoor temperature, energy use and indoor air temperature.

Energy use data showed that the case studies consume energy at the upper range of the supermarkets and at the lower range of the convenience stores. Sub-metering data showed that the refrigeration system consumes 60% of electricity with HVAC at 20%. After lighting system upgrade with LED system in October 2015, a bigger reduction in monthly energy use was observed in CS1 rather than in CS2 due to bigger in sizer sales area which requires bigger amount of lamps.

Indoor air temperature measurements in CS1 show bigger variation in comparison with CS2 although the set point is the same. CS1 indoor air temperature during trading times is maintained around set point apart from warmer months when the temperatures are 3^{o}C higher that set point. CS2 indoor air temperature does not vary significantly within the year although indoor air temperature is strongly correlated with the outdoor temperature. The 24h HVAC operation along with the smaller in size sales area justifies the higher energy use for CS2 in comparison with CS1.

The laboratory measurements of the frozen food cabinet illustrate that decreasing of the ambient temperature inside the stores; reduce the energy consumption of the cabinet by 10-15%. Surface temperature of the glass lid shows that there is no risk of condensation while night cooling is in operation.

Transactions data showed twice in size sales and significantly higher customers density in CS1 in comparison with CS2 and this can be explained die to the location of the CS2 which is located in an out of town retail centre and detached to a discounter supermarket.

The above data are used to understand significant input parameters for the EnergyPlus model development and validation in Chapter 5 along with understanding the energy and environmental profile of the two case studies.

Chapter 5

Development of Thermal and Energy Model

Introduction

This chapter presents the development procedure of the thermal and energy model. A supermarket is a complex system where many sub systems interact. Therefore, it is necessary to implement a systems model in order to predict and evaluate the introduction of new concepts and strategies.

5.1 The modelling process

The modelling process is the creation of a reflection of the reality. It consists of different phases from deciding on the reality of interest for the study according to objectives of the study itself to completion of the definitive model that answers the questions of the overall objectives identified in the beginning of the modelling process.

The first phase (Figure 5-1) after identifying the building and evaluating through monitoring its energy use and environmental conditions, is the identification of the objectives of the model development and the components that the model consists in order to evaluate the interactions between them (see section 5.2). Reddy et al. has mentioned that it is mandatory to identify the parameters that affect more significantly the building model accuracy. Once these are determined, the one as that are “weak” parameters can be fixed by nominal values and in this way the number of parameters that need validation is reduced (Reddy et al., 2007).

The next phase is the development of a quantitative model based on the conceptual model that was identified in previous step. For the specific case study supermarket stores, EnergyPlus is the software to create the quantitative model whose objectives and components are implemented in and transformed into physical and mathematical relationships. EnergyPlus has three basic components; (a) integrated solution manager, (b) a heat and mass balance simulation module and (c) a building systems simulation module. The simulation manager controls the entire simulation process. The heat balance calculations are based on IBLAST, a research version of BLAST with integrated HVAC systems and building loads. After the heat balance manager completes simulation for a time step, it calls the building systems simulation manager which controls the simulation of HVAC and electrical systems, equipment and components and updates the zones-air conditions (Engineering Reference, 2015).

The evaluation of the EnergyPlus model is carried by using data from the monitoring results of the real building. Kaplan at al. suggests validating models to short typical periods and not to annual data for example to monthly data (Kaplan et al., 1990).

Once the model is validated, the evaluation process results in sensitivity analysis of model which leads to model applications. At this phase, the EnergyPlus model attempts to explain the identified objectives of the first phase.

The objectives identified in the first step set the limitations and the input details of the EnergyPlus model which lead to several uncertainties. To improve the reliability of the model, changes to the input parameters should only be made according to available evidence such as on site measurements (Raftery et al., 2011). A model should be as complex so it will not insert uncertainties and create answers for the quality and reliability of the model. However, if the model is not complex enough, it cannot be reliable to depict the reality as close as possible.

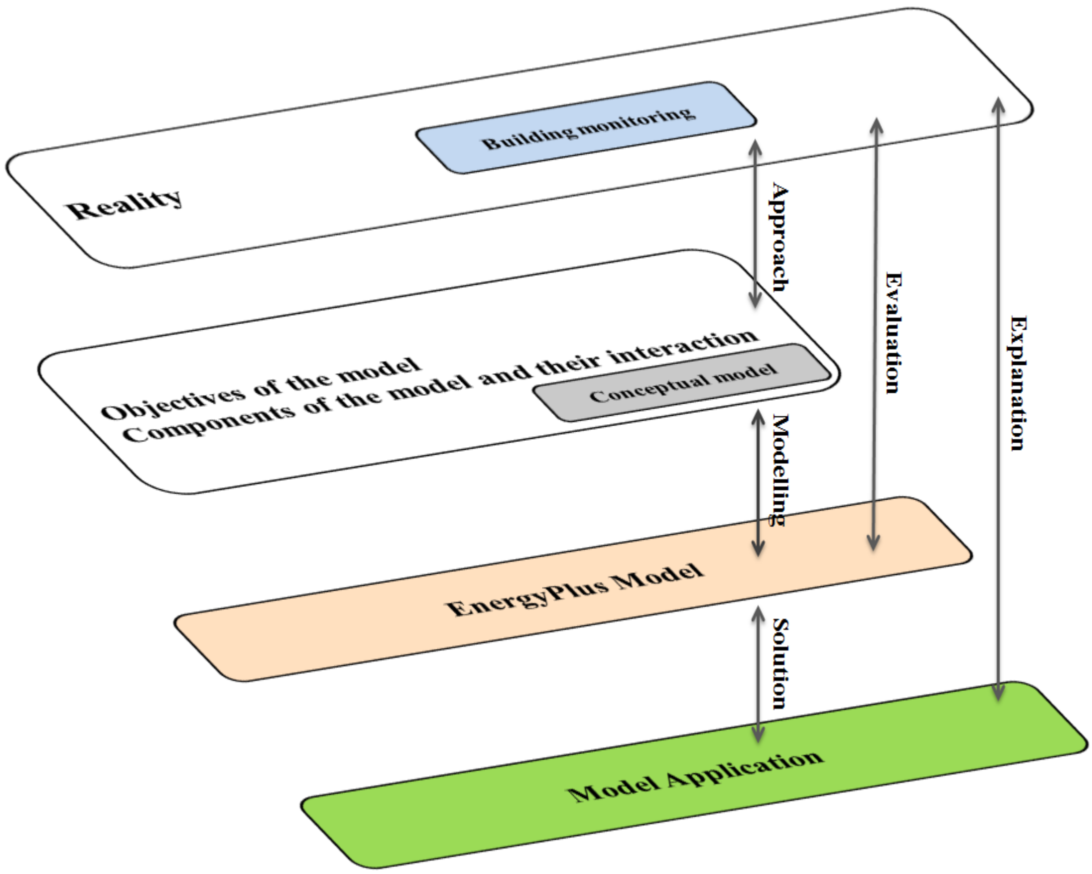


Figure 5-1: Modelling process

5.1.1 Limitations and Uncertainties

Although the validation purpose is to provide an accurate model as defined by the objectives (Figure 5-1), there are several number of limitations. The first one relies to the model itself. Although it is prepared to be as inclusive as possible, there is a number of abstraction and parameters that cannot be inserted to the model and a number of parameters are set to default values without insurance that they affect or not the model. Consequently, there is a possibility that the model will not represent exactly the real building.

Another limitation relies on the availability of data check the accuracy of the model. Even if a calibrated model seems to be accurate, it is not necessarily sure that it is accurate to predict the performance analysis of the building. Moreover, there is a limitation depending on real data regarding the accuracy of them. Measurements error can inset several uncertainties for accuracy of the model.

5.2 Description of model inputs

According to first step the objectives of the model needs to be identified. These are:

- Energy requirements predictions and
- The overall energy performance of the building
- The indoor air environmental predictions in the sales area.

All of them are interdependent and characterise the energy performance of the supermarket. The type of building energy modelling technique is the dynamic simulation which is based on time interval that are user-defined (one hour or less) in order to represent the variations of the model variables and properties of the building model.

Figure 5-2 presents the different systems of a supermarket. It shows different subsystems; (a) HVAC system, (b) refrigeration system, (c) cabinets' equipment, (d) lighting system, (e) customers' occupancy and (f) electrical equipment. These interact with each other and depend on each other.

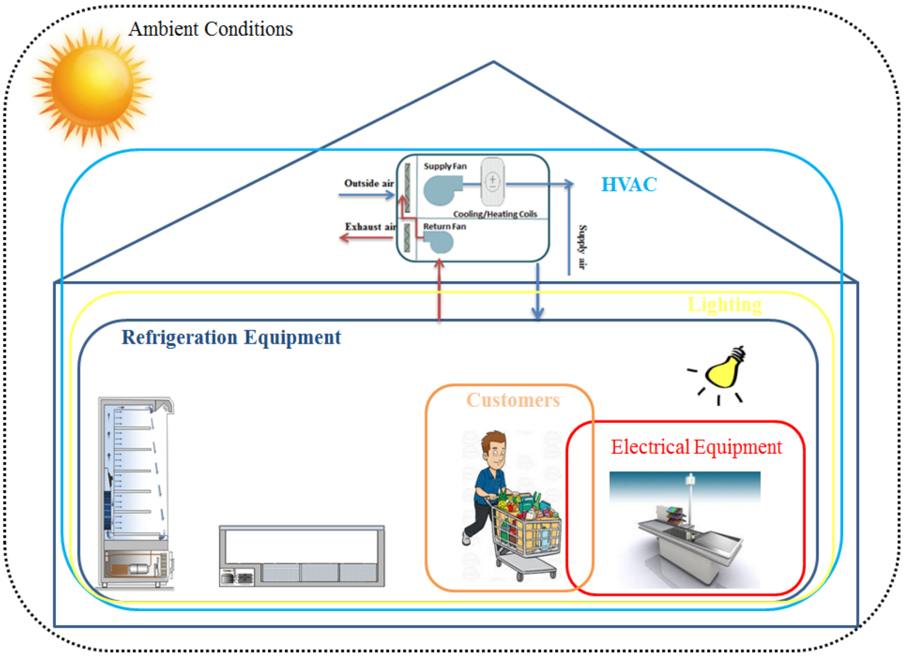


Figure 5-2: Supermarket as a system and its subsystem

Outdoor climate is an important factor. It affects the indoor air conditions through the building envelope, the HVAC system and the refrigeration system if this is indirect. The heating or cooling gains through the building envelope depends on thermal properties and the structural materials. Specific heat capacity, density and thermal conductivity of the envelope affect the heat transfer and storage of energy in the building structure. Infiltration is due to the temperature difference between indoor and outdoor air and wind velocities. Ventilation system supplies air from outside in order to provide comfort and acceptable indoor air quality.

Lighting system, electrical equipment, occupants and refrigeration cabinets affect the HVAC system requirements by adding heating or cooling loads in the supermarket.

Customers and staff emit heat and moisture and affect the heating and cooling loads of the HVAC system. Moreover, carbon dioxide levels in the ambient air of the supermarket affect the ventilation requirements as indoor air quality is needed both for customers and staff.

Indoor air of the supermarket is also affected by the heat and moisture of the refrigeration cabinets. The cold air from the cabinets' exchanges with the surrounding air affect the heating and cooling loads of the stores as the "cold aisle" prevent customers for big visits in the store and subsequently this could also affect the transactions. Refrigeration cabinets require specific ambient conditions for efficient operation in order to reduce refrigeration load and to avoid risk of condensation on products, lids, doors and coils.

HVAC system plays the key factor for the operation of the supermarket as it controls all the subsystems by managing the set point temperatures during trading and non-trading times. It provides desired thermal comfort and indoor air quality for customers and supermarket's staff.

5.3 Methodology of model development

A model for each case study within EnergyPlus was created using data and measurements from the operating stores. Figure 5-3 shows the method followed for the creation and the calibration of the model following available literature (Kaplan et al., 1990) (ASHRAE Guideline 14, 2002) (Reddy et al., 2007). Bertagnolio proposed two levels of model calibration; level 1 modelling is mainly based on available design data to create the as-built model with level 2 modelling to include as-built model and operating information (Bertagnolio et al., 2012)

The level 1 corresponds to the first proposed model which is based on available data (plans and drawings, observations, interviews and surveys, technical characteristics of system components etc.) This step concludes to an initial whole building energy model with separated thermal zones which are available for further upgrade. The detailed envelope composition is included in this step. Plans, drawings, observations and material properties datasheets are used for this step.

At level 2 internal loads (including occupancy) are inputted (lighting, electrical, refrigeration and HVAC systems. Inverse calibration is used in this level. According to Raftery et al, an iterative methodology could be used to update an EnergyPlus model with empirical data. Interviews, occupancy surveys and in situ observations enhance the model calibration (Raftery et al., 2011). Sub metering data from similar stores of the same supermarket chain were used for this purpose as well as the monitoring of the energy use cabinet in the store of CS2 which gave insights for the refrigeration equipment performance. Moreover, data from measured indoor air temperatures and cassettes and diffusers temperatures data are used for the creation of thermal zones temperature set point schedules of the HVAC systems.

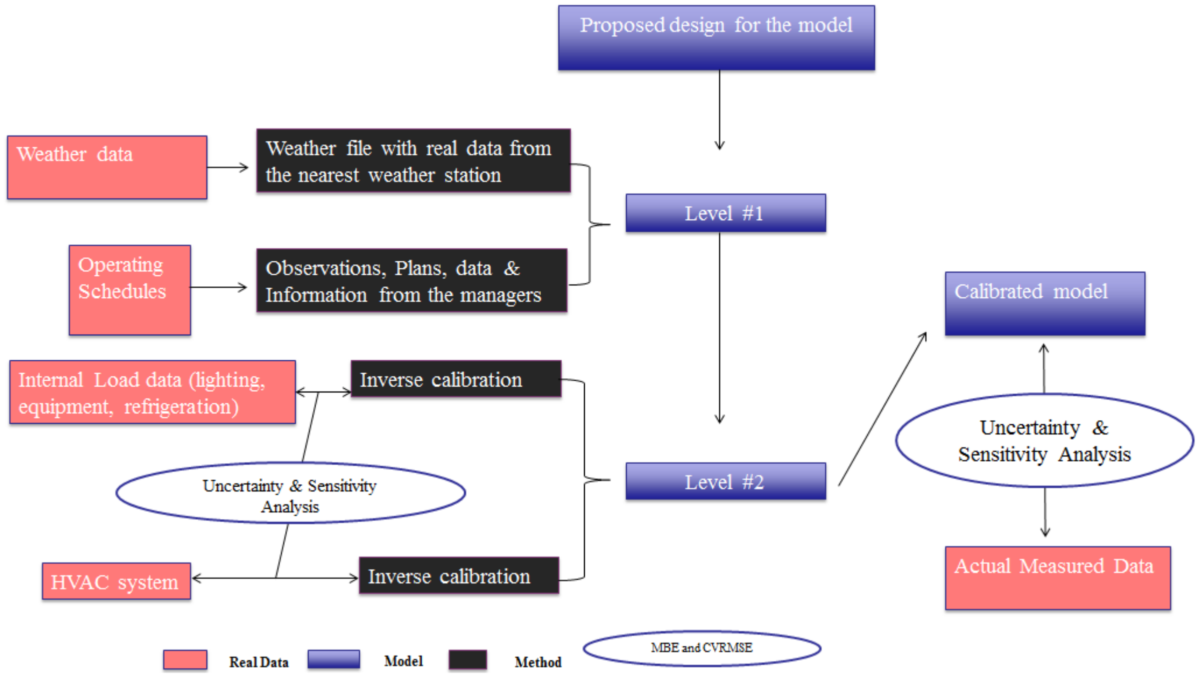


Figure 5-3: Model development and validation methodology

In this way a realistic thermal model was created. The characteristic have been updated on a zone by zone basis. The model contains the actual values derived from data collected from electrical and mechanical drawings, observations, technical datasheets, HVAC control strategy reports and transactions and customers' data. Several days of the year, such as Christmas day and Easter day have been scheduled differently due to the stores' closure.

The model created after level 2 is run and the accuracy is checked by comparing with measured energy and air temperature data on an hourly and monthly basis for one year by calculating the following criteria:

$$MBE = \frac{\sum_{i=1}^{N}(y_i - \hat{y_1})}{\sum_{i=1}^{N} y_i} \quad (1) \qquad CVRMSE = \frac{\sqrt{\sum_{i=1}^{N}(y_i - \hat{y_1})^2 / N}}{\overline{Y_s}} \quad (2) \qquad \overline{Y_s} = \frac{\sum_{i=1}^{N} y_i}{N} \quad (3)$$

With y_i and $\hat{y_i}$ are measured and simulated data at instance i, respectively; $\overline{Y_s}$ is the sample mean of the measured data and N is the sample size (8760 for hourly based validation analysis or 12 for monthly based validation analysis)

ASHRAE Guideline 14 recommends an MBE of less than 5% and a CVRMSE of less than 15% relative to monthly calibration data. If hourly calibration data are used, these requirements could be 10% and 30% respectively (ASHRAE Guideline 14, 2002).

Following the first run, an inverse calibration methodology was followed to make small adjustments to the operating schedules and the internal loads of the model using as a guide energy data from the sub-systems from previous periods or from similar stores for lighting, refrigeration cabinets and HVAC. As Liam et al. suggests, the HVAC system was adjusted last after other input parameters and systems were calibrated because most of these inputs will influence the HVAC system performance (Lam et al., 2014). Graphical comparison between simulated and metered results is also used for the calibration and validation methodology. This included hourly and monthly line graphs and bar charts respectively. Finally, scatterplots are used for visualising the errors between the real and simulated data.

5.4 Systems configuration

EnergyPlus Version 2.05 was used for the case study supermarket stores. As an energy analysis and thermal load simulation software, it simulates dynamically the building and associated energy systems when they are exposed to different environmental and operating conditions. EnergyPlus has a series of functional elements connected by loops and controlled by the integrated solution manager. It leads to multi-zone models which represent the current state of the art for estimating whole-building airflows. The solution is based on the iterative method using Gauss-Seidel philosophy until the reconciling of the demand and supply of the building (Engineering Reference, 2015). The model and their subsystems' connections are presented in figure 5-4. Arrows shows the interaction and influences between the systems. The model of each building as a system needs the weather parameters that lead to evaluation of its energy and environmental performance. The indoor air environmental conditions are strongly dependent internally by the lighting and electrical equipment, customers' density and behaviour, refrigeration system equipment and HVAC system which actually control the indoor air conditions. Refrigeration system is also dependent by the indoor air conditions, customers' behaviour (opening/closing doors and lids) and if the system is indirect then, the weather conditions also influences the performance of the refrigeration system.

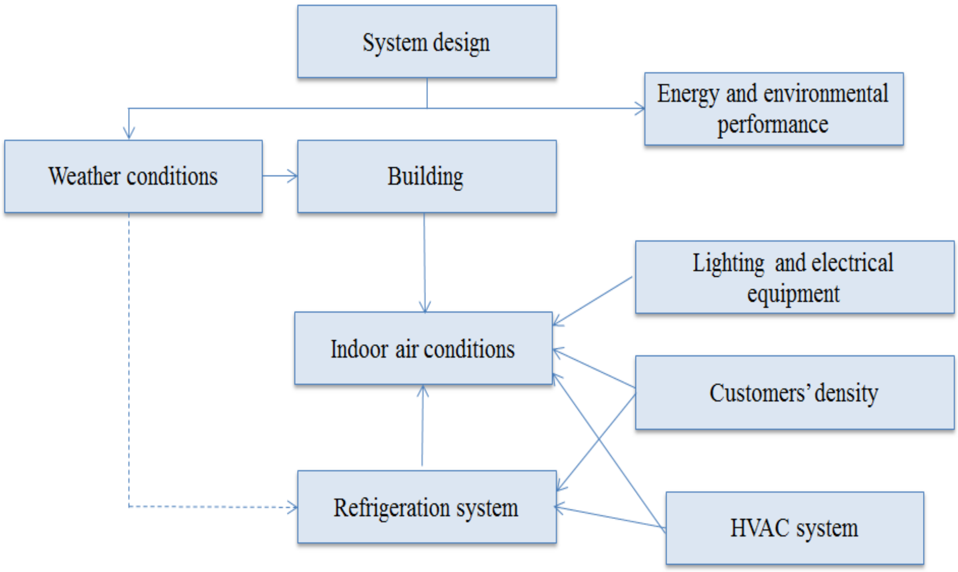


Figure 5-4: EnergyPlus supermarket model and subsystems

5.4.1Building model

The dynamic thermal models require 3-dimensional geometry and this was created in Google Sketchup. The building was separated into zones by similar functionality, boundary conditions and performance due to heat gains from occupants, lighting and equipment (ASHRAE Standard 90.1, 2007) (CIBSE, 2015).

EnergyPlus uses the combined heat and moisture finite element based solution technique for building thermal loads which gives the opportunity for simultaneous calculation of radiant and convective effects at both interior and exterior surfaces of the building. The zone air temperature becomes the main variable.

Figure 5-5 presents the 14 thermal zones as they have been constructed for CS1. CS2 has been separated in nine thermal zones (Figure 5-6).

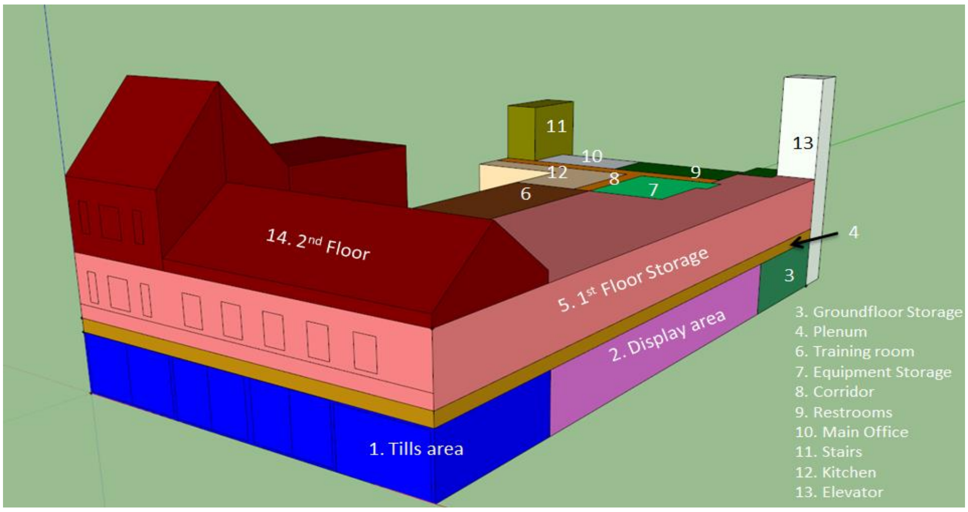


Figure 5-5: Sketchup 3-dimensional multizone building model, CS1

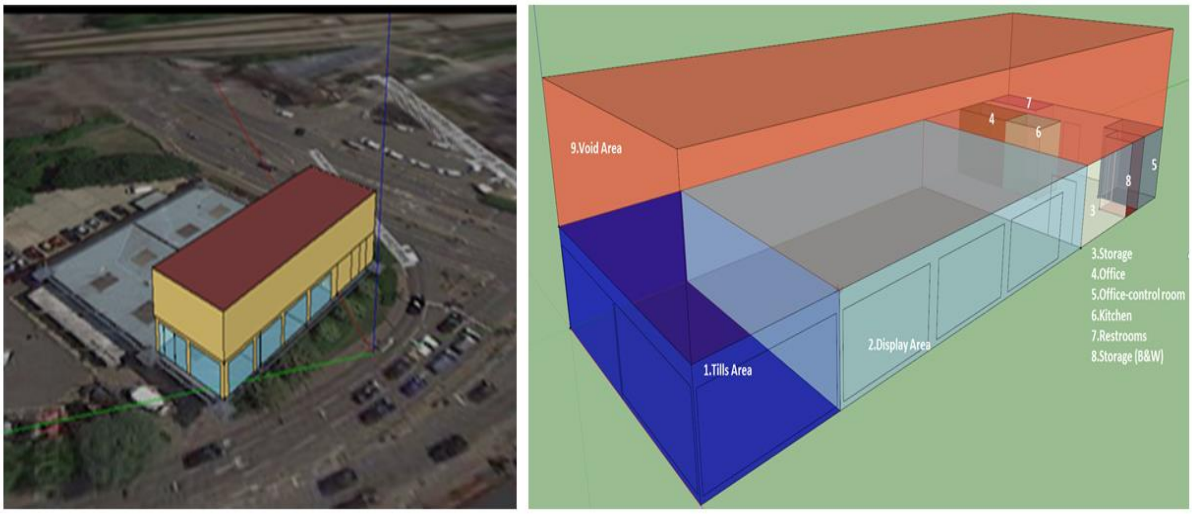


Figure 5-6: Sketchup 3-dimensional multizone building model, CS2

Construction of various elements (floor, rooms, external facades and internal partitions, windows, doors) was inputted.

CS1 is a partly refurbished and redesigned building in 2008 in order to fulfil the requirements of a supermarket store. The actual building is approximately from 1930s and U-values are taken by the in force UK building regulations of the time apart from the fabrics that were advised by the Energy manager of the store that have been insulated during the refurbishment . Internal partitions were added to separate the sales area from the groundfloor storage area and to separate the first floor into staff rooms, offices, and storage area. The roof was upgraded with waterproof and general insulation according to the store manager.

Table 5-1: Construction parameters input-CS1

Construction	U-value (W/m^2K)
External Wall	1.7
Ground Floor	0.5
Internal celling	1
Internal floor	0.4
Roof	0.3
Internal partition	0.6
Windows (Single glazed)	5.7

Table 5-2 presents the thermal properties for CS2 which was newly refurbished according to the latest UK regulations (Part L2A, Building Regulations, 2016).

Table 5-2: Construction parameters input-CS2

Construction	U-value (W/m^2K)
External Wall	0.35
Ground Floor	0.25
Roof	0.25
Internal partition	0.6
Windows (Single glazed)	5.7

5.4.2 Operating schedules and model configurations

The majority of the schedule parameters such as lighting in the staff areas where occupancy sensors are installed and the electrical equipment (office PCs, kitchen equipment, and tills machines) are dependent on the people presence and behaviour. Thermostatic controls are also defined here (20.5 ^oC -21.5 ^oC and 21 ^oC set point temperature for CS1 and CS2 respectively).

Opening times are 8:00 to 20:00 on weekdays and Saturdays and 10:00 to 16:00 on Sundays. Working shift starts one hour earlier than opening with 15 employees each day for 12 hours and it is separated in 2 shifts per day. Customer flow numbers and density were observed in-situ for several days in July 2013 and were supplemented by transactions data for a week (chapter 4, section 4.5). Figure 5-7 presents the occupancy density over a week. Hourly transactions data and customers counts lead to the hourly schedule of the customers' density in both sales and till area. Moreover, the in-situ spot observations enabled the mapping of the customers inside the sales area from which the customers' density in both tills and display area derived. According to these recordings the maximum number of customers per time step in the tills area set to 40 and 35 for tills and display area respectively for CS1. The maximum number of customers per time step for CS2 set to 10 and 17 for tills area and display area respectively.

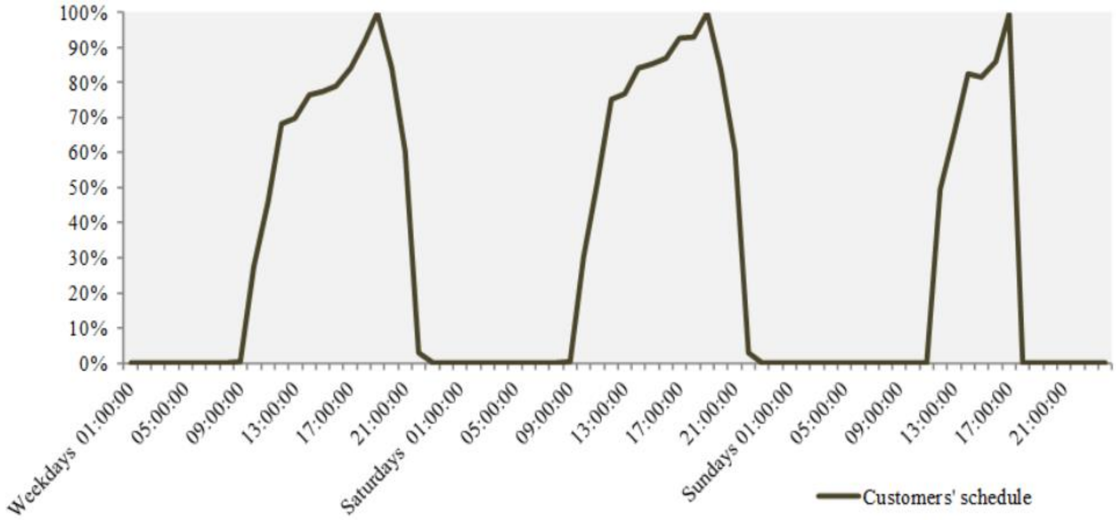


Figure 5-7: Operating schedules for customers' density

The lighting system operates from opening to closing time while the LED strips operate 24 hours. Tables 5-3 and 5-4 summarise the internal loads inputted to the model.

Table 5-3: Summary of parameters' input for customers' density, lighting load and electrical equipment, CS1

Location/Thermal Zones	Customers' Density (m^2/person)	Lighting Load (W/m^2)	Electric Equipment (W/m^2)
Tills Area	2.9	19.1	6.73 (Tills equipment)
Display Area	10.5	23.01	n/a
Groundfloor Storage	27.2	4.26	n/a
1st floor Storage	4.2	0.7	n/a
Training room	8	16.2	n/a
Equipment Storage	n/a	7.44	6.41 (PCs)
Corridor	n/a	13.83	n/a
Restrooms	n/a	7.04	64.7 (Heaters)
Main Office	n/a	10.68	18.41 (PCs, printers and control equipment)
Stairs	n/a	21.48	n/a
Kitchen	9.4	11.69	163.73 (Fridge, microwave, kettles, dishwasher)

Table 5-4: Summary of parameters' input for customers' density, lighting load and electrical equipment, CS2

Location/Thermal Zones	Customers' Density (m^2/person)	Lighting Load (W/m^2)	Electric Equipment (W/m^2)
Tills Area	15.2	32.9	5.9 (Tills equipment)
Display Area	15	16	n/a
Office-Control Room	5.9	9.9	30.6 (PCs, printers and control equipment)
Office	4.2	13.8	17.85 (PCs)
Kitchen	3.9	36.7	274.2 (Fridge, microwave, kettles, dishwasher)
Restrooms	n/a	10.6	137.4 (Heaters)
Storage Area	31.6	1.9	n/a
Storage Area (B&W)	n/a	18.8	n/a

In UK, air tightness tests are mandatory for buildings with floor are of more than 1000 m^2 and should be less than a maximum air permeability of 10 m^3 h^{-1} m^{-2} at a test pressure of 50 Pa. However for buildings less than 500 m^2 total useful area, like the case study store, a test is not necessary; air permeability is taken as 15 m^3 h^{-1} m^{-2} at 50 Pa (Part L, 2014). This is increased by 80% in the tills area to account for the opening of the main door; this was estimated from the customer flow observations.

5.4.3 HVAC System

In EnergyPlus the HVAC consists of various components that are connected physically in the actual system by ducts (CS1) or piping (CS2). All of the HVAC parts must be specified in such details so as to simulate correctly the systems. The parts of the HVAC systems are connected through nodes and each of the part has one inlet and one outlet node. Once specified, the parts are linked together within loops. Hence, the output node from one HVAC component is also an inlet node of the next component of the loop.

The HVAC system of CS1 is a roof mounted AHU with a DX cooling coil and an electrical heating coil. It is a CAV system which provides with 6 m^3/s in trading hours. In EnergyPlus this system is simulated by the all-air system which provides the two different thermal zones (tills and display area) with single duct.

HVAC system diagram is presented in figure 5-8. The EnergyPlus system is separated into two loops; the air loop supply side and the air loop zone equipment. The Air loop supply side is defined by the node that starts after the zone return streams combination of thermal zones (Air loop inlet node) and continues until the node that air streams are split to different zones (Air loop outlet node). The zone equipment section includes everything from where the ducts are spilt to serve different zones up through where the return ducts from these zones are mixed. The system includes a reheat coil for tills area.

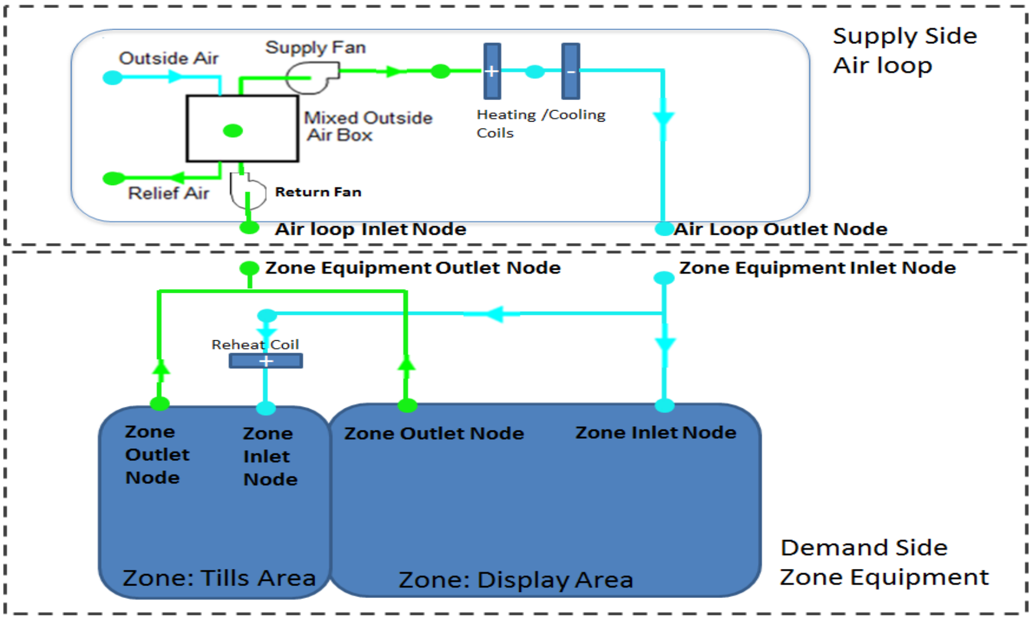


Figure 5-8: CAV system diagram, CS1

CS1 HVAC system consists of an AHU, a heating source, a cooling source, distribution ductwork, and appropriate delivery devices (terminal units).

The *Coil:Cooling:DX:TwoSpeed* is used to represent the two speed DX cooling unit. 6 m^3/s and 3.5 m^3/s are the two speeds that are specified, heating and cooling mode respectively. The inputs are rated total cooling capacity (88KW), COP (3) and rated air volumetric flow rate for the high speed and low speed states. The condenser is air-cooled. Performance curves regarding cooling capacity as a function of entering air wet-bulb temperature and outside dry bulb temperature and actual air flow rate across the cooling coil and Energy Input Ratio (EIR) as a function of the same parameters. The coefficients of the curves are set to default values according to EnergyPlus files for two speed DX cooling coils that are used in the AHU (See Appendix D).

The *Coil:Heating:Electric* is used to represent the heating coil model. It is a simple model with 24 kW capacity and used in the air loop simulation and in the zone equipment as a reheat coil in case of the tills area zone. It is controlled by temperature controller specified by the control strategy of the CS1.

The coils are not used by themselves but as a part of a system that provides control for the AHU. It is a virtual component that consists of a fan component, a cooling coil component and a heating coil component.

Two constant fans (*Fan:ConstantVolume*) are used for supply and return fan their characteristics are set according to manufacturers' data. Both of them according to control strategy are on 24h hours (Table 5-5).

The terminal units of each zone are constant volume which provides a supplementary reheat coil in a zone when needed. According to mechanical drawing of CS1 there is an electric reheat coil (18 kW) for tills area. It is uses to raise the temperature of the zone inlet air. This coil is controlled to raise the zone supply air temperature to match the zone load. A system availability schedule is defined to allow operational control of terminal units.

Ventilation rates for the exhaust system during trading hours have been set to 6 ach.

Regarding CS2, the HVAC system is a decoupled system; the heating and cooling requirements are fulfilled by a variable refrigerant system with ceiling mounted cassettes and the extract ventilation is done by a separate ductwork.

EnergyPlus can model the heat pump type VRF systems (Figure 5-9). The object *AirConditioner:VariableRefrigerantFlow* describes the outdoor unit which connects to the zone terminal units (indoor cassettes). Zone terminal units operate to meet the zone sensible cooling or heating demand as determined by the zone thermostat schedule. The actual operation mode is determined based on the master thermostat priority control type. For CS2 *LoadPriority* has been set which uses the total zone load to choose the operation mode as either cooling or heating. The *MasterThermostatPriority* operates the system according to the zone load where the master thermostat is located. The indoor unit supply fan is modelled as a constant volume (*Fan:ConstantVolume* object). Indoor units as well require the heating and cooling coils (*Coil:Cooling:DX:VariableRefrigerantFlow* and *Coil:Heating:DX:VariableRefrigerantFlow*). The operating capacity of the heat pump is calculated based on the rated cooling capacity, the ratio of indoor terminal unit capacity to outdoor unit capacity (combination ratio) and the actual operating conditions.

Performance correction factors are used to correct for not rated conditions (see Appendix D).

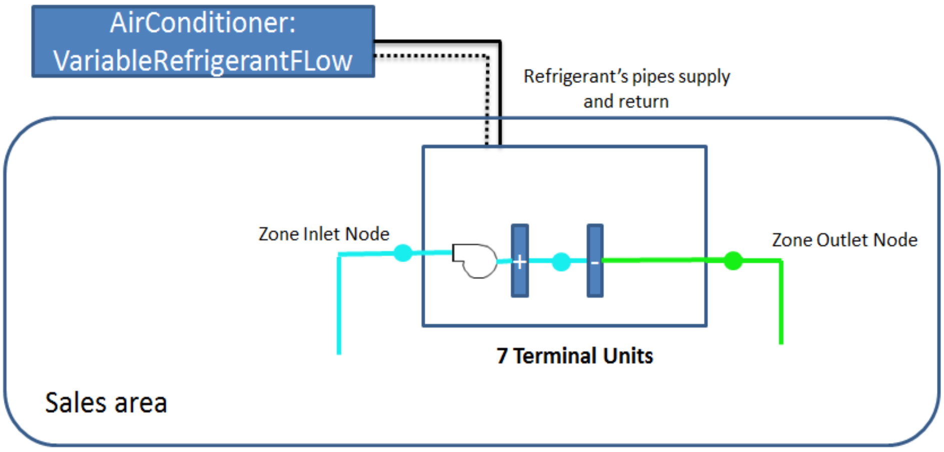


Figure 5-9: VRF system diagram, CS2

Each simulation time step, EnergyPlus performs a zone air heat balance to determine the zone load and then the VRF system operation mode is determined according to the specified master thermostat priority control. The actual output of each indoor unit is firstly calculated and then the capacity required by the outdoor unit is calculated. The total power consumption is calculated by incorporation the average room wet bulb temperature, outdoor dry bulb temperature and the part-load ratio.

Table 5-5: HVAC control strategy, CS1

Hours	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	8:30	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Night									*																
Day									*																

*8:00-8:30: The HVAC system is off and the temperature is expected to rise due to internal heat gains. If at 8:30 the temperature is at around 18-19 °C, then the HVAC system starts at heating mode.

Temperature °C	≤16	16	17	18	19	20	20.5	21.4	…	24	≥24
Free Cooling T_{out}-T_{in} ≤1°C											
Mode	Heating						Cooling Disabled	Cooling	Cooling	Cooling	Cooling
Supply Fan Low:3.5 m^3/s High: 6 m^3/s	Low Speed	High Speed	High Speed	High Speed	High Speed	High Speed	High Speed	High Speed	High Speed	High Speed	High Speed
Extract Fan (1.125 m^3/s)	Off	On	On	On	On	On	On	On	On	On	On
Return Fan (constant 4-4.5 m^3/s)	On	On	On	On	On	On	On	On	On	On	On

Temperature °C	≤16	...	19	19.5	20	20.5	21	21.4	22	...	24	≥24
Free Cooling T_{out}-T_{in} ≤1°C												
Mode	Heating	Heating	Heating	Heating disabled		Cooling Disabled	Cooling	Cooling	Cooling	Cooling	Cooling	Cooling
Supply Fan Low:3.5 m^3/s High: 6 m^3/s	Low Speed	Low Speed	Low Speed	Low Speed	Low Speed	Low Speed	High Speed	High Speed	High Speed	High Speed	High Speed	High Speed
Extract Fan (1.125 m^3/s)	Off	Off	Off	On	On	On	On	On	On	On	On	On
Return Fan (constant 4-4.5 m^3/s)	On	On	On	On	On	On	On	On	On	On	On	On

5.4.4 Refrigeration System

The refrigeration systems information is shown in Table 5-6. The refrigeration display cabinet specifications are summarised in Table 5-7 and the coldrooms' specification in Table 5-8.

Table 5-6: Refrigeration systems information

Case Study	Chilled food open front multi-deck cabinets	Lift up lid frozen food cabinets	Open top case frozen food cabinets	Freezer Coldroom	Chiller Coldroom
CS1	10	70	3	60m^2	12 m^2
Refrigeration Load (kW)	**20.3**	**30.7**		**30**	**5.2**
CS2	7	58	3	29m^2	6m^2
Refrigeration Load (kW)	**10.4**	**26.3**		**16**	**2.3**

Table 5-7: Refrigeration display cabinets' specification data

	Display Cabinets		
	Open front multi deck chilled food	**Lift up lid frozen food**	**Open top case frozen food**
Capacity (kW)	1.46	0.2	1.75
Dimensions (L/D/H-m)	1.9/0.9/2	1.7/0.74/0.89	1.75/1/0.9
Operating temperature (^{o}C)	1 to 2	-20 to -22	-23
Defrost Type	Off Cycle	Off Cycle	Off Cycle
Refrigerant	R404a	R134a	R404a
Compressor COP	2.3	1.5	2.3
Condenser Type	Air Cooled	Air Cooled	Air Cooled

Table 5-8: Coldrooms specification data

	CS2		CS2	
	Chiller	**Freezer**	**Chiller**	**Freezer**
Number	1	1	1	1
Capacity (kW)	5.2	30	2.3	16
Dimensions (L/D/H-m)			2.4/2.4/3	7/4.2/3
Operating temperature (^{o}C)	0-2	-20	0	-20.5
Defrost Type	Electric	Electric	Electric	Electric
Refrigerant	R404A	R404A	R404A	R404A
Compressor COP			1.69	1.5
Condenser Type	Air Cooled	Air Cooled	Air Cooled	Air Cooled

The remote plugged in cabinets are modelled by a compressor rack object combining the compressor and condenser into a single unit with the performance determined by the heat rejection environment and total case load.

All the display cabinets of the case study store are in the sales area, and thus variations of space air parameters (temperature and humidity) can greatly affect the cabinet refrigeration load. Refrigerated cases (display cabinets) performance is based on the combined effects of evaporator load, fan operation, lighting, defrost type, and anti-sweat heater operation. The refrigeration case models use performance information at rated conditions along with performance curves for latent case credits and defrost heat load to determine performance at off-rated conditions. Energy use for lights, fans and anti-sweat heaters, defrost heat load and the heat load due to the restocking of the products are modelled based on inputs for nominal power, schedules and control type. The model assumes that these load components are known for a refrigerated case at rated ambient air conditions and the specific case operating temperature.

A combination of input curves and fixed correlations adjust for case performance at off-rated conditions as the latent load on the refrigerated case evaporator will vary with ambient humidity. Therefore, the refrigerated case model requires a latent case credit curve to adjust these case credits based on ambient humidity. Case temperature method is used for the refrigeration cabinets of the stores and it is dependent on user-definied coefficients using a cubic curve. Default curve coefficients for curve type are provided in table 5-9. They derived for RH_{rated}=55% and ambient T_{rated}=23.9 ^{o}C. (Howell, 1993b) (Engineering Reference, 2015).

Table 5-9: Latent case credit curve coefficients for case temperature method (Engineering Reference, 2015)

Coefficient	Single-self horizontal case	Multi-self vertical case
m	2.0376E-2	2.6520E-2
n	2.4378E-4	1.0780E-3
o	1.1400E-5	-6.0256E-5
p	1.8110E-7	1.2373E-6

Several of the load components are provided by the manufacturer (total rated load, fan, lighting, anti-sweat heater and defrost load). The remaining load components are estimated by the model. For estimating the latent air infiltration load, the model requires the latent heat ratio (LHR) for the refrigerated case at rated conditions. The rated LHR for refrigerated case typically ranges from 0.1 to 0.3 depending on the case configuration (i.e. glass door reach-in versus multi deck open case) and case operating temperature. The sensible energy removed from thermal zones due to refrigeration cases, named as “rated sensible case credits” are calculated by subtracting the known loads at rated conditions (fans, lighting, anti-sweat heater, defrost and latent case credits) from the rated total cooling capacity of the case which is provided by the case manufacturer. For every simulation step, the rated sensible case credits are then adjusted to account for variations at off- rated ambient air temperatures. A case credit fraction schedule is also defined to identify cases that operate differently during specific times. For example, curtains that are installed on the open front multi deck cabinets during not trading hours which significantly reduces the case credits compared to occupied hours.

The compressor’s electric consumption is calculated based on the evaporator load for the connected case and the coefficient of performance (COP) for the compressor.

Regarding the centralised systems a more detailed model configuration is used in conjunction with the refrigeration cases to simulate the performance of the case study store. The whole system is imported by using different objects for refrigeration loads, compressors and condensers. The refrigeration load is based on the required load as it was calculated from the real supermarket data. The condensers are modelled as air cooling condensers. One or a list of compressors must be defined as well to match the cooling requirements. The heat rejection can be done by different ways. Heat is rejected outdoors in a condenser by direct air flow or to a cascade condenser cooled by another refrigeration system.

For this kind of systems, the performance data from each compressors are required as well as the condenser performance curves (Section 6.7.1). The process of simulating the centralised detailed systems starts with calculation of the refrigeration cases in order to provide the first value for the refrigeration load as wells as the evaporating temperature. The performance of refrigeration compressors is dependent upon the condensing and evaporating temperatures. The calculation starts with an estimated condensing temperature, which is used to calculate the compressor power use.

The next step that follows is the use of these values to determine the total heat rejection load on the condenser, which produces a new estimate for the condensing temperature. A few iterations are usually necessary to converge upon final condensing temperature and compressor power for each time step of the system. Once the corrected capacity of the compressors is calculated, the compressors are dispatched one at a time until the system load is met.

The condenser is modelled to determine the condensing temperature and the enthalpy of the refrigerant entering the refrigerated cases, both of which will influence the efficiency of the compressors. The condenser performance modelling also determines the auxiliary power consumption for fans and pumps.

Cascade condensers allow the use of higher temperature refrigeration system (primary system) to serve as a heat rejection sink for a lower temperature refrigeration system (secondary system). The selection of the condensing temperature represents a trade-off in performance between the primary system absorbing the heat rejection and the secondary system rejecting heat (reference). The condensing temperature has been set to “fixed”, so the secondary system condensing temperature is held constant at the temperature specified for the cascade condenser. The refrigeration load where the cascade condenser places upon the primary system is classified as a “transfer load”, because it transfers load from one system to another. The total load is coming from the required supermarket load to serve the MT or LT plus secondary loop’s compressor power.

A detailed transcritical CO_2 booster refrigeration system can be modelled by EnergyPlus and it can be either single stage serving MT or a two-stage system for LT loads and for both MT and LT loads as well. For the LT loads, the transcritical CO_2 system uses a two-stage compressor. Apart from the case load lists and the list of the required compressors, a gas cooler is also needed to be determined. Heat is rejected to the outdoors via the air-cooled gas cooler. To model the performance of the CO_2 compressors during subcritical and transcritical operation, cubic polynomials are used to curve fit manufacturers' performance data (Section 6.7.1). For subcritical operation, the power consumption and cooling capacity of a CO_2 compressor is a function of the saturated suction temperature, t_{ss} (^oC) and the saturated discharge temperature, t_{sd} (^oC).

For transcritical operation, the power consumption of CO_2 compressor is a function of the saturated suction temperature and the gas cooler pressure, p_{gc} (Pa), while the cooling capacity of the transcritical CO_2 compressor is a function of the saturated suction temperature and the gas cooler outlet enthalpy, h_{go} (J/kg). The correlation coefficients of the two equations to calculate the compressors cooling capacity and consumption are taken from manufacturer's data.

Once the corrected capacity is calculated for each compressor, the compressors are dispatched one at a time until the system load is met. The last compressor dispatched is assumed to run at full load for the fraction of the time step necessary to meet the load.

Only one gas cooler is allowed per transcritical refrigeration system and currently only air-cooled gas coolers are modelled. The gas cooler performance is modelled to determine the gas cooler pressure, gas cooler outlet temperature and outlet enthalpy of the refrigerant, and the auxiliary power consumption for the fans.

When the compressor discharge conditions are such that the CO_2 is in the transcritical region, then the high-side operating pressure is independent of the gas cooler exit temperature (Sawalha, 2008). Therefore, for a given gas cooler exit temperature, there is an optimum pressure to achieve the maximum COP. Tsamos et. al. presented an analysis of the pressure and temperature outlet of the condenser/gas cooler based on the experimental investigation outcomes (K. Tsamos et al., 2017).

There are several researchers that have developed correlations to determine the optimum gas cooler pressure in CO_2 refrigeration systems (Chen & Gu, 2005), (Ge & Tassou, 2011), (Kauf, 2005), (Liao & Zhao, 2000), (Sawalha, 2008). Using a similar curve fitting procedure the gas cooler pressure is calculated in EnergyPlus. During transcritical operation, the gas cooler outlet pressure in EnergyPlus is not allowed to fall below 7.5×10^6 Pa to ensure proper operation. During subcritical operation, the gas cooler behaves as a condenser and the condensing pressure is dependent on the ambient conditions. The gas cooler fan power is determined by the type of the fan control, which can be either fixed, variable speed or two-speed. This depends on the CO_2 refrigerant outlet temperature settings. The power is determined as the one of the air-cooled condensers.

Regarding the thermodynamic properties of refrigerants users are allowed to add or remove refrigerants data to the input file and their properties are calculated by interpolating the tabulated data in the input file. Common refrigerants are listed within an extensive Reference Data Set (RDS) that is provided with the EnergyPlus program.

Table 5-10 presents the thermodynamic properties that R134a and R404A have in the in the RDS of the EnergyPlus.

Table 5-10: Thermodynamic properties of the refrigerants in EnergyPlus

Refrigerant	Saturated Temp range (^oC)	Superheated Temp range (^oC)	Super Pressure range (Pa)
R134a	-103 to 101	-103 to 158	400 to 1.6 $x10^7$
R404A	-72 to 72	-72 to 72	$2.3X10^4$ to 3.7 $X10^6$

Modelling of transcritical CO_2 booster refrigeration cycle requires the thermodynamic properties of CO_2 in the saturated (liquid and vapour), superheated and supercritical regions. The refrigerant properties database within EnergyPlus includes saturated, superheated and supercritical thermodynamic data for CO_2, including temperature, pressure, density, enthalpy and specific heat.

5.4.5 Outdoor Climate

An EPW weather file was constructed for the location, with data from the nearest meteorological station from Weather Underground (www.wundergound.com) to correspond to the period considered for the models validation. This weather file was based on the existing EPW file for the nearest location (Heathrow and Gatwick for CS1 and CS2 respectively) with air temperature and relative humidity changed to represent the actual location conditions. Solar radiation and wind data were not changed as data were not available for the location; however, Heathrow is less than 8 km from CS1 and Gatwick is less than 5 km from CS2 so solar radiation would be similar and wind would not affect ventilation patterns as the store uses a mechanical ventilation system.

5.5 Model validation

Building model validation is an approach to modify and adapt the design case study model based on measured data in order to generate a model that can accurately reflect the actual building operation performance. The validation of a forward building energy model is a highly complex problem that would result in a non-unique solution. According to Kaplan et al. it will never be possible to identify the exact solution of the validation problem and always sensitivity issues may occur (Kaplan et al., 1990). ASHRAE Guidelines defines evaluation criteria for building modelling validation which suggest monthly and hourly data as well as spot and short-term measurements. Mean Bias Error (MBE) to capture the mean difference between measured and simulated data and the coefficient of Variation of the Root Mean Squared Error (CVRMSE) to reflect the accumulated magnitude of error are used as evaluation indices (ASHRAE Guideline 14, 2002). MBE negative values indicate that results from the building model are higher than results from measurements and vice-versa for positive values.

5.5.1 Energy Use simulation results

This section presents the energy use simulation results in comparison with the real measured data and their validation methodology. Data are discussed for the whole store (rather than normalised by sales area) because the focus is on the comparison of the measured data with simulation results. Table 5-10 summarises energy use comparison for both case study stores.

Figure 5-10: Comparison of metered and simulated energy use

	CS1		**CS2**	
Validation period	June 2014-May 2015		June 2014-May 2015	
	Metered	Simulated	Metered	Simulated
Annual energy use (kWh/m² sa)	1103.6	1086.6	1143.4	1104.2
Deviation (%)	1.5		3.4	
Minimum (kWh)	34.5	26	19.5	23.6
Maximum (kWh)	109.3	101.8	71.5	69.9
Average (kWh)	63.2	62.3	41.1	39.7
Standard deviation (σ)	15.1	16.1	9.2	10.4

Figure 5-11 and 5-12 enable a quick visual inspection of measured and simulated energy use for two indicative weeks. Figure 5-11 refers to CS1 while figure 5-12 to CS2.

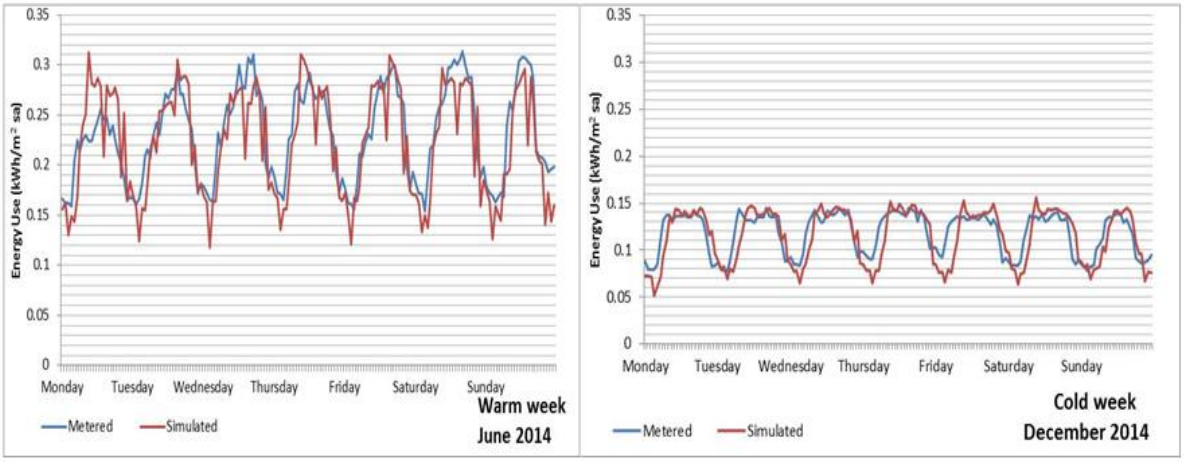


Figure 5-11: Comparison between metered and simulated hourly energy use for an indicative warm and cold week, CS1

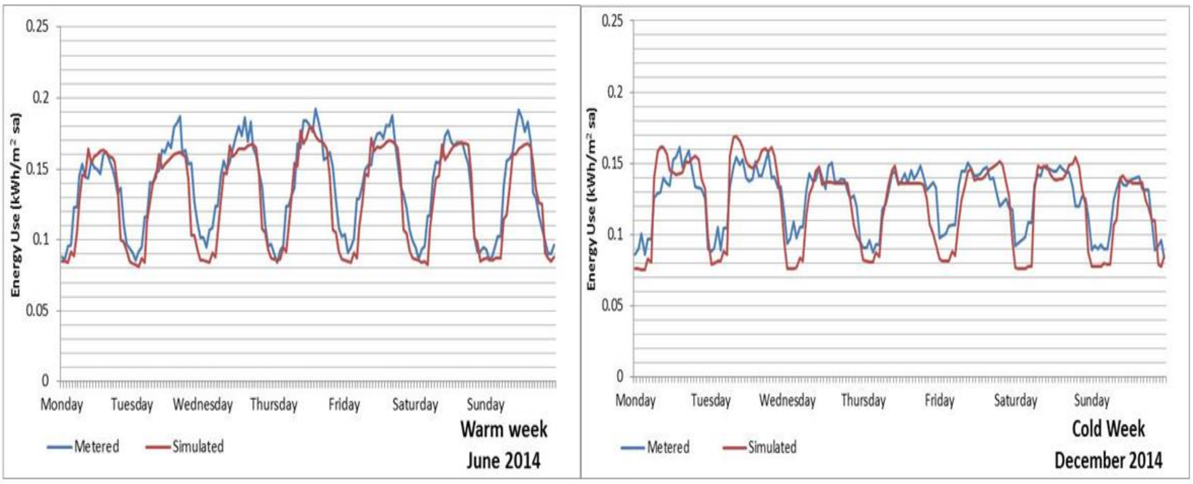


Figure 5-12: Comparison between metered and simulated hourly energy use for an indicative warm and cold week, CS2

Figures 5-13 and 5-14 presents their statistical variations as these have been calculated by MBE and CVRMSE indices.

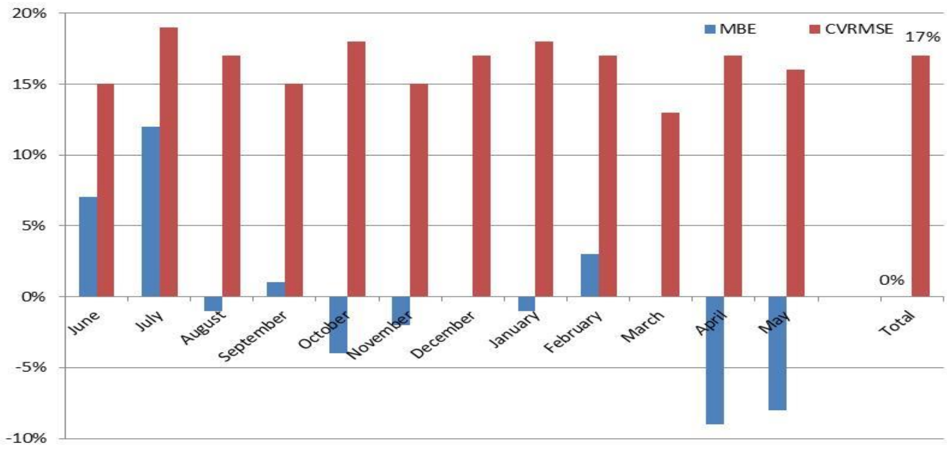


Figure 5-13: MBE and CVRMSE analysis of the energy use based on hourly data, CS1

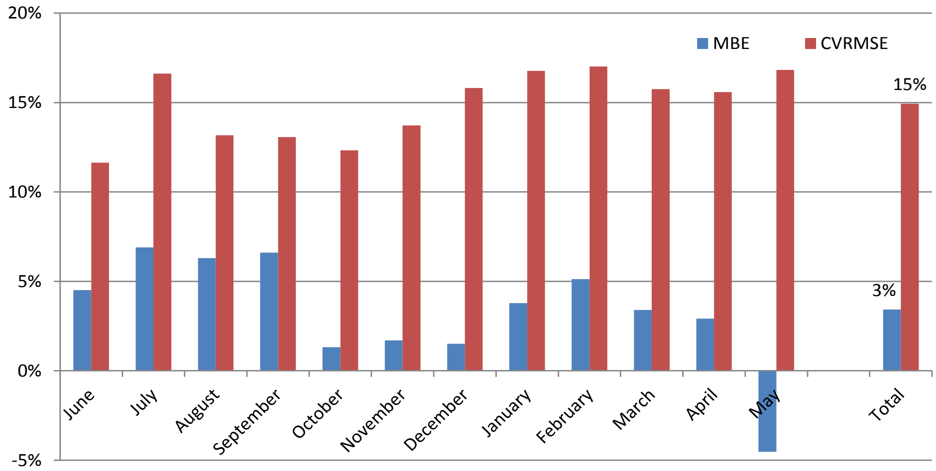


Figure 5-14: MBE and CVRMSE analysis of the energy use based on hourly data, CS2

Residuals are estimates of errors obtained by subtracting the measured data from the predicted responses from the models. Residuals can indicate whether the assumptions of the models are reasonable and consequently the model is reliable. They are the difference between the measured value and the predicted value.

Scatterplots are showing the spread of errors in correlation with hourly energy use. Figure 5-15 refers to CS1 and a constant spread of errors is observed which are distributed on both sides of residuals (negative and positive). The under prediction of the energy use is observed in the lower energy use values while as the energy use increases during the day the model tends to over predict the energy use. The model maintains a constant level of accuracy across the full range of predicted energy use values with an average error of 0.97 kWh per time step. The minimum error (35.02 kWh higher than the metered energy use) that occurred is on the 19th of July 2014 during the start-up of the HVAC system. The maximum error (53.17 kWh lower than the metered energy use) occurred during the 22nd of October at the start-up of the store.

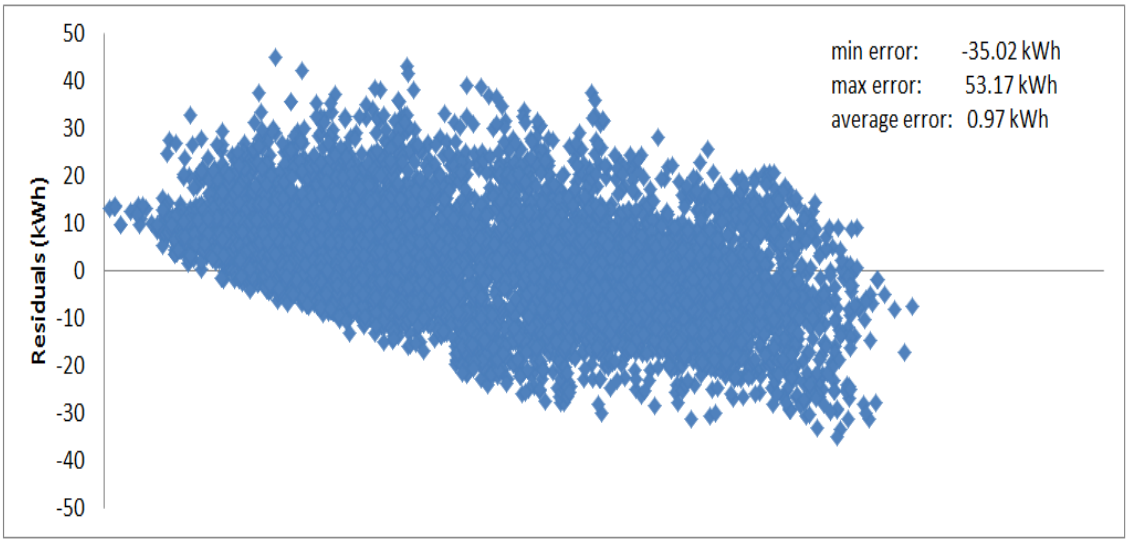


Figure 5-15: Scatterplot of energy use residuals in correlation with the simulated energy use, CS1

For CS2, figure5-16 shows a constant spread of errors that are equally distributed on both sides with a slight under prediction of energy use values (m=1.85 kWh). Similarly to the CS1 model the under prediction of the energy use is basically observed in the lower energy use values while as the energy use increases during the day the model tends to over predict the energy use. This model also maintains a constant level of accuracy across the full range of predicted energy use values with an average error of 2 kWh per time step. The minimum error (29.9 kWh higher than the metered energy use) that occurred is on the 24th of July 2014 for 3 hours only during the evening. The 24th of July 2014 was the day that the highest temperature observed (27^{o}C) during these three hours. Moreover, even the maximum error (21.1 kWh lower than the metered energy use) occurred during summer days. This is also evident from figure 5-14 and MBE values that are higher than the cold months of the year.

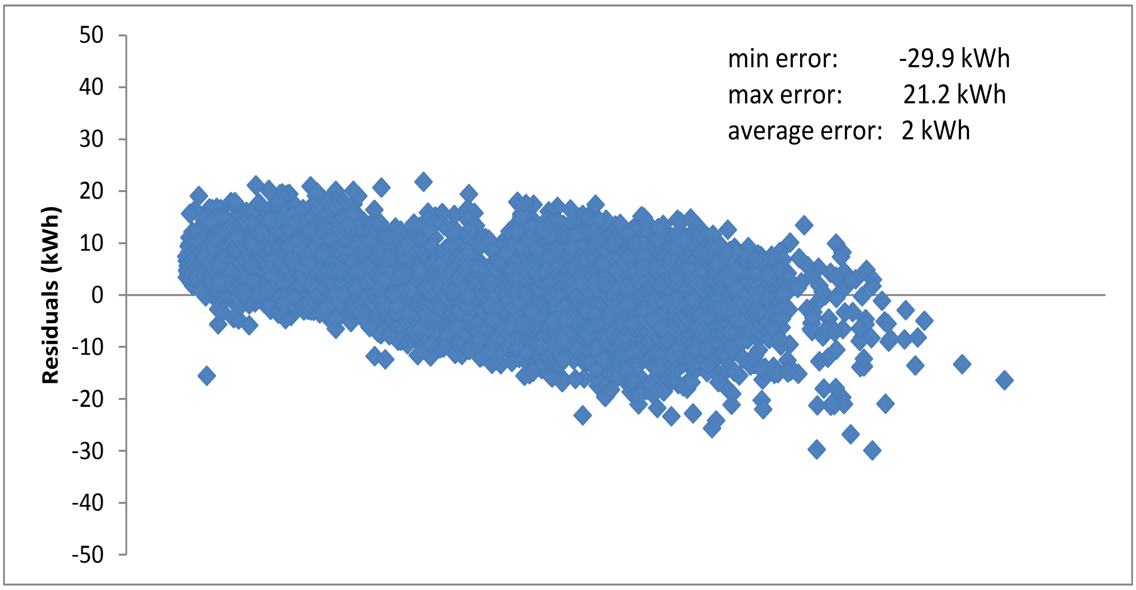


Figure 5-16: Scatterplot of energy use residuals in correlation with the simulated energy use, CS2

Energy use hourly residuals follow normal distribution (figure 5-17) and thus table 5-11 summarises both models' ability to predict the hourly energy use in relative terms. The histogram of hourly residuals provides quantified conclusions of the magnitude and spread of errors of the annual hourly energy use.

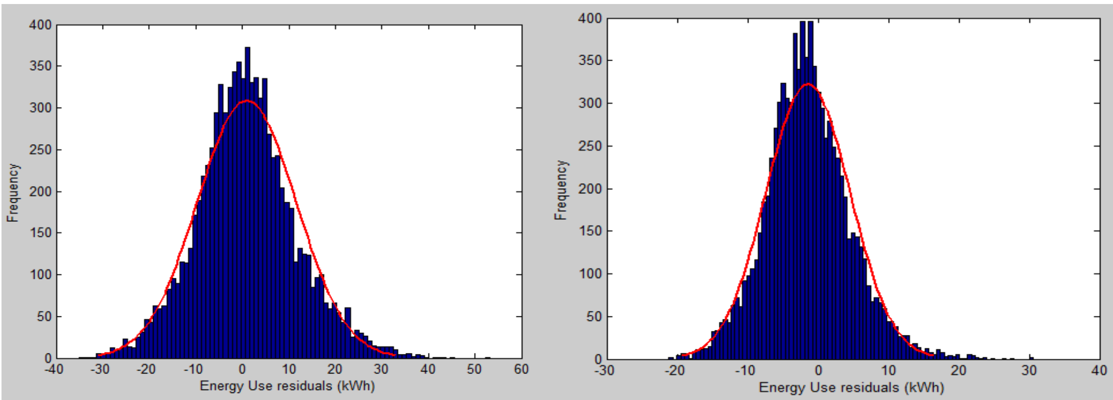


Figure 5-17: Histogram of energy use residuals, CS1 (left) and CS2 (right)

A normal probability plot of the residuals (figure 5-18) is a scatter plot with the theoretical percentiles of the normal distribution on the y-axis and the sample percentiles of the residuals on the x-axis. The normal probability plot of the residuals is linear and the errors are normally distributed. The closer the data are to the normal (red line) the closely the results of the model to the reality. The right upper end of the normality plots of both models bends bellow the straight line which means that the population distribution of the data is light-tailed; the extreme portion of the data are spread out less far relatively to the width of the centre of the distribution. This is obvious as well from the histograms (figure 5-17) and the scatterplots (figure 5-15 and 5-16) where the maximum errors (predicted values area higher than the measured ones) are less than the error occurred from under-prediction of the energy use. In other words, the over prediction of the energy use is less frequent.

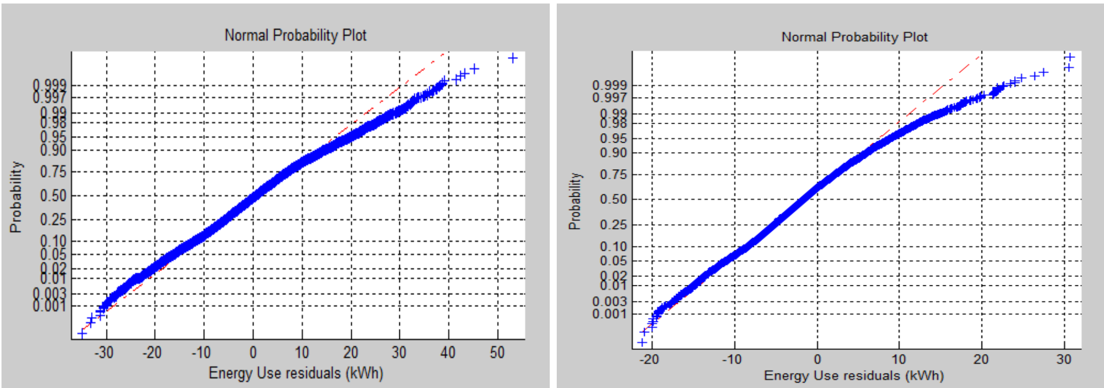


Figure 5-18: Normal probability plot of energy use residuals, CS1 (left) and CS2 (right)

From figures 5-17 and 5-18 it can be concluded that the residuals of the models of both case study stores follow normal distribution and table 5-11 summarises the information for the normal distribution.

Table 5-11: EnergyPlus models energy use prediction ability

Residuals	CS1	CS2
Median (kWh)	0.97	-1.4
Standard deviation (σ) (kWh)	10.61	5.97
Magnitude of errors		
95% of errors (kWh)	-20.25 to 22.19	-13.34 to 10.54
99.7% of errors (kWh)	-30.86 to 32.8	-19.31 to 16.51

Finally, the calibrated model was run for the next available operating data (June 2015–May 2016) in order to check its accuracy. The MBE and CVRMSE values were found to be within acceptable limits according to guidelines and the percentage error between metered and simulated monthly energy use does not exceed 10%.

5.5.2 Sub-systems energy use validation

Apart from the total energy use validation, a sub systems energy use should be validated as well. Lighting, electrical equipment, HVAC and refrigeration systems energy use are sub metered but available for only one month for similar supermarket stores of the same chain (Section 4.2) and not for the case study stores. For that reason only the daily energy use breakdown of the systems are used for subsystems energy use prediction validation of the models.

Table 5-12 presents the comparison between the measured data from the sub systems with the prediction breakdown of the models based on hourly energy use.

Table 5-12: Subsystems comparison of measured and simulated data

Percentage Breakdown (%)	Measured	CS1	CS2
Electrical Equipment and Lighting	5-25	10-22	5-20
HVAC	12-50	9-28	17-27
Refrigeration	43-60	48-78	50-70

CS2 presented and unremarkable difference in the hourly energy use of the sub-systems between measured data and predictions of the EnergyPlus models. The biggest variation is observed in the HVAC system and this could be the different control strategy of the each store (i.e night free cooling for CS1 and 24h operation for CS2). Each store's manager and staff in the target stores also take a very proactive role and the set points within the space are regularly updated in response to staff comments. This adds a greater probabilistic pattern to actual building performance as opposed to the static and user's driven nature of simulation.

Regarding the refrigeration system validation, the energy use of the majority of the refrigeration system cabinets (lift up lid frozen food cabinets) has been monitored in store operation (section 4.3.2.2). The metered average daily energy use is 2.4 kWh. The simulation results of this cabinet showed that the daily energy use is 2.7 kWh.

5.5.3 Environmental conditions simulation results

This section presents the temperature simulation results inside stores in comparison with the real measured data and their validation methodology.

Figure 5-19 presents a visual comparison between metered and simulated temperatures in tills and display area of CS1. According to them, both metered and simulated data follow the same pattern within the simulated year with unremarkable differences in average monthly temperatures. However, there is a difference in the median of each month presents differences while the simulated ones are close to trading times temperatures for cold months and close to non-trading times for warmer months. That means during cold months there is bigger variations in non-trading times and this is due to the fact that night free cooling depends on the external temperature. Similarly, during warm months, where night free cooling is not effective and sometimes disabled due to inappropriate external temperatures ($T_{out} \approx T_{in}$) there is no big variations in the predicted temperature values of the sales area. On the other hand, bigger variation there is in trading times during warm months due to heat gains but quite stable in colder months. Although, metered and simulated temperature both for tills and display area, are following similar pattern, insignificant variations indicated for trading and non-trading times. EnergyPlus calculations are more sensitive to external conditions and infiltrations rates.

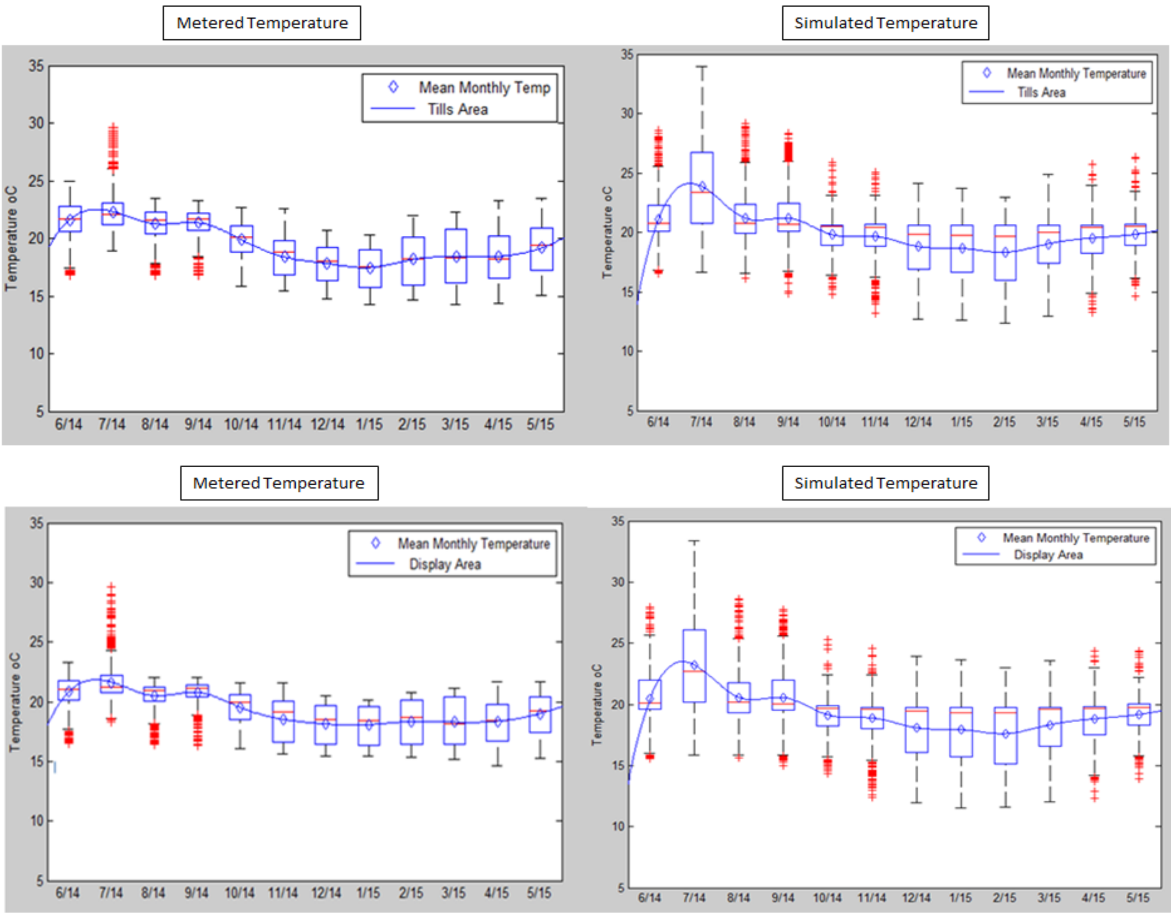


Figure 5-19: BWM plots of metered and simulated air temperature for the Tills and Display area (hourly based), CS1

Figure 5-20 shows a visual comparison for both metered and simulated temperatures in the tills and display area of CS2. The measured mean temperatures in the tills area have fluctuations (19-22^{o}C) during the year with the lowest to occur during December and the highest in July. Although the set point temperature is 21^{o}C 24h, the tills area does not maintain the temperature within the desirable set point. In comparison with the measured data, air temperatures of simulations are significantly more stable during the year and maintained slightly lower than 21^{o}C. Similarly to the measured data, during cold months (December and January) lower values than set point temperature are predicted in the tills area. These results indicate that a more accurate model for air infiltration through the entrance door needs to be developed if more accurate air temperature prediction in the tills area is required.

In display area, a more stable mean temperature (20-21^{o}C) during the year was measured. Simulation shows that the temperature is maintained during the year to the set point and only in cold months a remarkable drop was observed in some hourly values and a slight increase (around 2^{o}C) during July which was the warmest months of the simulated year. As it was observed in the prediction of the energy use values, extreme external weather conditions increases the error.

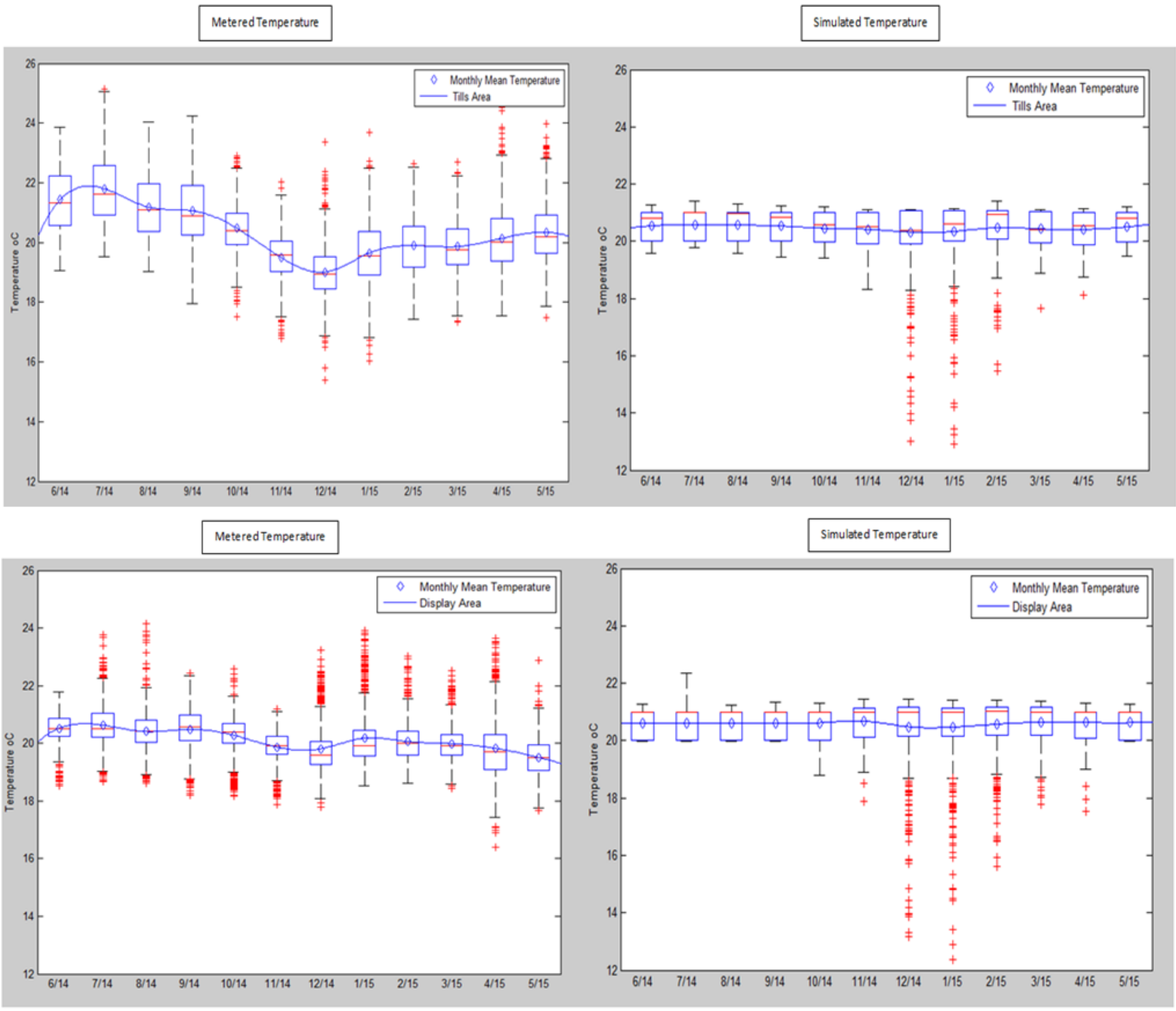


Figure 5-20: BWM plots of metered and simulated air temperature for the Tills and Display area (hourly based), CS2

Figures 5-21 and 5-22 display the MBE and CVRMSE error checks of temperature results based on hourly data for model EnergyPlus models. Figure 5-21 shows the evaluation of CS1 temperature results. As it has been mentioned before, July was the month with the highest accumulated error in both zones. In general, annual values are within the acceptable guidelines, indicating the model has the ability to predict bulk air temperature of the two thermal zones accurately. The same applies for CS2 (figure 5-22). For this case study and according to MBE and CVRMSE temperature error checks, December is the month with the highest accumulated error in both zones.

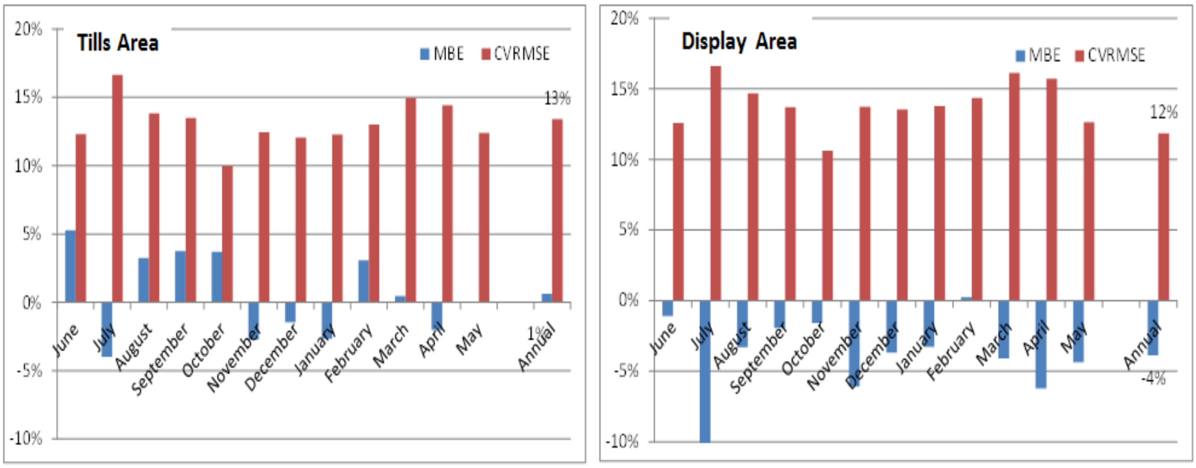


Figure 5-21: MBE and CVRMSE analysis of the air temperature based on hourly data, CS1

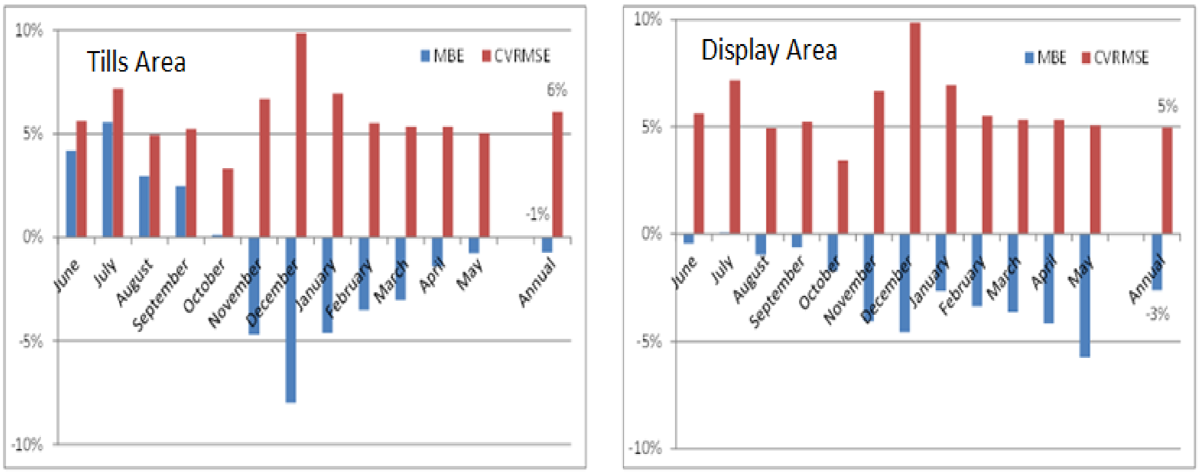
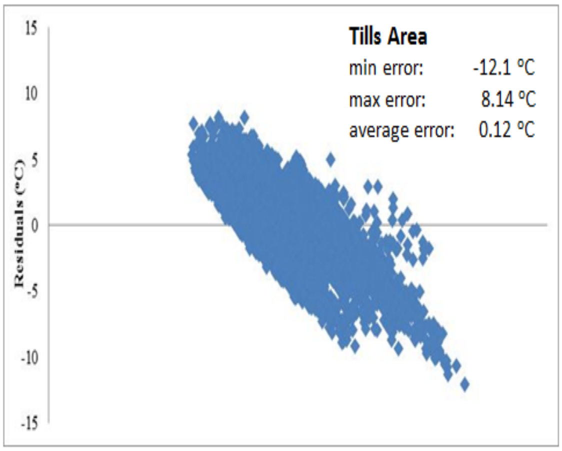


Figure 5-22: MBE and CVRMSE analysis of the air temperature based on hourly data, CS2

Figure 5-23 refers to the residuals of CS1 in correlation with the simulated temperature of both thermal zones. In the tills area the mean values of the residuals is 0.21°C and equal distribution of the errors occurs in both sides of (positive and negative errors). Regarding the display area, the mean value of the residuals is -0.5°C. In this case the model tends to slightly over predict the temperature in the display area. The scatterplots for tills and display area demonstrate that EnergyPlus mode of CS1 maintains a constant level of accuracy across the full range of predicted temperatures. The highest negative error occurred in warmer days of July while the highest positive error occurred in several non-trading times where free night cooling is in operation. It can be concluded that the EnergyPlus model is more sensitive to external weather conditions which means that whenever the night cooling control strategy permitting, the simulation results are more precise to control strategy while in reality the system might not react completely due to the sensitivity of systems, or manually changes in the HVAC control strategy from store's staff.

Figure 5-24 shows the scatterplots for CS2 temperature residuals in correlation with the simulated temperatures of tills and display area. In the tills area the mean value of the residuals is almost 0 (-0.1^{o}C) and an equal distribution of the errors occurs in both sides. Similarly to CS1, the display area, the mean value of residuals is 0.52^{o}C which shows a slight over prediction of the temperatures inside the display area. The spread of errors with increasing simulated temperature proves a constant level of accuracy across the full range of predicted temperatures. The highest error occurred during the winter period which means that the external weather conditions introduce a large element of error in the predictions of the temperatures of the thermal zones which in combination with the customers occupancy levels uncertainty lead to the difference between metered and simulated data. In the display area of CS2 model, the scatterplot also indicated significant negative errors which are also evidence of the ability to slightly over predict the temperature of this thermal zone. However, as it was observed for the tills area, the highest errors occurred in the warmest and coldest month of the simulated year (December and July).



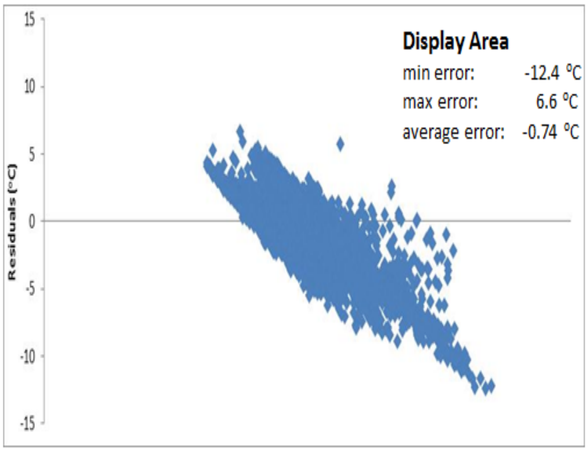


Figure 5-23: Scatterplot of air temperature residuals in correlation with the simulated temperature results for the tills and display area, CS1

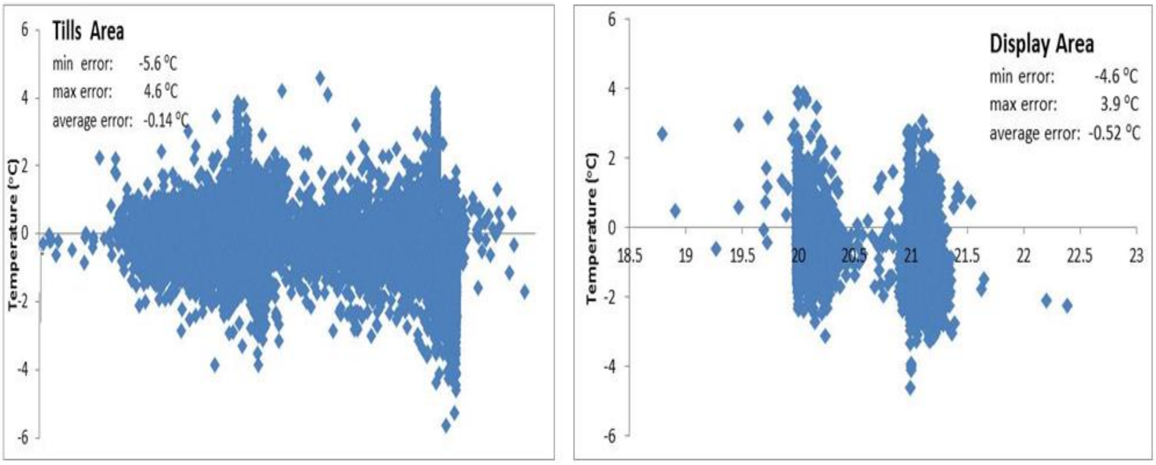


Figure 5-24: Scatterplot of air temperature residuals in correlation with the simulated temperature results for the tills and display area, CS2

Chapter's summary

This chapter described the development procedure of the thermal and energy models of the two case studies by Energy Plus. It started with the explanation of the modelling process by analysing each step of the process and the objectives of the models development which refer to energy requirements and indoor air environmental predictions, the overall energy performance of the building. The inputs of the models and their interdependence are discussed along with the limitation and uncertainties that several parameters introduce to the models.

In addition, the methodology of the model development was explained in detailed by identifying each step and the required data and inputs. The validation process of the models analysed in this section as it is a crucial step for the models. Guidelines and recommendations for this step are mentioned and equations used were presented.

Following, the systems configuration and input data were presented for each case study which referred to building construction data, operating schedules and internal heat gains per zone. HVAC and refrigeration systems configuration analysed in more detail to depict the process and the 'objects' used for each system.

Finally, the model validation process was presented carried out with customised EPW weather files to correspond to the period and the area considered. Results from the model validation of both case studies shows that both models have the ability to predict with a small deviation (1.5% for CS1 and 3.4% for CS2) the annual energy use with an average error of approximately 1-2 kWh per time step. Both models were validated to predict sub systems energy use by comparing the simulation results with metered data. Finally, an environmental condition results validation completed the overall ability of the models to represent as close to reality as possible the two case studies.

These two validated models against measured data are used in Chapter 6 for application of different systems and strategies in order energy saving to be achieved by maintaining the energy performance of each sub system and the desirable indoor environmental conditions. The two validated models enabled the use of each subsystems in the different applications and can be considered as representative of coupled and decoupled HVAC systems.

Chapter 6

Applications of developed model: Results and Discussion

Introduction

The last phase of the modelling process is the model application. The idea behind the validated EnergyPlus model development was to facilitate comparison of different solutions which will lead to total energy use reduction without affecting the performance of the subsystems. Firstly the EnergyPlus model developed is used to identify the objectives that have been set in the second phase of the model application. These objectives are the energy performance of the sub systems, their interactions and interdependence. First, an energy benchmarking was carried out including comparison of the systems of two case studies (coupled and decoupled HVAC) with current performance of similar supermarkets. The second step includes a comparison of alternative systems/strategies with the previous performance of the systems and building as a whole. The implementation of different parameters such as

1. amendments on building constructions
2. more efficient lighting systems
3. changes in the HVAC control strategies
4. ventilative night cooling and its influence on the energy use of the different subsystems
5. different refrigeration systems and their impact on the whole building energy use but on the impacts on the sub-systems as well

All investigated parameters in the EnergyPlus models were simulated with the Test Reference Year (TRY) weather file from CIBSE apart from the section 6.7 where different refrigeration systems are applied. For this specific section the Design Summer Year (DSY) weather data from CIBSE is used as default weather data which represents warmer than typical year and is used to evaluate the consequences in the centralised refrigeration systems operation. Heathrow-London is identified as location for all the applications.

6.1 Energy Performance evaluation: Key outcomes

The annual energy use breakdown of both stores was derived in order to understand whether they have similarities between each other and to understand the most energy use intensive system. The energy use is normalised by the sales area for easiness of comparison.

Figure 6-1 shows the annual energy use breakdown which confirms that the most energy use intensive system is the refrigeration system (60-62% of the total annual energy use) which is higher than conventional supermarkets. Tassou et al. mentioned that the balance between refrigerated/frozen and ambient product is an important factor that influences and justifies higher energy use (Tassou et al., 2011). CS1 has slightly higher energy consumption due to refrigeration system because it includes bigger sales area (30% bigger) and consequently includes more refrigeration display cabinets and bigger in capacity coldrooms for products storage.

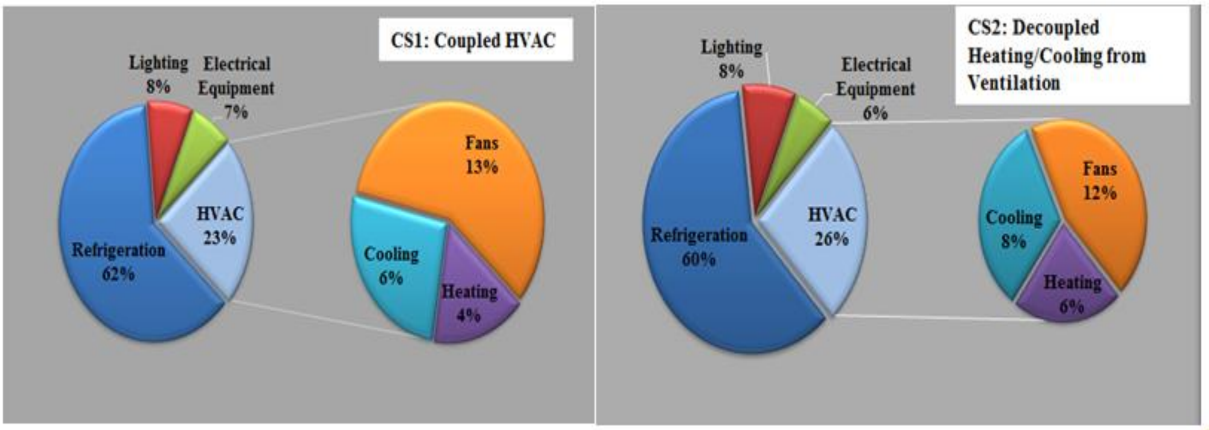


Figure 6-1: Annual energy use breakdown

The second most intensive system is the HVAC; 23% for CS1 and 26% for CS2. The main difference of the two stores as described in section 3.2 is the HVAC systems. CS1 with a typical all air constant volume system has lower energy intensive HVAC system in comparison with CS2 which has a decoupled heating/cooling from ventilation systems, most dominant in convenient stores and small supermarkets. However, the control strategy (hours of operation and set points) of these systems also plays an important role. Night free cooling is in operation in CS1 while HVAC system in CS2 is in operation 24h. Simultaneously and due to the above, it can be noted that the percentage of the fans energy use is the same while the heating and cooling demand in CS1 is lower than CS2.

These results differ from typical supermarket sub-systems breakdown because refrigeration energy use is higher by about 10-20% which leads to higher energy use than typical supermarket (Table 2-4, Section 2.1.3) Reported energy use by sub-systems assign 35% to refrigeration, 26.8% to HVAC and 18.6 to light (DECC, 2013) (Tassou & Ge, 2008).

A daily analysis on the subsystems' energy use will help to evaluate the impact of internal air temperature on them and how it affects their energy use. There are several variables that determine the energy consumption of the subsystems of the stores; the calendar day, opening hours, customers shopping habits, temperature, humidity and daylight.

HVAC system provides thermal comfort for customers and staff but enable the maintenance of the sales area in appropriate levels necessary for non-refrigerated products conditions. Moreover, they provide appropriate conditions for refrigeration equipment operation. One would expect HVAC energy use of supermarket stores to be weather dependent but results show otherwise. For both stores a weak or no correlation between HVAC energy use and external temperature was found. Only CS1 where night free cooling is in operation calculated to have a weak correlation. This is not typical for buildings, but in the case of supermarkets stores, the HVAC control strategy plays the most important role which maintains the sales area temperature at low levels (~21^{o}C) for both stores for better maintenance of display products and for more energy use of refrigeration cabinets' equipment. Figure 6-2 presents a comparison of the daily HVAC energy use in correlation with the external temperature. The points on the figure at which energy use is at its lower levels is the balance point. Both stores present these points around 9^{o}C and 8-12^{o}C for CS1 and CS2 respectively. These outcomes have been mentioned in the total daily energy use signature of the stored derived from measured data (Figure 4-6, Section 4.1). It is also observed that the bulk daily HVAC energy use is within the range of 0.48 – 0.8 kWh/m^2 sa for CS1 and 0.52 – 1.04 KWh/m^2 sa for CS2. The remaining points are because of extreme warm/cold conditions or specific days closures. The difference in the control strategy is obvious in the figure 6-2; CS1 with free night cooling and non 24h HVAC system as CS2, presented lower daily HVAC energy use.

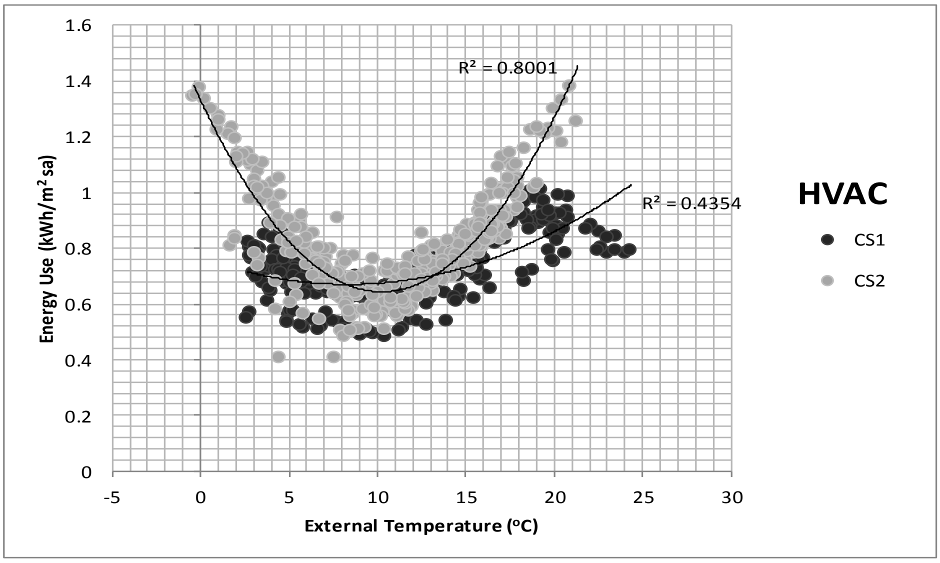


Figure 6-2: HVAC daily energy use per sales area in correlation with external temperature

Figure 6-3 presents in more detail the previous analysis as they separate heating, cooling and fan daily energy use per sales area. Heating and cooling energy use is more equally balanced in CS2 with the heating to be more dominant due to the night time HVAC operation. On the contrary CS1 heating energy use is lower than cooling energy use and this is due to night free cooling which reduces both cooling and heating requirements on the following day. Another aspect that needs to be taken under consideration is the two single glazed window facades of CS2 which strengthen the heat gains/losses and affects the indoor air temperature. Calculations show a strong positive correlation (0.85) of the heat losses due to the single glazed facades on the sales area of CS2 with the heating energy use and slightly weaker (0.7) for heat gains with the cooling energy. Moreover, as expected there is a very strong correlation between heating/cooling energy use with the external temperature; negative for heating and positive for cooling.

As both stores include significantly high refrigeration load which is remote and releases heat in the sales area, the heating/cooling requirements are opposite to typical supermarket stores which have centralized systems with the majority of the cabinets to be open multi deck chilled food cabinets. For this reason, the cooling needs in these cases are the main parameter of the HVAC systems. The zero points of heating energy use in CS2 occur in Christmas and Easter days closures.

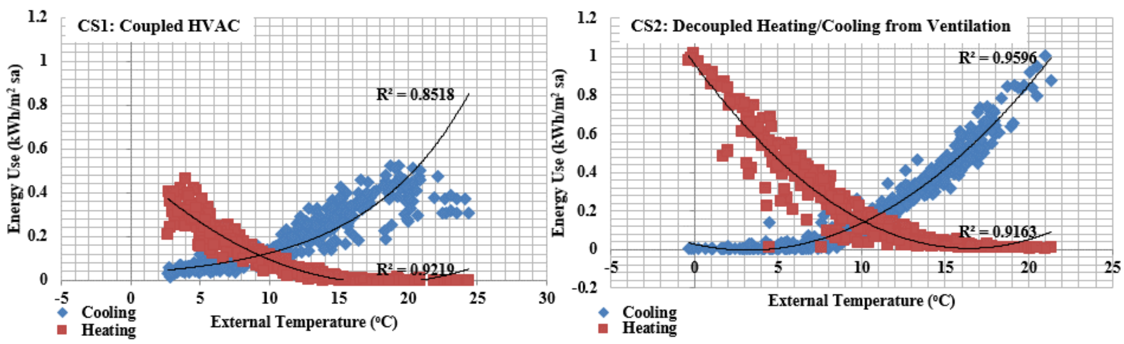


Figure 6-3: Cooling/Heating daily energy use per sales is in correlation with external temperature

Figure 6-4 shows the fans daily energy use in correlation with the external temperature. There difference on the HVAC control strategy between the two stores is obvious in the fans energy use. 24h HVAC in CS2 resulted in a generally constant fans daily energy use. Slightly lower is the one that is simulated for Sundays when the trading hours are reduced to half. The fans energy use on Christmas and Easter day closures which is mainly due to ventilation are indicated with a black circle.

On the other hand, for CS1 and during warmer days the fans energy use is higher while during colder days this energy use is reduced significantly because these temperatures enable the night cooling operation to cool effectively the sales area although fans in night free cooling mode are in operation at the higher air flow rate (6m^3/s). For London climate where the night time temperatures do not exceed the 15-17 ^{o}C, night cooling is a solution with good potential for buildings that has high cooling demand as the frozen food case study stores.

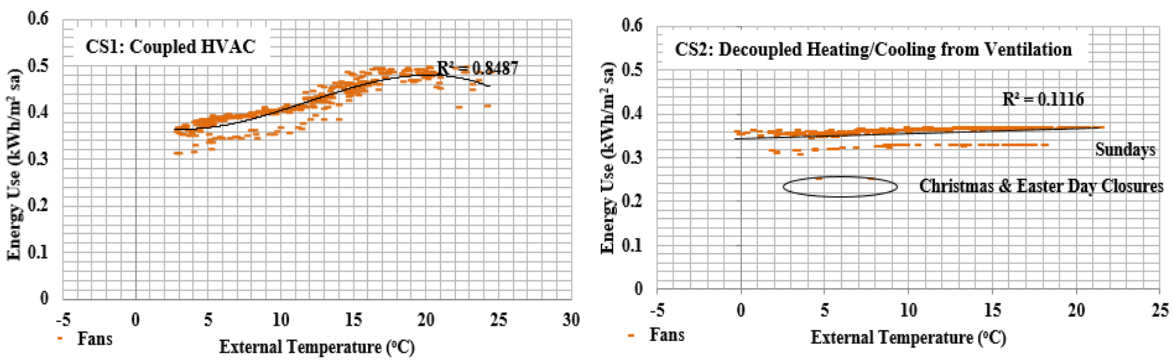


Figure 6-4: Fans daily energy use per sales in correlation with external temperature

Figure 6-5 shows the refrigeration energy use of both stores in correlation with the sales area temperature. In this figure only the display cabinets (for both chilled and frozen food) energy use is presented. There is a difference in the daily energy use of the display cabinets between the two stores. CS2 sales area temperature remains almost stable during trading and non-trading hours and as the HVAC operation is for 24h and this lead to almost stable display cabinets' energy use. On the other hand, CS1 where night free cooling results in lower temperature in the sales area (up to 16^{o}C) presents stratification in the daily energy use of the display cabinets. Lower temperatures in the sales area lead to up to approximately 17% lower daily energy use of the remote refrigeration cabinets. These results have been also verified in laboratory experiments with the same refrigeration cabinet for different ambient temperature (Section 4.3.2.3). The load of the refrigeration cabinets is mainly driven by conditions in the sales area, infiltration from the surround environment around the cabinets through radiative, convective and conductive heat transfer.

The amount of ambient conditions interactions depends on the type of cabinet, operating and control conditions. For example, the infiltration of the multi deck open front chilled food cabinets and the open top frozen food cabinets is higher than the lift-up lid frozen food cabinets (Carbon Trust, 2012). In the case study the majority of the cabinets are lift-up lid cabinets (85% of the cabinets) and consequently the heat gains from the compressors' heat release to the sales area are significantly higher than the heat transfer from the cabinets to the sales area air. In both stores, the open cabinets are located in the back area and this is the reason why this area presents slightly lower temperature than the other areas of the stores. This is better observed in CS1 as CS2 presents more stable temperature and its back area is also affected from the south west single glazed façade. A stronger correlation (0.9) is found as well between cooling demand with the refrigeration energy use in CS1 while a weaker (0.6) is observed for CS2 for the above reasons.

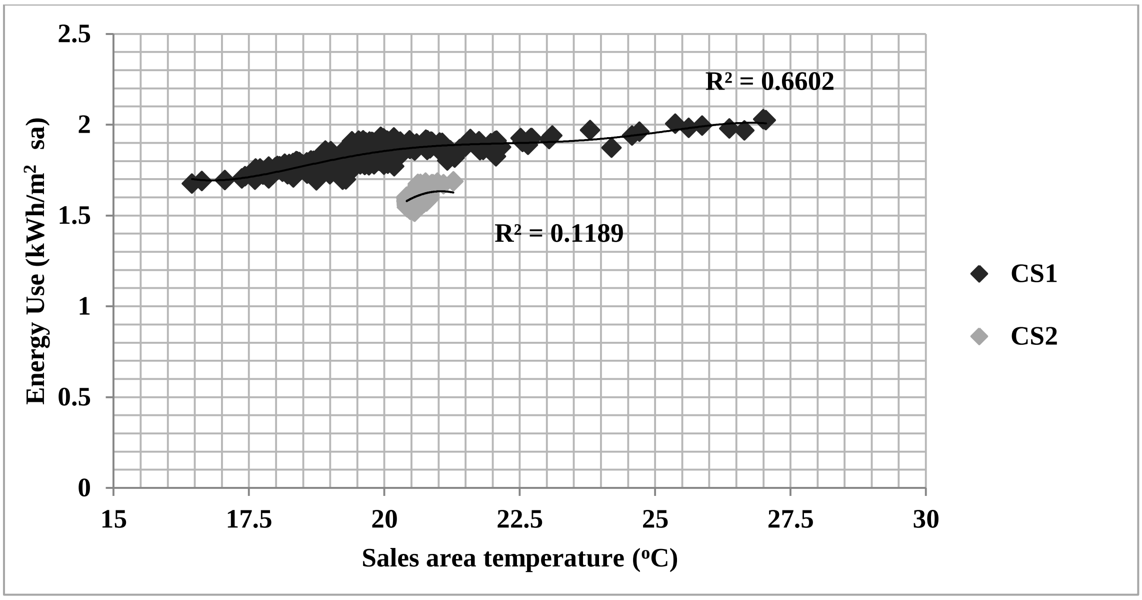


Figure 6-5: Remote cabinets' daily energy use per sales area in correlation with sales area temperature

The amount of the heat gains and the cabinets' energy use of the cabinets are also influenced by customers' usage and the restocking of the products. During an opening of a glass lid an amount of warm air entering the case and consequently the refrigerants' coil temperature is increased which afterwards increases the compressor running time. Data showed (Section 4.3.2.1) that there is a stable number of openings during the days apart from Saturday which was also the busiest day on the stores according to transactions data. Overall, the increase of the temperature leads to increase cabinets' energy use.

Figure 6-6 and 6-7 present the hourly energy use breakdown of both stores for two typical winter and summer days. Most energy intensive system is the refrigeration for both stores during all hours. However, there is a difference in the energy use of the refrigeration system in winter days as night free cooling is effective and sales area temperature is around 16^{o}C. This is not observed in CS2 (Figure 6-7) because the sales area temperature is maintained at the same levels all the 24h for the whole year. Heating and cooling energy use is also different and in CS2 it is observed a high cooling energy demand which is explained both from heating gains from the refrigeration remote cabinets' equipment and the solar heat gains from the south-west single glazed façade. The same applies for the heating requirements.

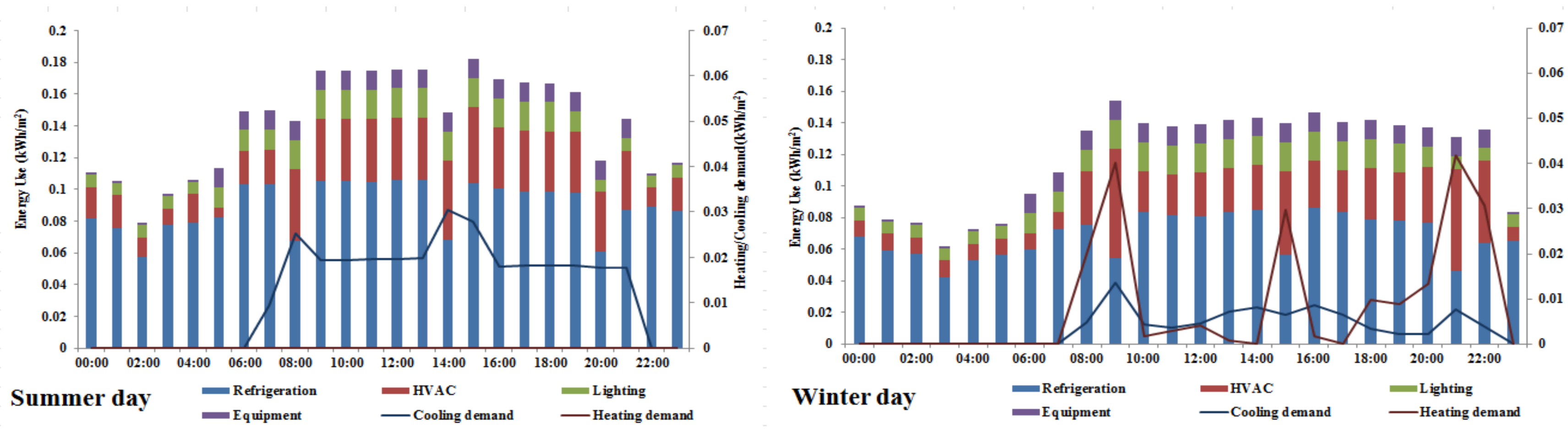


Figure 6-6: Hourly energy use breakdown for typical days, CS1

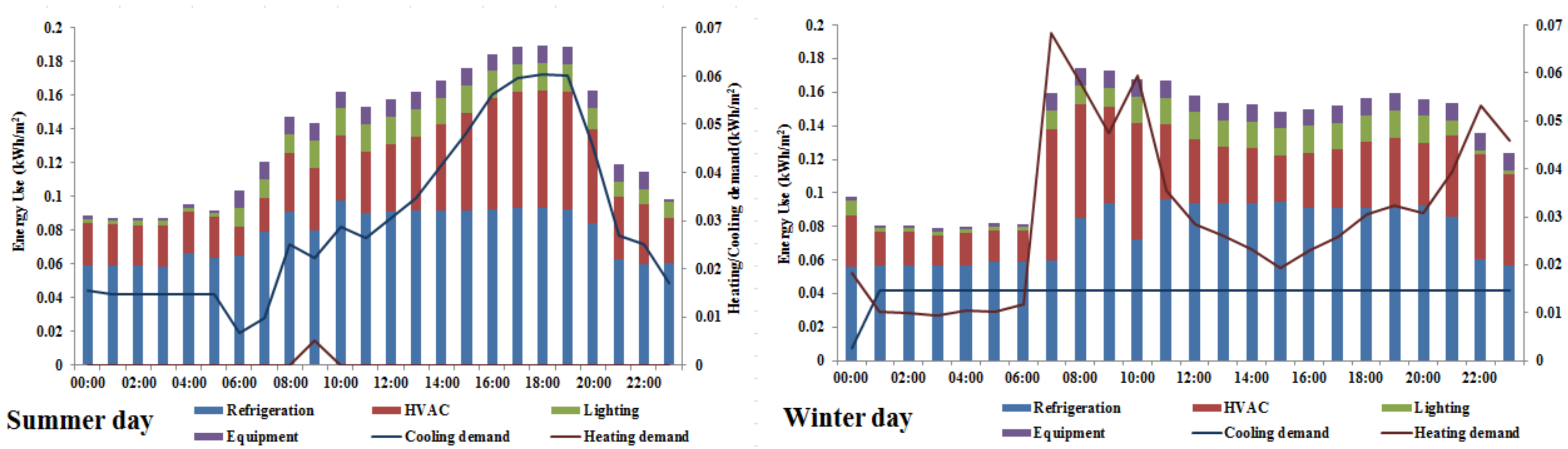


Figure 6-7: Hourly energy use breakdown for typical days, CS2

Figures 6-8 and 6-9 present heating and cooling energy use for the two stores. Heating energy use is lower in CS1 while CS2 building is more vulnerable to external conditions due to its fabric and thermal mass (medium weight building). Moreover, the 24h operation of the HCAV in CS2 it is observed in winter and summer days as a significant percentage of night time hours both heating and cooling are required which eventually increases the total energy use of the store.

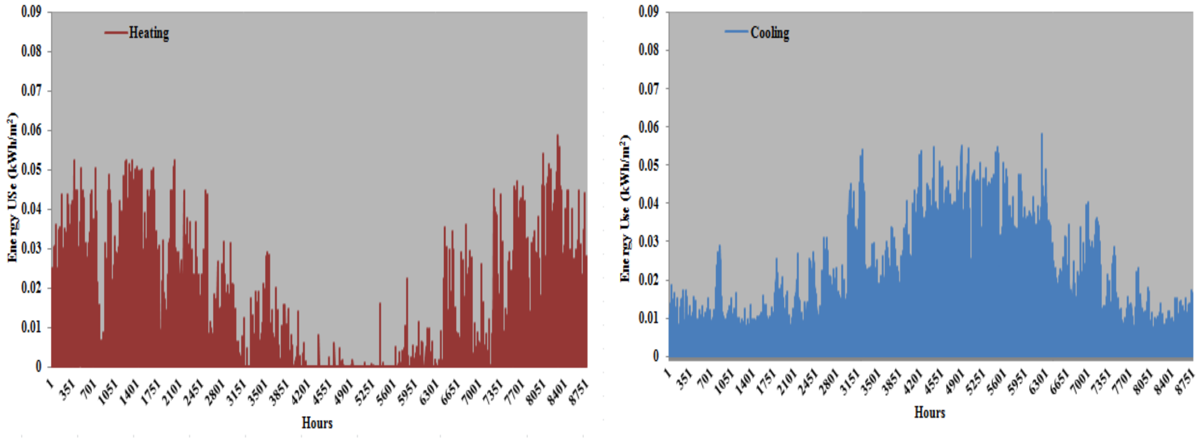


Figure 6-8: Hourly heating/cooling energy use per sales area, CS1

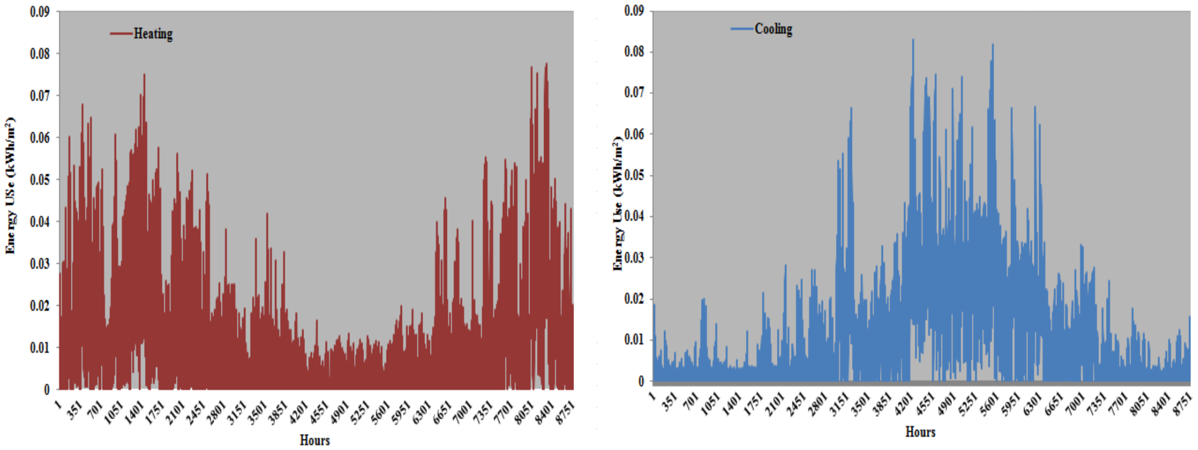


Figure 6-9: Hourly heating/cooling energy use per sales area, CS2

6.2 Energy model's applications

This section present different applications implemented in the validated against real measurements model. Table 6-1 summarises all the parameters' changes in the subsystems of stores which refer mainly in the most energy use intensive systems; refrigeration, HVAC and lighting. Several changes in the building envelope have been done in decoupled HVAC case study as well as its construction enabled so in order to evaluate the interdependence of the better energy use performance of the subsystems with the external weather conditions.

Table 6-1: Models applications amendments

Subsystem	Incentives	Strategies
Lighting	Energy savings in lighting system	LED Lamps
	High levels of light intensity in CS2	Daylight
HVAC	Energy savings in HVAC system	Hours of operation
	a) Reduction in cooling requirements which are high due to heat release from remote refrigeration equipment b) Higher energy use performance of remote refrigeration cabinets	Night Cooling
Building envelope	High correlation of heat gain/losses through the single glazed windows with the HVAC	Double glazed windows
		Better insulation (walls, roof)
Refrigeration	a) Energy performance of the refrigeration system b) EU F-Gas regulation for low GWP refrigerants and natural refrigerants	Centralised systems Versus Remote system i) Centralised DX system ii) Cascade system iii) Transcritical CO_2 booster

6.2.1 Lighting system and Daylight

The lighting system upgrade took place in both case study stores in October 2015. Typical T8 type fluorescent luminaires replaced by LED lamps with 38% less power consumption. The results due to this change are presented here. Figure 6-10 shows the two lighting systems before and after the upgrade and table 6-2 summarises the lighting loads per thermal zone before and after the upgrade in both stores.

Figure 6-10: Lighting before (left) and after (right) the upgrade with LED lamps

Table 6-2: Lighting loads per zone before and after the upgrade

Lighting System (W)	Before Upgrade		After Upgrade	
	Tills Area	Display Area	Tills Area	Display Area
CS1	2268	6804	1407	4820
CS2	2484	3240	1546	2609

The above changes reduce the total energy use by 2.4 % and 1.3 % the total energy use of CS1 and CS2 respectively. The lighting systems energy use dropped by 23.5 %. It is worth mentioning that the heating requirements of both stores increased as the internal heat gains from lighting are decreased. After the upgrade of the systems on October 2015, metered data for total energy use are available and confirmed the reduction of the total energy use (Section 4.2).

Refrigeration energy use is not affected by the lighting changes as HVAC energy use performance is not affected although heating energy requirements increased by 2.5 – 6.5 % but cooling requirements which are dominant in the HVAC energy use decreased by 2-3.7 %.

Table 6-3: Percentage changes from baseline in the total energy use and the sub-systems

					HVAC		
	Total	**Refrigeration**	**HVAC**	**Lighting**	Heating	Cooling	Fans
CS1	**2.4%**	0.0%	0.3%	23.3%	-6.4%	3.7%	0.4%
CS2	**1.8%**	0.0%	0.1%	23.8%	-2.5%	2.1%	0.0%

Light intensity results in CS2 showed high levels of light intensity in tills and the middle area of the sales area especially in the evening times (Figure 4-24). This is due to the orientation of the building and the glazed south-west façade. The average levels are 500 lux which during evening times reaches up to 2000-3000 lux. For that reason daylight control strategy is implemented in order to maintain the ligating levels at 750 lux according to recommendation from CIBSE Guide A (2015) and literature review from supermarket stores (Section 2.4.2).

Three sensors are installed in the sales area; one in the tills and two in the display area (Figure 6-11). They have been installed in 0.8m height in order to ensure proper display conditions of the products.

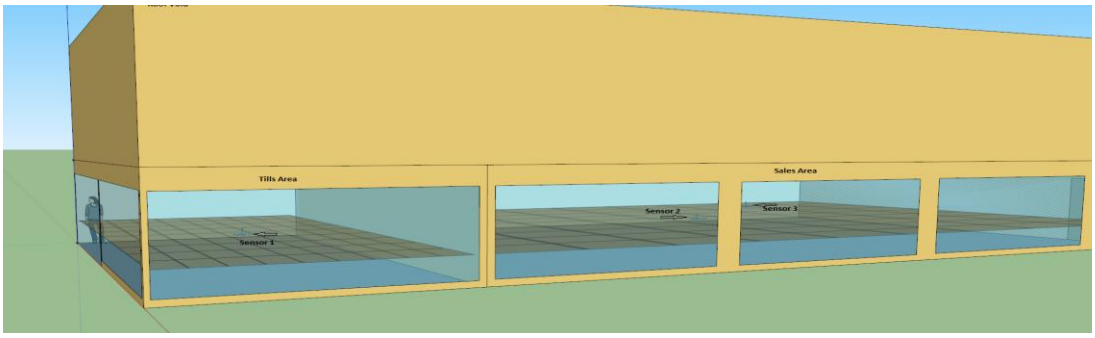


Figure 6-11: Lighting sensors inside CS2 sales area

Results showed a 42.3% reduction in the lighting energy use which equals to 3.2 % in the total annual energy use of CS2 store.

Table 6-4: Percentage changes from baseline in the total energy use and the sub-systems

					HVAC		
	Total	**Refrigeration**	**HVAC**	**Lighting**	Heating	Cooling	Fans
LED upgrade & daylight	**3.2%**	0.0%	0.4%	42.3%	-3.8%	4.0%	0.0%

Figure 6-12 and 6-13 present the changes in hourly lighting energy use in the baseline CS2 mode (red line) and after the upgrade with the LED lights and lighting control sensors for two indicative months. Solar direct radiation is also indicated in the figures to enable the visualisation of the daylight during these two months. A reduction in the lighting energy use is observed in warm months when daylight is effective and lighting system can be switched off.

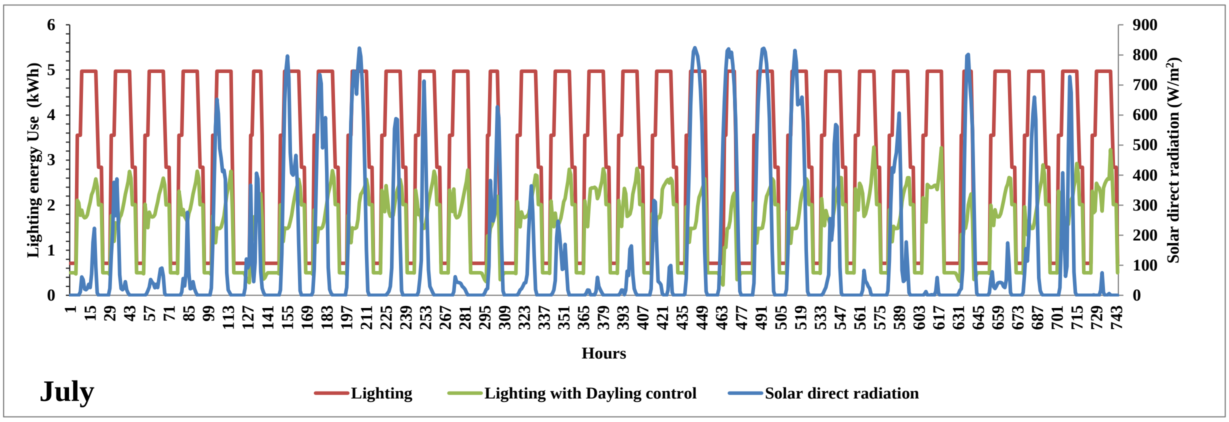


Figure 6-12: Lighting energy use before and after LED upgrade and lighting control levels for indicative warm month

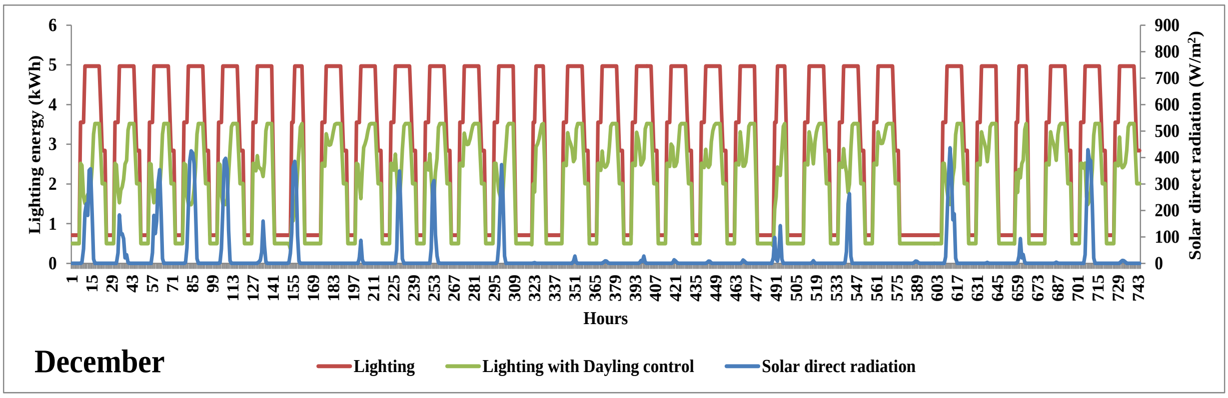


Figure 6-13: Lighting energy use before and after LED upgrade and lighting control levels for indicative cold month

6.2.2 HVAC control strategies

HVAC systems contribute to a considerable amount of the total energy use and it is estimated that around 20%-35% of a supermarket's energy use consumed in HVAC. Food retail markets are complex environments designed to have high visibility display of goods with sufficient thermal comfort to encourage longer stay for the customers. The refrigeration requirements of the display goods and indoor environmental conditions are sometimes in conflict because of the significant heat exchanges between them. Thus, optimised control strategies for HVAC systems are required in order to achieve acceptable environmental conditions for customers and good operation of the refrigeration system.

In the frozen food supermarkets with the high refrigeration load, HVAC control strategy is of great importance for the operation of the big amount of refrigeration equipment. Considerable opportunities exist to reduce the HVAC energy use but the total energy use of the store as well. The key issue is to reduce the HVAC energy use without affecting the energy performance of other sub-systems and especially the refrigeration system. In this section free night cooling will be optimised for CS1 and implemented as well in CS2. The scope is to investigate the effect of the night ventilative cooling within both coupled and decoupled HVAC cases in order to evaluate its general potential for savings.

<u>Ventilative vs. active night cooling</u>

Night Cooling (NC) has been receiving attention in recent years because of the energy saving potential mainly in buildings with reasonably high thermal mass. Most published work focuses on domestic buildings and offices. This section is a study for the energy use and the potential for savings due to mechanical night ventilative cooling of the HVAC systems of frozen food supermarkets. Few studies to date have considered ventilative cooling strategies for supermarkets (Wu et al., 2006). Wu et al. has concluded that longer night cooling activation results to fewer hours of AC system operation and higher energy savings (Wu et al., 2006). However, studies for offices and other non-domestic building have indicated that three control aspects should be taken into consideration (Kolokotroni, 1998); duration, system initiation and system continuation in order to maximise energy savings. In this case study, the following rules were implemented: i) initiation: $T_{out}<T_{in}$, ii) continuation: $T_{out}<T_{in}$ and $T_{out}-T_{in}<T_{offset}$ and iii) termination: continuation rule and $T_{in}=T_{min}$.

The continuation rule ensures that the outside air brought in is effective in cooling the building. When the temperature difference between inside and outside air (T_{offset}) is low, the incoming air will have little effect on cooling while the ventilation fan energy use will increase the total energy use. However, if the outside air temperature is significantly lower than the inside air temperature, T_{min} will be achieved fast and the duration of night ventilation is decreased (Aria & Akbari, 2007).

Moreover, although NC could increase the total energy savings of the stores, attention should be paid in the air conditions (temperature and RH) brought in store as it may affect the cold surfaces of the cabinets from condensation or it may be harmful to the operation of the refrigeration system or its controls. The stores' LT cabinets are glass lift up lid cabinets which during NC operation remain closed so the evaporator coils are not affected by the ambient air (if hot or humid) and thus crucial problems are not created in the evaporator coils operation. However, action might be taken to prevent condensation on the surface of the glass. Fogging and risk of condensation on the external side of the glass or the multi deck cabinets' curtains might occur in humid climatic conditions while reducing the ambient temperature. For that reason, experimental results from laboratory test in the CSEF centre facilities took place in order to evaluate the $T_{surface}$ of the glass lid of the LT cabinets (Section 3.6.2 & 4.3.2.3). This temperature gives insights of the RH levels that must be maintained in the sales area in order to prevent condensation on the glass lid.

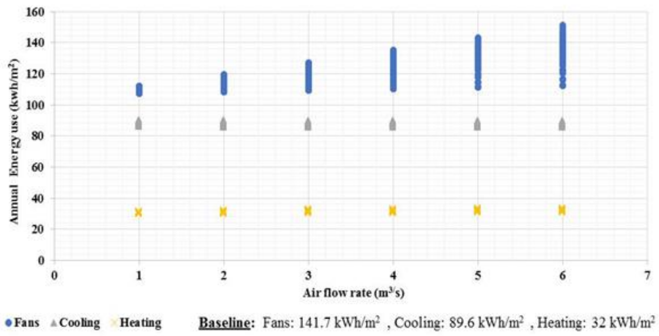
6.2.2.1 Coupled HVAC: CS1

NC is already in operation in CS1 during non-trading times. The system is designed to provide free night cooling with 6 m^3/s when the return air and outside air temperature have 1^oC difference and until the inside temperature reaches 16^oC.

The parametric analysis was performed for different airflow rates according to fan speed (1-6 m^3/s), T_{offset} (1-20 ^oC) and T_{min} (10-17^oC). Minimum temperature inside the store was chosen not to fall below 10^oC in order to avoid condensation on the glass cabinets. While setting the T_{min} to the lowest levels (10^oC) and according to lab experiment results (section 4.3.2.3) that glass surface temperature does not drop below 7^oC, RH should be maintained lower than 80% which would ensure avoidance of condensation. According to simulation results, the sales area RH does not exceed the 80% during night time.

Figure 6-14 presents fan, heating and cooling energy use for different air flow rates, T_{offset} and $T_{min;}$ the combinations are integrated and are presented as a range of energy use in the graph. Figure 6-15 presents the cooling energy use for different T_{offset} and T_{min}. The air flow rate during night cooling plays an important role as the higher airflow increases the fans' energy use. However, low air flow rates could have similar effect on cooling demand with a reduction of heating requirements during the following day. In Figure 6-14, the fans' annual energy use range is indicated as a result of the different T_{offset}. Higher air flow rate has wider range because the reduction of the internal temperature to T_{min} is achieved fast and the duration of the NC is decreased.

For lower air flow rates there is a point where the maximum total energy use reduction occurred; energy use starts increasing until reaching the point where NC is not effective (total energy use equals the total energy use when NC is off) (Figure 6-16). This is due to the increase of the cooling energy which afterwards leads to an increase of the total energy use (Figure 6-15). This point is observed to range between 5-7^{o}C. Refrigeration system energy use decreases with lower T_{min} but after 5-7^{o}C T_{offset} starts increasing again until the refrigeration energy use observed when NC is not in operation (Figure 6-17). The optimum combinations of parameters leads to up to 3 % of the total energy use from the baseline model – this equates to energy use reduction of 35.3 kWh/m^2/year in the store.



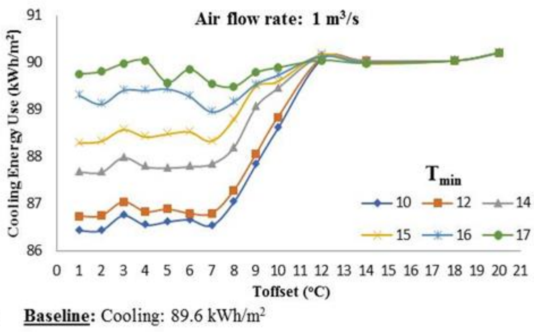
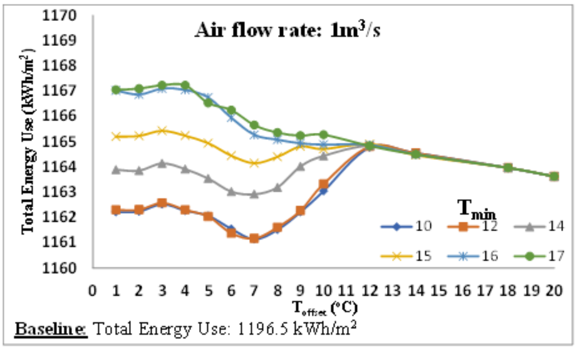


Figure 6-14: Heating, Cooling and Fans energy use for different air flow rates (CS1), Figure 6-15: Cooling energy use for different T_{ofsset} and T_{min} (CS1)



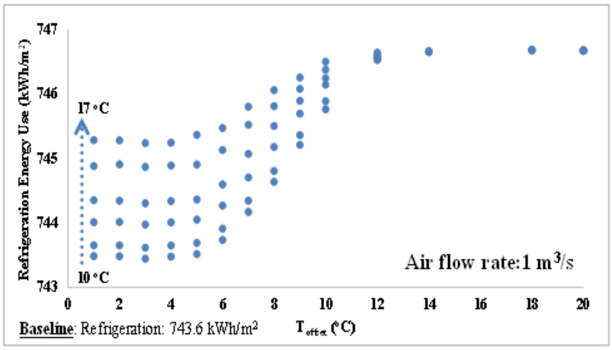


Figure 6-16: Total energy use for different T_{offset} and T_{min} (CS1), Figure 6-17: Refrigeration energy use for different T_{offset} and T_{min} (CS1)

Finally, figure 6-18 summarises the significance of the optimised control strategy of the HVAC system for NC operation. Lower air flow rates reduce the fans energy use and enable the bigger duration of the NC. Moreover, lower T_{min} inside the store reduces slightly the cooling demand of the store in comparison with the baseline model (dark blue) without affecting negatively the refrigeration system operation.

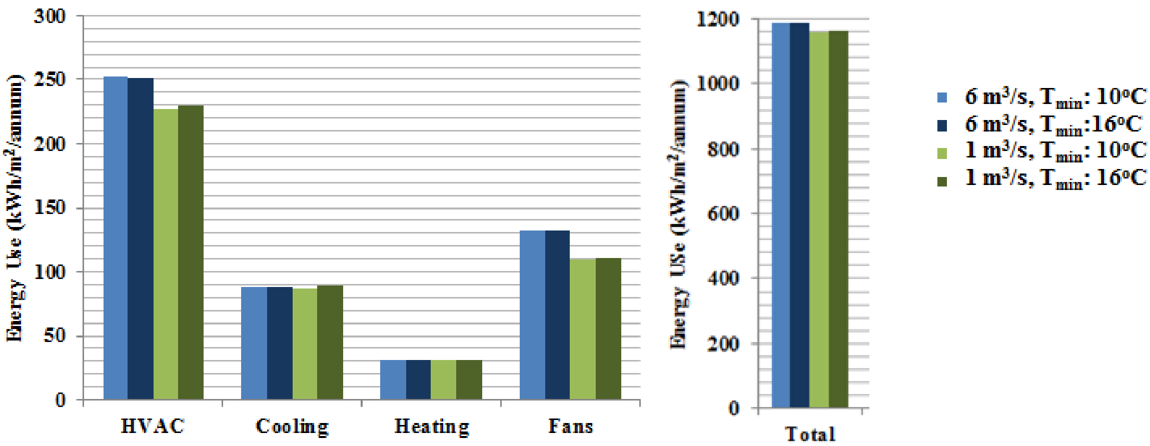


Figure 6-18: Total annual energy use and sub-systems energy use for different air flow rates and T_{min}, CS1

6.2.2.2 Decoupled heating/cooling from ventilation: CS2

For CS2 two different ways of providing night cooling were studied; exhaust and intake night ventilation. The same parameters as CS1 were used for the parametric analysis; different airflow rates according to fans speed (1-10 ach), T_{offset} (1-20 ^{o}C) and T_{min} (10-17^{o}C).

For both scenarios the HVAC control strategy of the store changed to facilitate night ventilation as follows: operation between 6:00 to 23:00 for weekdays and Saturdays and 9:00 to18:00 for Sundays rather than 24h of the baseline model. This change alone would save 41 kWh/m^2 sales area per year (4%) without any effect on the refrigeration system operation and consumption but with significant decrease in the HVAC (15%) due to reduction in fans energy use and cooling requirements.

Without any change to the HVAC system of the CS2, control strategy for exhaust night ventilation resulted that the lowest air flow rates resulting to lower total energy use due to reduced fans energy consumption (Figure 6-19). Higher air flow rates presented to have strongest correlation with the T_{offset} as mentioned for CS1; while T_{offset} increases, a sharper reduction is occurred and this is because the cold air that is brought inside has bigger effect on the inside air temperature and T_{min} is achieved quickly and thus the duration of the NC is decreased.

It is also observed that for low air flow rates there is a specific T_{offset} where the total energy use starts slightly increasing (T_{offset} >5°C) . After that point, where the optimum total energy use reduction occurs, the cooling energy demand increases and with higher T_{offset} the cooling energy use increases more significantly as the NC is not more effective (Figure 6-20). For higher air flow rates this T_{offset} increases up to 7 °C. The optimum combinations of the parameters lead to 3.6% reduction in the total energy use which equals to 40.8 kWh/m^2 per year. Refrigeration energy use was found to follow the same pattern with what was analysed for CS1; after a specific T_{offset} refrigeration energy use increases to the levels that NC is no more effective.

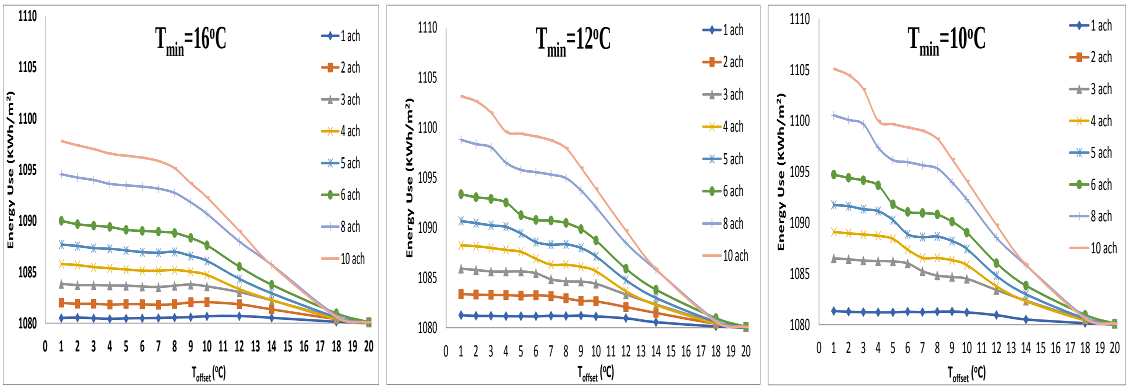


Figure 6-19: Total energy use with different air flow rates for different T_{offset} and specific T_{min} (CS2)

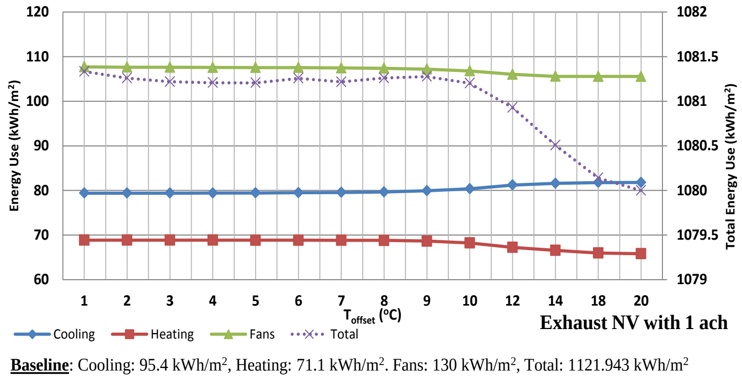


Figure 6-20: Cooling, heating, and fans energy use for different T_{ofsset} for T_{min}=10oC and with 1 ach flow rate (CS2)

For intake NC the results agreed with what has been discussed for exhaust NC control strategy but with results from CS1 as well. The air flow rate is a key parameter for the night cooling and the lower air flow rates lead to lower total energy use due to fans energy use decrease but with the same effect of night cooling due to the fact that the night cooling duration is bigger. However, as is proposed for CS1 for lower air flow rates there is point that the cooling requirements start increasing and NC is no more effective (T_{offset} > 7°C). With higher T_{offset} than 2°C, although the cooling energy demand increases, the fans energy use drops more significantly and leads to lower total energy use. The highest total reduction observed for lower air flow rates. As the T_{min} increases the duration of the NC is decreasing and unremarkable reduction is observed on the total energy use. A reduction of around 3.2% on the total energy use (35 kWh/m^2/annum) is calculated for this case study for intake night ventilation.

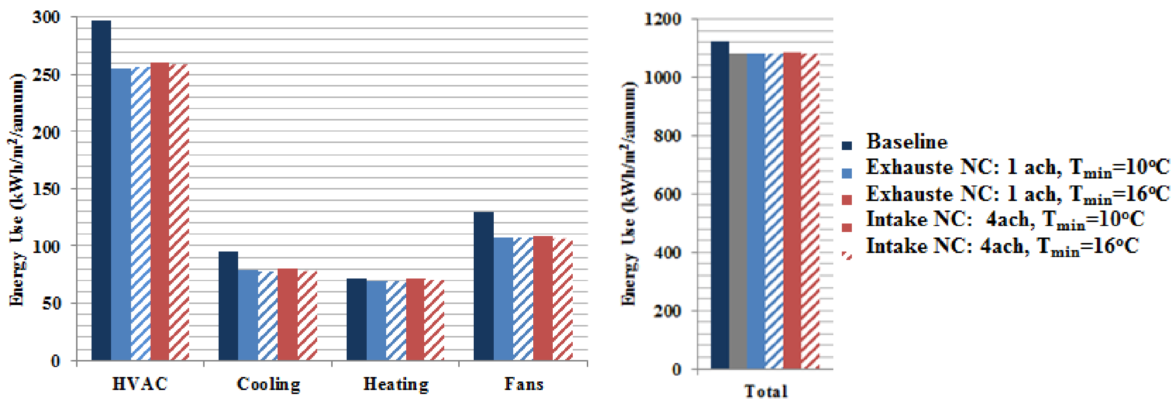


Figure 6-21: Total annual energy use and sub-systems energy use for different air flow rates and $_{Tmin}$, CS2

Finally, figure 6-21 summarises the significance of the optimised control strategy of the HVAC system for NC operation for CS2. It includes results from both exhaust and intake NC. Lower air flow rates are presented as they are lead to the highest reductions in all systems due to reduction in fans energy use. Lower T_{min} inside the store reduces results in same reduction as higher T_{min} because different T_{min} is not as strongly correlated with the cooling demand as in CS1. This can be explained by the fact that CS1 is a heavy-weight building and is able to store the amount of cooling energy better than CS2 which is a medium-weight building.

6.2.3 Building construction applications

This section refers mainly to CS2 with decoupled HVAC system only as its construction enabled so. According to the previous evaluation and the correlation of the heat gains/losses through the single glazed window facades (south-west and north-west) with the HVAC energy use, amendments on the fabric materials are implemented in order to evaluate the difference on the total energy use and their impact on sub-systems' performance such as the refrigeration and the HVAC system. Single glazed windows are also implemented for simulation to CS1.

Table 6-5 presents the results of the changed on the building construction.

The first changes refer to double glazed windows in sales area (U-value= 2.6 $W/m^2 K$). An insignificant reduction is observed in the total energy use of the CS1 which is a result on the 0.3 % reduction of the HVAC system. Heating and cooling energy use both drops with double glazed windows with the heating needs reduction to be more dominant. Analysis on the correlation between the heating gains/losses through windows with the cooling and heating energy use respectively showed a strong positive correlation especially between heat losses and the heating requirements (0.92). Hence, by upgrading to double glazed windows in CS1, the biggest savings occurs in the heating energy use as expected.

Regarding CS2, results due to enhance of the single glazed windows in the sales area are more remarkable. According to them although a small reduction observed in the total energy use (1.5%) which is due to HVAC energy use reduction, significant are the changes on the heating and cooling requirements in the sales area. Double glazed windows reduces the heating requirements by almost 10% but the increase of the cooling requirements on the sales area end to only 1.5% reduction on the HVAC system. The sensitivity analysis on the heating losses through the windows showed a strong correlation with the heating requirements (0.86) and this is why the double glazed windows lead the biggest reduction in the energy use to be in the heating demand. However, due to the fact that two of the facades are windows, the implementation of double glazing window lead to an increase in the cooling energy use due to the solar gains.

Table 6-5: Percentage changes from baseline in the total energy use and the sub-systems

CS1					HVAC		
Scenarios	**Total**	**Refrigeration**	**HVAC**	**Lighting**	Heating	Cooling	Fans
#1	**0.1%**	0.0%	0.3%	0.0%	1.6%	0.5%	-0.1%
CS2					HVAC		
Scenarios	**Total**	**Refrigeration**	**HVAC**	**Lighting**	Heating	Cooling	Fans
#1	**1.5%**	0.0%	1.5%	0.0%	9.9%	-3.0%	10.3%
#2	**0.7%**	0.1%	3.1%	0.0%	6.7%	3.6%	-0.1%
#3	**0.8%**	0.1%	-2.7%	0.0%	-24.2%	9.5%	10.9%

#1: Doubled glazed windows (U-value= 2.6 W/m^2)

#2: North – west single glazed side replaced with an external wall (U-value=0.35 W/m^2)

#3: Insulation above the acoustic tiles between sales area and Void Area (U-value=0.25 W/m^2) instead of the external roof insulation of the Void Area

Higher insulation on the north-west side lead to reduction to both heating and cooling demand which results to 3.1% reduction in the HVAC system and ends to only 0.7% in the total energy use. Finally, by changing the insulation of the external roof and installing it in the interior ceiling reduces the cooling demand and increases heating demand because of changes in the void air temperature which acts as an additional layer. Alternative refrigeration systems

6.2.4 Alternative refrigeration systems

Researches have shown that there are difficulties in food retail to make a final choice when it comes to refrigerants and systems type. Many refrigerant options and system configurations have been battling to receive attention. Supermarket refrigeration system has been in the environmental spotlight and it has been revealed that leakage of HFCs in centralised systems is a major challenge. At the same time, energy efficient has gained top priority in order to save costs and reduce the carbon footprint. Lately natural refrigerants and mainly CO_2 is becoming mainstream refrigerant in the refrigeration systems for retail stores and a number of novel designs are being used in the industry including cascade transcritical, transcritical booster and secondary loop (ATMOsphere, 2015).

Work to date has focused on typical supermarkets with MT load to be the dominant in the refrigeration system. There is no published work focusing on investigation of different refrigeration systems including plugged-in and centralised systems in an operating case study supermarket store. Beshr et al, (Beshr et al., 2015) presented results from comparison between different refrigeration systems in a supermarket modelled in EnergyPlus but the reference model was based on the construction reference supermarket model developed by the U.S Department of Energy (Deru et al., 2011). Ge et al. also presented a supermarket model in SuperSim validated against operational data which afterwards was used to compare the energy performance of conventional R404A centralised system with transcritical CO2 system (Ge & Tassou, 2011).

This section presents and discusses 3 different combinations of system technologies and refrigerants which are referred as "systems". They include one parallel centralized system feed by HFV refrigerant, one cascade system with high pressure (HP) supplied by HFC refrigerant and low pressure (LP) supplied by CO_2 and one CO_2 transcritical system. Energy and environmental performance of those systems are presented and compared with the remote system of the CS1. The cost savings are also briefly discussed.

As both stores include the same refrigeration equipment for display cabinets and refrigeration load is approximately the same in terms only of display cabinets, CS1 is used in this section as a reference baseline frozen food supermarket store.

The London Design Summer Year (DSY) from CIBSE is used as default weather data. The DSY file represents warmer than typical year and is used to evaluate consequences in centralised systems operation. Heathrow-London was identified as location in which the refrigeration systems comparisons take place because the CS1 is located nearby Heathrow Airport. Figure 6-22 presents the monthly outdoor temperature for London-Heathrow based on hourly data and Using BWM plot. The highest frequency for temperature is at 9 ^{o}C for 588 hours per year (6.71%). According to Figure 6-23, the outdoor temperature in London is higher than 27 ^{o}C for about 1.28% of the time and transcritical operation occurred for the cases where the CO_2 is used at the HP of the CO_2 refrigeration system

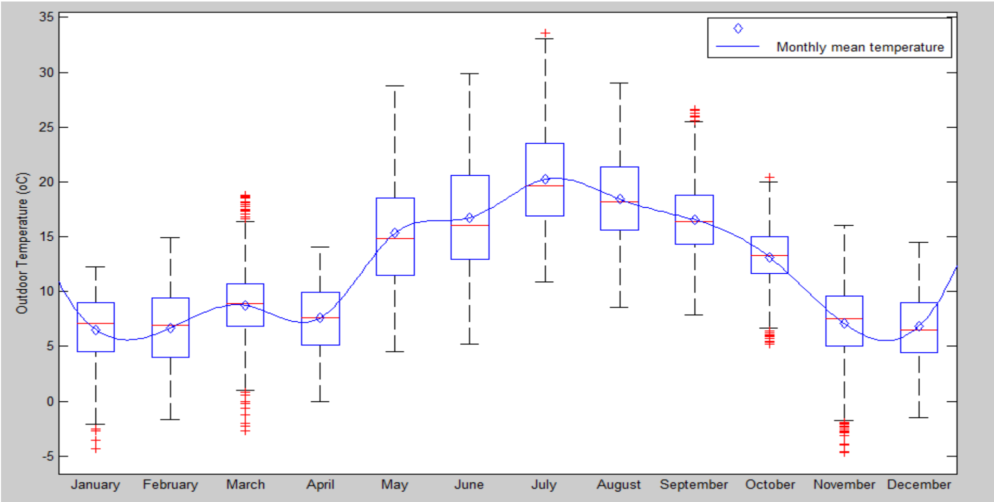


Figure 6-22: BWM Outdoor environmental condition of London-Heathrow based on hourly data

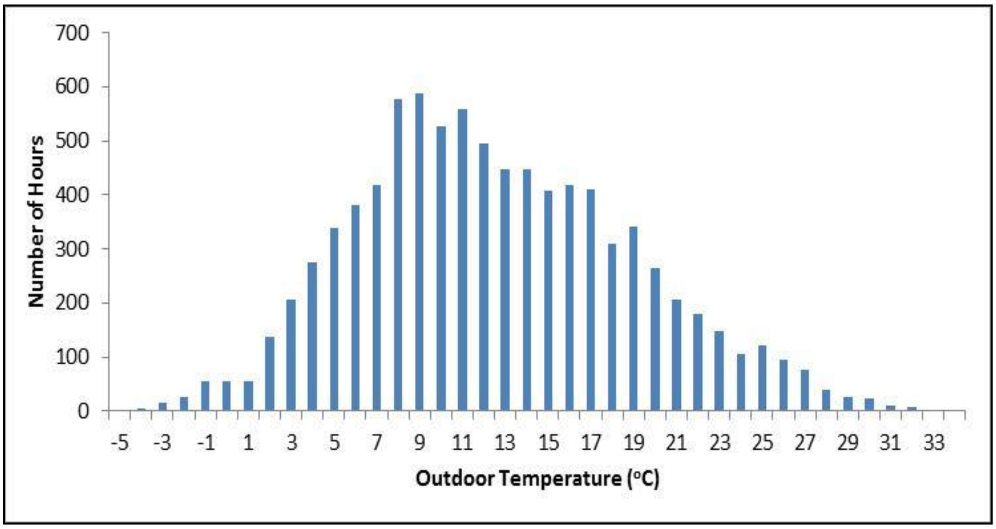


Figure 6-23: Frequency of different outdoor temperatures

6.2.4.1 Refrigeration systems configurations

Table 6-6 summarises the different configurations of the refrigeration systems that are implemented in the CS1 EnergyPlus model.

Table 6-6: Summary of the different refrigeration systems configurations

	Types		**Refrigerant liquid**		**GWP**	
	MT	**LT**	**MT**	**LT**	**MT**	**LT**
S1	Open front multi deck integrated cabinets	i) Lift up lid integrated cabinets	R404A	R134a	3922	1430
		ii) Open top case integrated cabinets		R404A		3992
S2	Centralised DX system	Centralised DX system	R134a	R134a	1430	1430
S3	Cascade	Cascade	HP:R134a LP: R744	HP:R134a LP: R744	HP:1430 LP: 1	HP:1430 LP: 1
S4	Transcritical CO_2 booster		R744		1	

Stand-alone refrigeration system (S1):

The baseline model includes stand-alone (plug-in) refrigeration cabinets for both MT and LT system. Table 6-7 presents the refrigeration loads and details in refrigerant type and amount of charge (kg). The refrigerated cabinets are located in the sales area. For this application the heating (warm air) produced from the MT condensers only is extracted outside to avoid a very high temperature in sales area. An example of the LT horizontal curved glass lift-up cabinet, the LT open top cabinet and MT open vertical refrigerated cabinet used for the baseline model are illustrated in Figure 6-24.

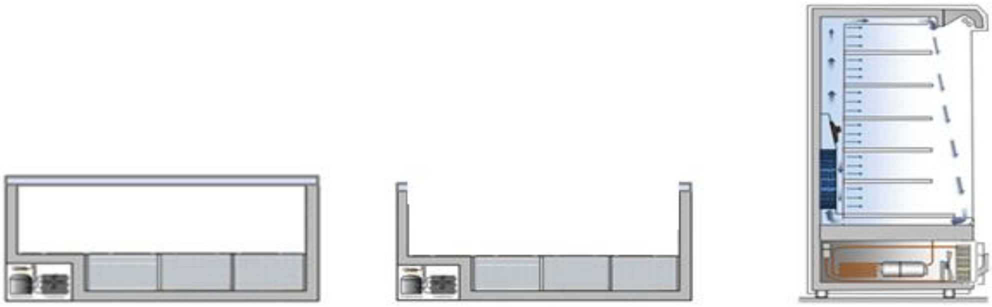


Figure 6-24: a) LT lift-up lid frozen food cabinet, b) LT open top frozen food cabinet, d) MT open vertical cabinet

Table 6-7: Refrigeration equipment (S1)

	MT		LT	
	Open front multi deck		**Lift up lid**	**Open top case**
Number	8	2	70	3
Capacity (kW)	2.18	1.46	0.36	1.64
Dimensions (L/D/H-m)	2.5/0.9/2	1.9/0.9/2	1.7/0.74/0.89	1.75/1./0.9
Operating temperature (^{o}C)	1 to 9	3 to 9	-20 to -22	-23
Defrost type	Off Cycle	Off Cycle	Off Cycle	Off Cycle
Refrigerant	R404A	R404A	R134a	R404a
Compressor COP	2.3	2.3	1.5	2.3
Condenser Type	Air Cooled	Air Cooled	Air Cooled	Air Cooled
Refrigerant charge (kg)	2.8	1.4	0.47	0.75

The stand-alone refrigerated cabinets are self-contained refrigeration systems. This type of refrigeration systems is widely used in small and supermarkets. The biggest advantage is the ease of maintenance/replace for case of faulty unit without causing any effect to the rest of the refrigerated cabinets. On the other hand, the low compressor efficiencies lead to lower performance comparing with the centralised refrigeration systems. One reason for the low compressor efficiencies is due to the one speed operation without effect from the required load capacity. Energy reduction can be achieved by varying the compressor speed with respect to load required. This can easily achieved by installing a compressor variable speed inverter. Nowadays, a lot of effort focused in this solution. Nonetheless, this application still in very early stage and more data required to proof the concept of variable speed inverters for low capacity compressors. In additional, the cost for this solution needs to be further investigated.

Centralised system (S2)

The parallel refrigeration systems solution is illustrated in Figure 6-25. Both systems consist from an air cooled condenser, a direct expansion (DX) evaporators and the compressor rack. Other components such as refrigerant liquid receiver, filters and safety or regulating valves are not presenting on the simplified diagram. The parallel systems are used to satisfy the refrigeration MT and LT loads of the store and the details of the systems are given in table 6-7. R134a is used for both systems. The parallel application is used in small supermarket or convenient store applications. The advantage of this application is the individual operation for the MT and LT systems.

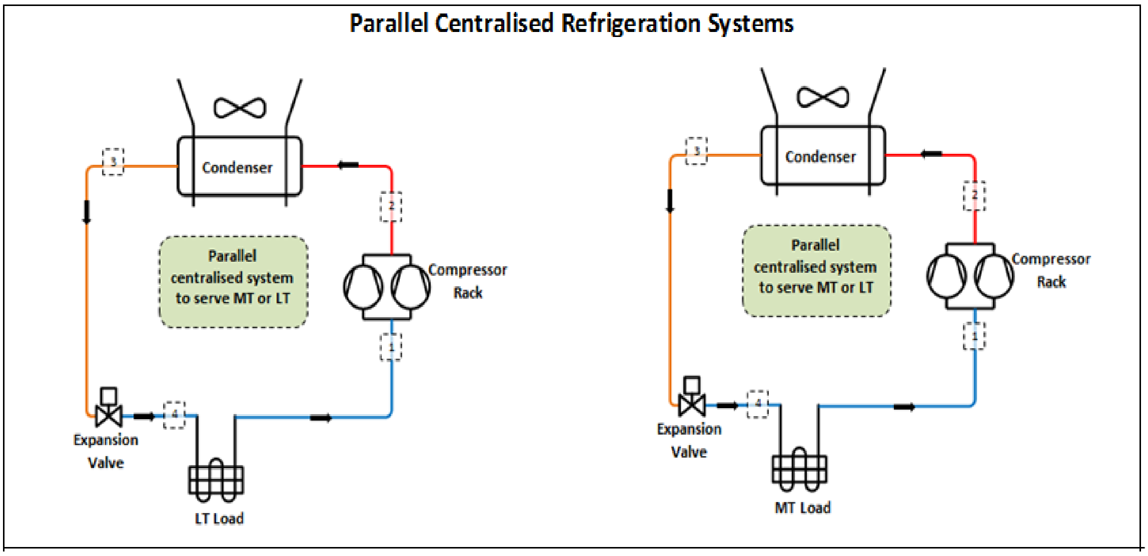


Figure 6-25: System configuration of parallel centralised refrigeration systems (S2)

Cascade R124a/CO_2 (S3)

System 3 (S3) (Figure 6-26) is referred to a parallel solution where MT and LT are operated by a different refrigeration system as S2. In this case the refrigeration system is divided in two cycles including the high stage and low stage. Both are connected using a cascade heat exchanger. The cascade heat exchanger acts as evaporator for the high stage system and as a condenser for the low stage system. The high stage of the system is using R134a and CO_2 is used for the low stage side. With this configuration we make sure that the CO_2 stage is operated in subcritical cycle all the year around without affecting from the ambient conditions.

Both systems, in this parallel applications are included an air cooled condenser, an expansion valve, the cascade heat exchanger (evaporator side) and HP compressor rack on the high stage of the system. The low stage comprises the cascade heat exchanger (condenser side), a DX evaporators and the low pressure (LP) compressor rack.

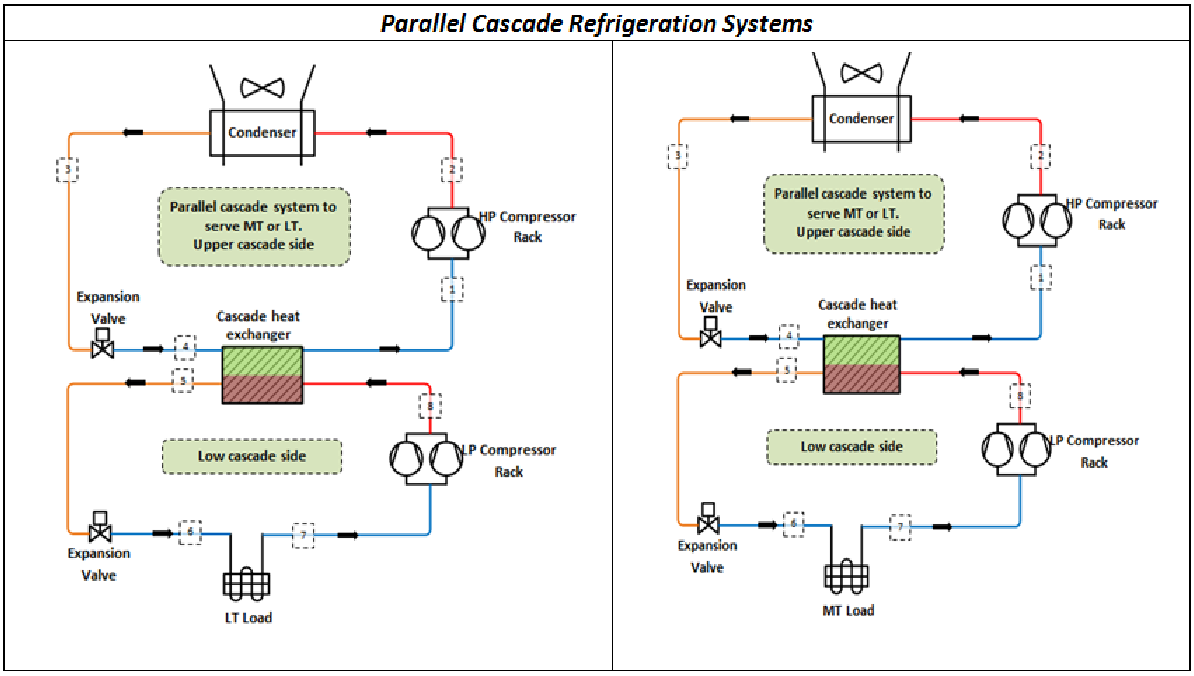


Figure 6-26: System configuration of parallel cascade refrigeration systems (S3)

<u>Transcritical CO_2 booster</u>

System 4 (S4) refers to a typical layout of a convectional booster CO_2 system refrigeration system (Figure 6-27). This solution is become very popular over the last decades due to the attractive thermo-physical properties of CO_2. The booster refrigeration system can operate in both subcritical and transcritical cycles depending on the ambient temperature. When the refrigeration system operates in transcritical cycle the heat exchanger is well known as gas cooler. The gas cooler rejects heat from the

superheated refrigerant gas to ambient air without condensation in single phase heat transfer process.

Unlike the cascade systems, the CO_2 refrigerant feed both MT and LT load cabinets inside the sales area. To control the pressure difference between the MT and LT side a double stage compression solution applied in this configuration. The refrigerant from the LT evaporator outlet (point 9) is drawn into the low-stage compressor suction line. The discharge of the low stage compression is mixed with the outlet of MT evaporator (point 11). The pressure at this point is equalised to avoid any refrigerant back-flow to the MT evaporators. The superheated mixture of CO_2 flows to the high pressure compressor suction. Before entering the suction it is mixed (point 1) with the gas by-passed refrigerant from the CO_2 liquid receiver. Then the refrigerant is compressed in the high pressure side of the system. In this stage the pressure is regulated from the HP expansion valve and the control parameters in condenser/gas cooler. The high temperature-high pressure refrigerant enters to HP expansion valve. The two phase CO_2 (point 4) enters to the liquid receiver. The liquid phase flows to evaporators (point 5) and the gas is returned through the gas by-pass valve (point 12-13) at the suction of the HP compressor to complete the cycle.

The booster refrigeration system is divided in four pressure levels including the high pressure side (points 2-3), intermediate pressure side (points 4-5-12), medium pressure side (6-7-10-11-13-1) and low pressure side (points 8-9).

The main advantages of this arrangement comparing with the existing HFCs systems are the smaller direct global impacts, the refrigerant price, availability and the safety classification.

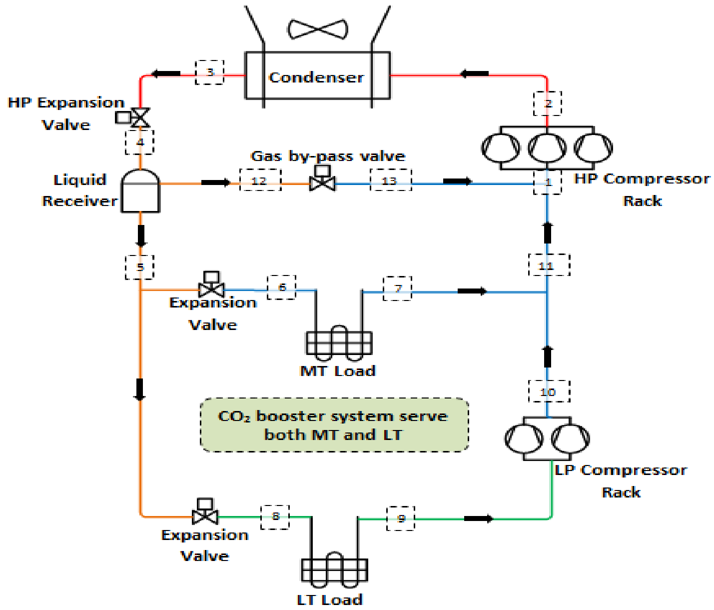


Figure 6-27: System configuration of transcritical CO_2 booster system (S4)

It is assumed that the evaporating temperature of the systems is set 5 ^{o}C less than the inside cases temperature for MT and 10^{o}C less than the inside case temperature for the LT. This value is taken into account only in centralised systems for compressor's performance evaluation. The minimum condensing temperature for System S2 and S3 is set at 20^{o}C.For the lower side of S3 the minimum condensing temperature was set at -3^{o}C. For S4 the temperature difference between the gas cooler outlet and the air entering the gas cooler (approach temperature) is 3 ^{o}C for transcritical operation. The minimum condensing temperature is set to be equal to 10^{o}C.

For all systems, the performance of the compressors was determined from manufactures' data and listed in Table 6-8.

Table 6-8: Compressor models used in simulations

Systems	MT Load	LT Load
S2	2 x Carlyle_R-134A_ 06TRE048	3 x Carlyle_R-134A_ 06TRE048
S3	HP: 2 x Carlyle_R-134A_ 06TRE048 +Carlyle_R-134A_ 06TRC033 LP: 1 x Bitzer 2DSL-5K-4SU_sub 1x Bitzer 2JSL-2K-4SU_sub	HP: 3 x Carlyle_R-134A_ 06TRE048 LP: 1 x Bitzer 4DSL-10K-4SU_sub
S4	HP: 1 x Bitzer 4HTC-15K_trans 1 x Bitzer-1- 4KTC-10K_trans LP: 1 x Bitzer 4DSL-10K-4SU_sub	

6.2.4.2 Energy Use performance

Table 6-9 summarises the total energy use comparison with the different refrigeration systems as well as the refrigeration energy use. The percentage changes from the reference base line model (S1) showed the highest reduction occurs with S4 refrigeration system.

Figure 6-28 presents the comparison between the sub systems of the store for different refrigeration systems. The highest reduction presented by S4 which is a CO_2 transcritical booster. Despite the fact that CO_2 systems does not perform as the outdoor temperature increases (Figure 6-29 and Figure 6-30) the overall refrigeration energy use is dropped by 28.2 % which results to a 17.4 % total annual energy use reduction.

Table 6-9: Total and refrigeration energy use comparison between the EnergyPlus with different refrigeration systems

Systems	S1	S2	S3	S4
Refrigeration Energy Use (kWh/m^2)	750.6	609.6	643.2	538.7
Refrigeration Energy Use Percentage reduction (%)	-	18.8	14.3	28.2
Total Energy Use (kWh/m^2)	1201.2	1062.9	1096.4	991.9
Total Energy Use Percentage reduction (%)	-	11.5	8.7	17.4

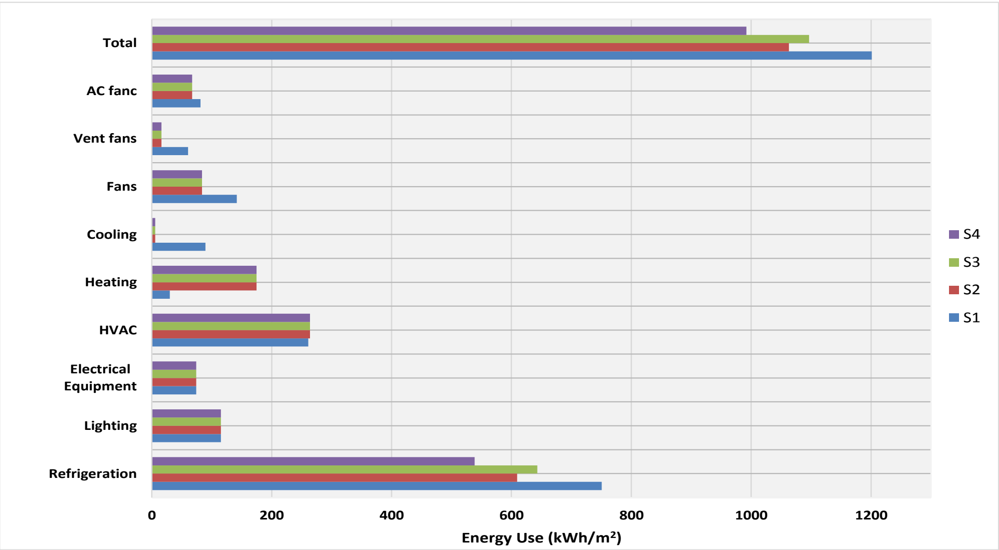


Figure 6-28: Systems energy use breakdown comparison between EnergyPlus models with different refrigeration systems

Apart from the energy use of the refrigeration systems, the changes in the heating/cooling demands are mentioned as well. S1 system which is the baseline model as a remote system with plug in cabinets with the condenser heat to be released into the sales area where the cabinets are installed lead to a different profile in terms of heating and cooling need in comparison to the other systems. The 88% of the total number of store cabinets are LT which the most of them (96%) are lift up lid cabinets. The heat realised into the sales area and this leads to higher cooling demands in order to keep the store temperature under the set point. On the other hand, with the centralised systems where the internal heat gains from the cabinets are insignificants due to the outdoor compressors heat release, a converse results takes place and heating is remarkable higher than cooling energy use which is almost negligible due to the refrigeration cold aisle effect in the sales area. The above results to the same HVAC energy use for all the systems because although the cooling and fans energy use is reduced the heating energy use increases significantly. Figure 6-29 presents these changes in the heating and cooling use per month for the test year.

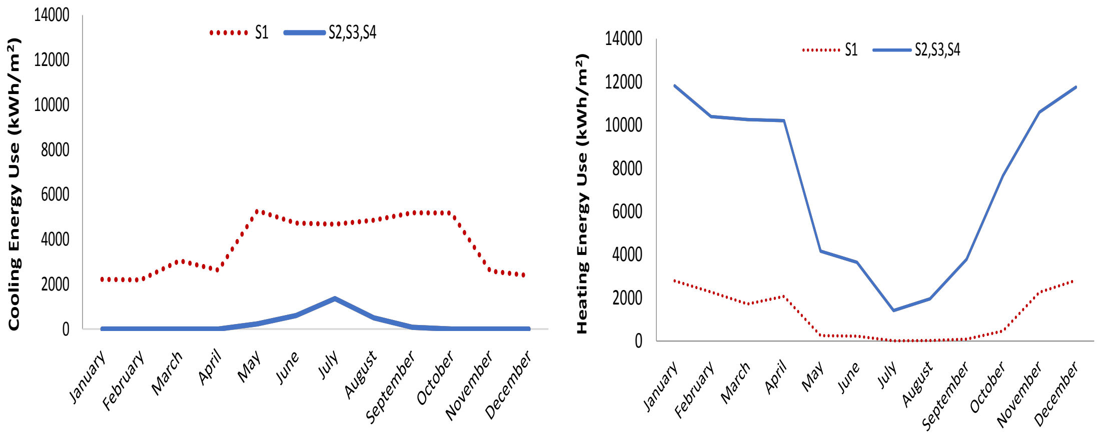


Figure 6-29: Cooling and heating energy use annual profile for EnergyPlus models with different refrigeration systems

Figure 6-30 presents the percentage reduction of the refrigeration energy use per month in comparison with the reference model (S1). All the centralised systems have lower refrigeration energy use specially during cold months; 23% - 36% reduction in comparison with the stand-alone system (S1). One reason is the lower isentropic compressor efficiencies for the stand-alone cabinets in S1. During warmer months and in summer the performance of the centralised refrigeration systems is reduced due to the higher outdoor temperatures and this leads to lower reduction in the refrigeration energy use. This is more evident for systems S2 and S3 but also S4 performance observed to be reduced during warmer periods. Figure 6-31 shows in more details the performance of the refrigeration systems in terms of outdoor temperatures. The transcritical CO_2 booster system does not perform in higher temperatures as efficiently as in lower temperatures. Moreover, S3 performance is lower than the S2 due to higher refrigeration load (cascade condenser) and two stage compressors. This leads S3 to have lower performance due to higher cooling capacity.

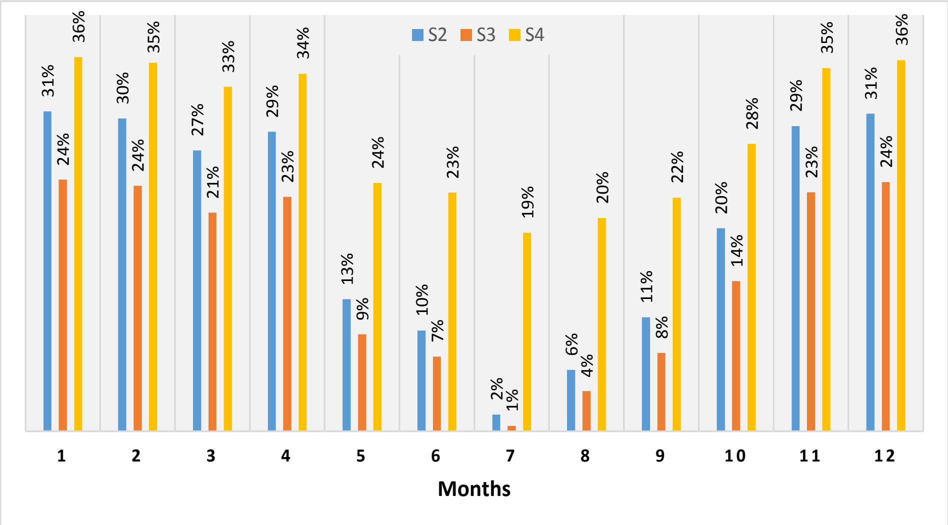


Figure 6-30: Percentage reduction of the refrigeration energy use per month in comparison with the reference model (S1)

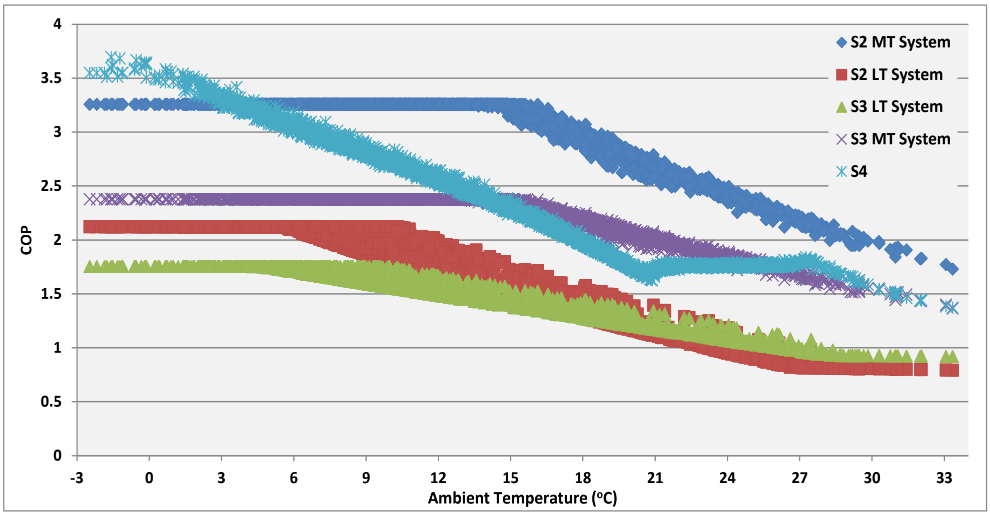


Figure 6-31: Performance comparison between the different refrigeration systems

Different weather files for different locations across UK were tested in order to evaluate the effect of different ambient conditions to centralised refrigeration systems but insignificant changes (1%) in the total annual energy use derived from simulations between a north part to a south part of UK. However, a difference of around 10% in the annual refrigeration use was observed between all the centralised refrigeration systems.

The annual electricity running costs of the four systems are shown in Figure 6-32. Electricity prices were assumed to be £0.142/kWh (www.gov.uk, 2016). System S4 will result in annual total cost saving of around £15000 compared to baseline model with system S1 which is due to the lower operation cost of the refrigeration system.

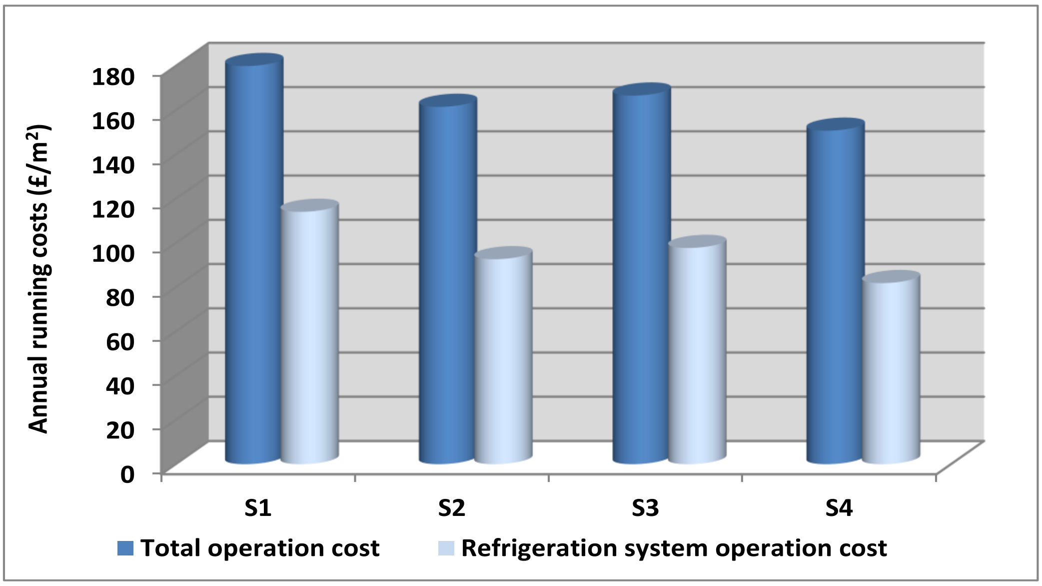


Figure 6-32: Electricity running costs of the different Energyplus models with different refrigeration systems

6.2.4.2 Emissions results analysis

The environmental impact of a refrigeration system is measured by the direct and indirect carbon dioxide emissions from the operation of the refrigeration system. The direct carbon dioxide emissions results from refrigerant leakage and type on the system and the indirect emissions depend on the electrical power used by the system. The Total Equivalent Warming Impact (TEWI) equations used to compared and assess the environmental impact of different refrigeration systems due to direct and indirect carbon dioxide emissions (BS EN 378-1, 2016). It is designed to calculate the total global warming contribution of the use of a refrigerating system. It is only valid for comparing alternative systems or refrigerant options for one application in one location. It varies from one system to another and depends on assumptions made relative to important factors like operating time, service life, conversion factor and efficiency.

$$TEWI = TEWI_{direct} + TEWI_{indirect}$$

$$TEWI_{direct} = GWP \cdot L \cdot n + GWP \cdot m \cdot (1\text{-}a_{recovery})$$

$$TEWI_{indirect} = E_{annual} \cdot \beta \cdot n$$

Where GWP is the value for the refrigerant in the system, relative to CO_2,“L” is the annual leakage rate in kg per year , “n” is the system operating time in years, m is the refrigerant charge in kg,“$a_{recovery}$ “ is the recovery/recycling factor which set to be 0.95 (Emerson Climate Technologies, 2010), “E” annual is the energy consumption of the system in kWh/year and “β” is the indirect CO_2 emission factor in $kgCO_2$/kWh.

GWP can be found in table 4. The annual leakage rate “L” is assumed to be 5% for remote systems and 15% for centralised systems. The operating lifetime “n” of the refrigeration systems assumed to be 10 years for all the different systems (UNEP, 2014). Regarding the refrigerant charge, for S1 the manufacturer’s data were used while for the centralised systems it was assumed that the refrigerant charge is 2 kg/kW cooling load for S2, S3 (high pressure side of the cascade) and 1.2 kg/kw cooling load for S3 (low pressure side of the cascade) and S4 (Emerson Climate Technologies, 2010) (Shilliday, 2012). The recycling factor of the refrigerant “a” which is taken into account as well for the direct emissions was assumed to be 95% (UNEP, 2014).

The direct carbon dioxide emissions are resulted from refrigerant leakage from the system, GWP and the charge of the refrigerants. Figure 6-33 presents the direct and indirect emissions of the different refrigeration systems used in the case study store.

S1 although included refrigerants with high GWP there is low leakage rate and as it is a remote system in comparison with the other centralised systems. S4 has negligible direct emissions due to very low GWP of R744. The highest direct emissions presented in S2 system where R134a. S3 system presented slightly lower direct emissions than S2 because of the R744 use in the low pressure side of the system.

The indirect emissions for the TEWI calculations take into account the annual energy use of the refrigeration systems which derived from the EnergyPlus model and the emission factor “b” was taken 0.35 $kgCO_2/kWh$ for London (GOV.UK, 2017). Due to highest energy use of the S1 refrigeration system, S1 presents the highest indirect emissions while S4 was the one with the lowest indirect emissions.

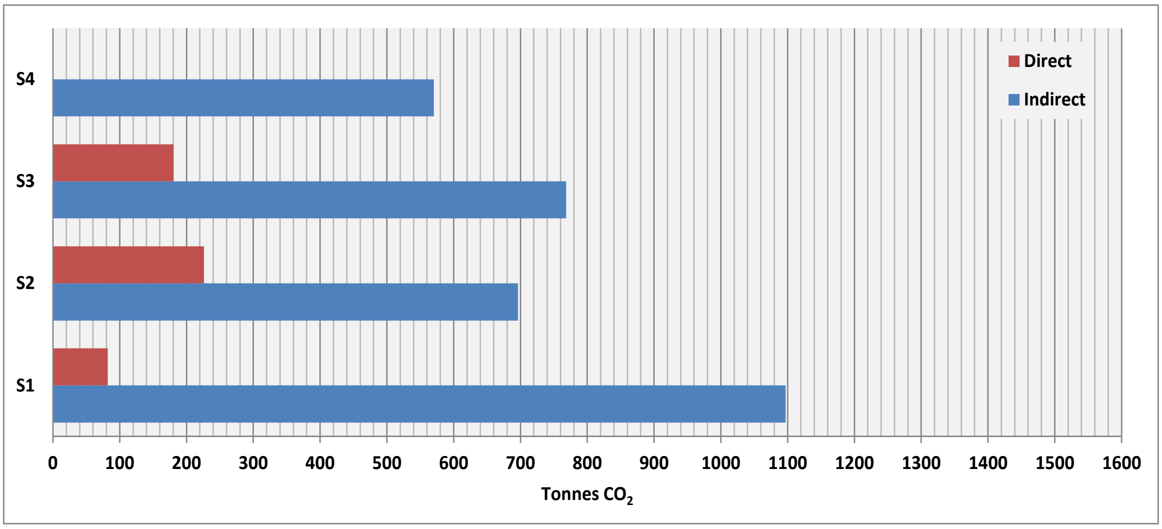


Figure 6-33: Direct and indirect emissions of the different refrigeration systems

Figure 6-34 shows the total TEWI of the four systems. For London reference climate conditions, S4 observed to have the lowest total emissions arising primarily from the lowest refrigeration energy use but due to the refrigerant (R744) that uses with negligible GWP. Although S2 presented higher direct carbon dioxide emissions in comparison with the S3 due to refrigerants GWP, it has lower refrigeration use which finally leads to has slightly lower total TEWI.

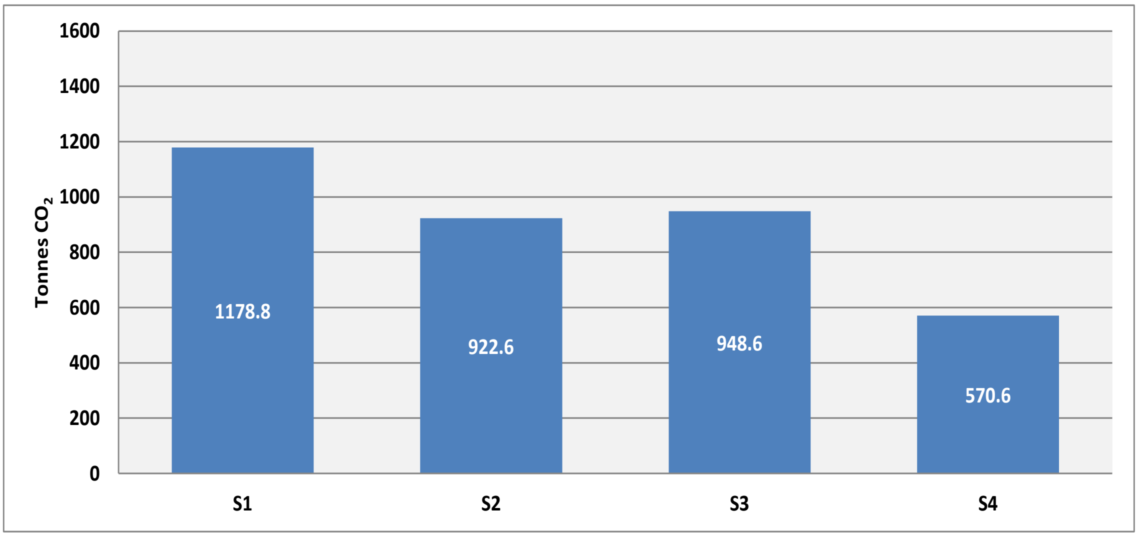


Figure 6-34: TEWI of the different refrigeration systems

6.3 Results' overview

The results of the previous sections are shown in Table 6-10 and Table 6-11. The energy efficiency improvements introduced were divided into packages. Pack A for coupled HVAC system and Pack A and B for decoupled HVAC system have all the improvements implemented and the rest of the packages present the changes in the night ventilative cooling optimisation of control strategy and the implementation of alternative refrigeration system separately. This is done because night ventilative cooling has been chosen to be implemented in the specific supermarket stores due to high cooling requirements from the heat release of the remote refrigeration cabinets. By changing the remote type refrigeration system with centralized transcritical CO_2 booster, the balance of heating/cooling needs are changed and there is no need for strategies to reduce cooling requirements as heating is most dominant in that cases. In fact, if night ventilative cooling is implemented along with centralised transcritical CO_2 booster, although a 19.8% reduction is achieved in total energy use, there is an increased energy use in HVAC as heating requirements are further increased.

Pack B for a store with coupled HVAC system which includes LED lighting system, double glazed windows and transcritical CO_2 booster refrigeration system results in the highest energy reduction in total (20.1%) due to 29% energy use reduction in the refrigeration system. As it has been analysed in section 6.2.4.2 the heating energy use is increased significantly while cooling energy use is reduced to minimum. However, HVAC energy use is almost maintained the same.

However, if there is no change in the refrigeration system and lighting system as LEDs has been already in operation since 2015 and only double glazed windows and optimised control strategy for night ventilative cooling are implemented, a reduction of 6% is achieved mainly due to the reduction in the lighting and HVAC system.

In store with decoupled HVAC system, all the changes implemented including LED lighting system and daylight control strategy, double glazed windows and northwest single glazed side replaced with an external wall, optimised control strategy for exhaust or intake night ventilative cooling and transcritical CO_2 booster refrigeration system lead to a ~16.4% total energy use reduction (Pack A and Pack B). The balance of heating/cooling demand is changed as in store with coupled HVAC system. However, different control strategy in operation hours in store with the decoupled HVAC, fans' energy use in Packs where centralised refrigeration system is implemented do not drop as significantly and for that reason the HVAC increased by 18-20%. This is further explained by the thermal mass of the CS2 building in comparison with CS1 (medium and heavyweight respectively). If night ventilative cooling is not in operation in the energy efficient store (Pack E), a 16.9% reduction is achieved due to an 18.2% reduction in the refrigeration system and 39.2% reduction in the lighting system.

In case the refrigeration system remains as a remote type in store with decoupled HVAC system, the optimised control strategy for exhaust/intake night ventilative cooling, LED lighting system and daylight control strategy, double glazed windows and northwest single glazed side replaced with an external wall, a reduction of 6-6.7% in total energy use is achieved (Pack C and Pack D). The highest reduction though is achieved with exhaust night ventilative cooling (Pack C).

In both case studies where night ventilative cooling is implemented in stores with remote type refrigeration system, apart from the overall energy use reduction, the annual energy use of refrigeration drops insignificantly by 0.04%-0.1%.

Table 6-10: Total energy efficiency improvements in comparison with baseline model: CS1

Coupled HVAC system in operation					HVAC		
	Total	**Refrigeration**	**HVAC**	**Lighting**	Heating	Cooling	Fans
Pack A	19.8%	29.3%	-5.6%	23.3%	-539.8%	97.9%	49.6%
Pack B	20.1%	29.2%	-3.9%	23.3%	-530.0%	97.9%	50.4%
Pack C	5.9%	0.0%	13.9%	23.3%	5.2%	-0.6%	22.7%

Pack A

LED system

Optimised control strategy of night ventilative cooling

Double glazed windows (U-value= 2.6 W/m^2)

Transcritical CO_2 booster

Pack B

LED system

Double glazed windows (U-value= 2.6 W/m^2)

Transcritical CO_2 booster

Pack C

LED system

Optimised control strategy of night ventilative cooling

Double glazed windows (U-value= 2.6 W/m^2)

Table 6-11: Total energy efficiency improvements in comparison with baseline model: CS2

Decoupled HVAC system in operation					HVAC		
	Total	**Refrigeration**	**HVAC**	**Lighting**	Heating	Cooling	Fans
Pack A	16.6%	18.2%	-18.3%	39.2%	-269.4%	97.8%	19.0%
Pack B	16.2%	18.2%	-19.9%	39.2%	-275.3%	97.8%	18.3%
Pack C	6.7%	0.0%	13.5%	39.2%	-8.1%	23.7%	16.6%
Pack D	6.0%	0.1%	10.7%	39.2%	-16.9%	25.5%	13.3%
Pack E	16.9%	18.2%	-17.4%	39.2%	-266.5%	97.8%	19.6%

Pack A

LED system and daylight control

Optimised control strategy of exhaust night ventilative cooling (1 ach, T_{min}=10°C, T_{offset}=5°C)

Double glazed windows (U-value= 2.6 W/m^2)

North – west single glazed side replaced with an external wall (U-value=0.35 W/m^2)

Transcritical CO_2 booster

Pack B

LED system and daylight control

Optimised control strategy of exhaust intake ventilative cooling (4 ach, T_{min}=10°C, T_{offset}=7°C)

Double glazed windows (U-value= 2.6 W/m^2)

North – west single glazed side replaced with an external wall (U-value=0.35 W/m^2)

Transcritical CO_2 booster

Pack C

LED system and daylight control

Optimised control strategy of exhaust night ventilative cooling (1 ach, T_{min}=10°C, T_{offset}=5°C)

Double glazed windows (U-value= 2.6 W/m^2)

North – west single glazed side replaced with an external wall (U-value=0.35 W/m^2)

Pack D

LED system and daylight control

Optimised control strategy of intake ventilative cooling (4 ach, T_{min}=10°C, T_{offset}=7°C)

Double glazed windows (U-value= 2.6 W/m^2)

North – west single glazed side replaced with an external wall (U-value=0.35 W/m^2)

Pack E

LED system and daylight control

Double glazed windows (U-value= 2.6 W/m^2)

North – west single glazed side replaced with an external wall (U-value=0.35 W/m^2)

Transcritical CO_2 booster

More detailed are Figures 6-35 and 6.-36 which depict the energy use comparison per system after the implementation of the different Packs.

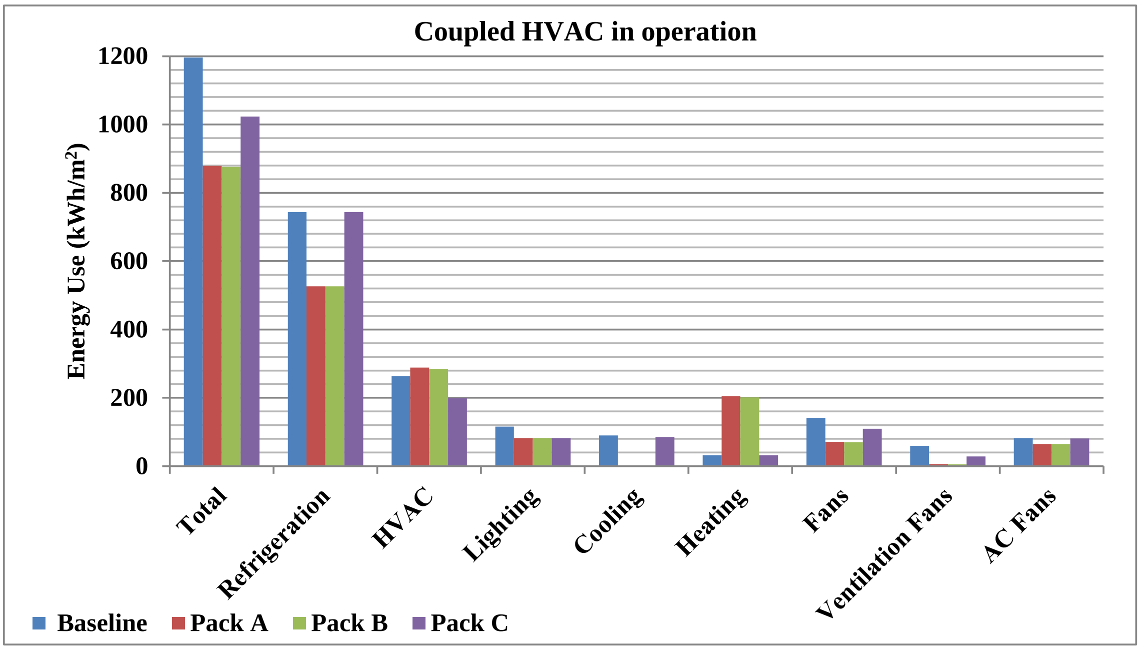


Figure 6-35: Comparison of energy use per system for different packages of energy savings solutions: CS1

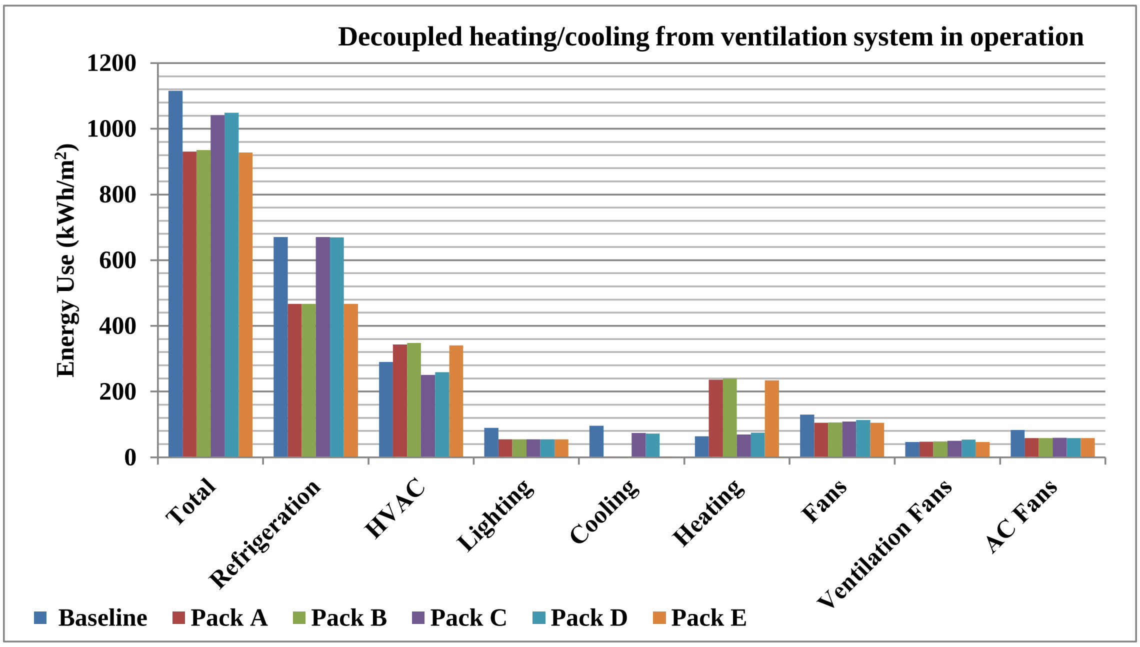


Figure 6-36: Comparison of energy use per system for different packages of energy savings solutions: CS2

Figure 6-37 presents the annual electricity running costs of the different implemented Packs in both case studies as described in Tables 6-10 and 6-11. Electricity prices were assumed to be £0.142/kWh (www.gov.uk, 2016). Squared columns present Packs that include different refrigeration system and consequently installation costs should be taken into account in order to evaluate in more details this concept. Stripped columns represent amendments without changing the refrigeration system. By only optimising the parameters affecting the night ventilative cooling and upgrading the insulation of the sales area windows will result in annual total cost savings of around £3000-£5000/annum/store compared to baseline models. Considering that this food retail chain has 880 similar in size stores in UK where night ventilative cooling has great potential due to weather conditions, approximately £2.6- £4.4 million per year could be saved by upgrading the insulation of the sales area and optimising the control strategy of the night ventilative cooling.

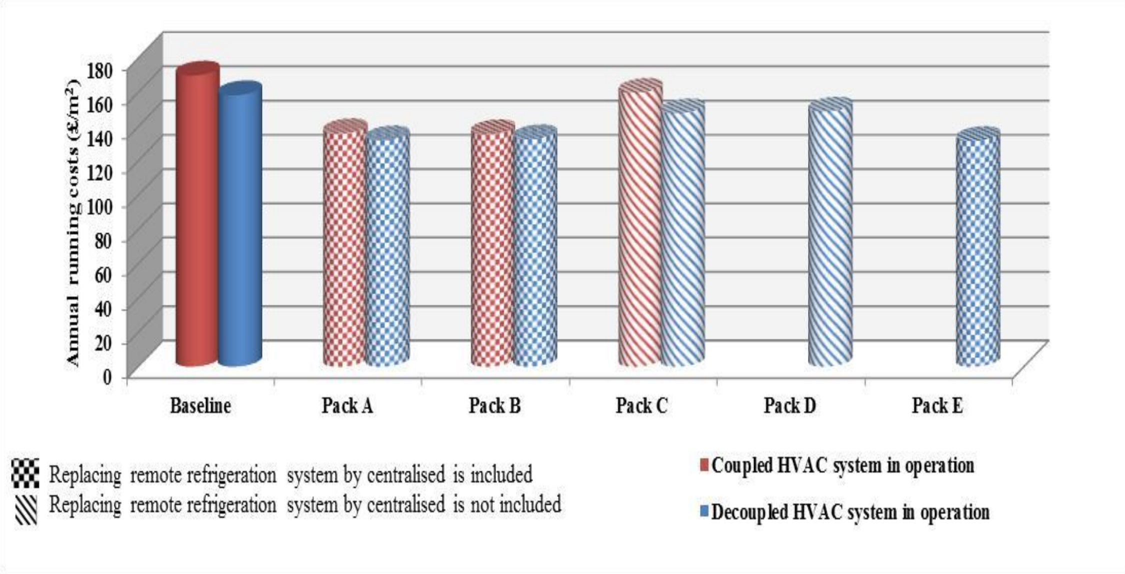


Figure 6-37: Electricity running costs of the different applications

Figure 6-38 present the annual CO_2 emissions calculation of the different implemented Packs for the two case studies of the HVAC systems. The calculations carried out with emission factor 0.35 kgCO_2/ KWh (GOV.UK, 2017) as the store is fully electricity served. According the results the biggest reduction (20%-24%) is achieved when the remote refrigeration system is replaced by centralised CO_2 transcritical booster system. This is due to the lowest energy demand of the centralised refrigeration system. Further analysis on the TEWI of the transcritical CO_2 system can be found in section 6.2.4.2. A smaller reduction but significant reduction in the CO_2 emissions is achieved (13%) by only optimising the parameters affecting the night ventilative cooling and upgrading the insulation of the sales area windows.

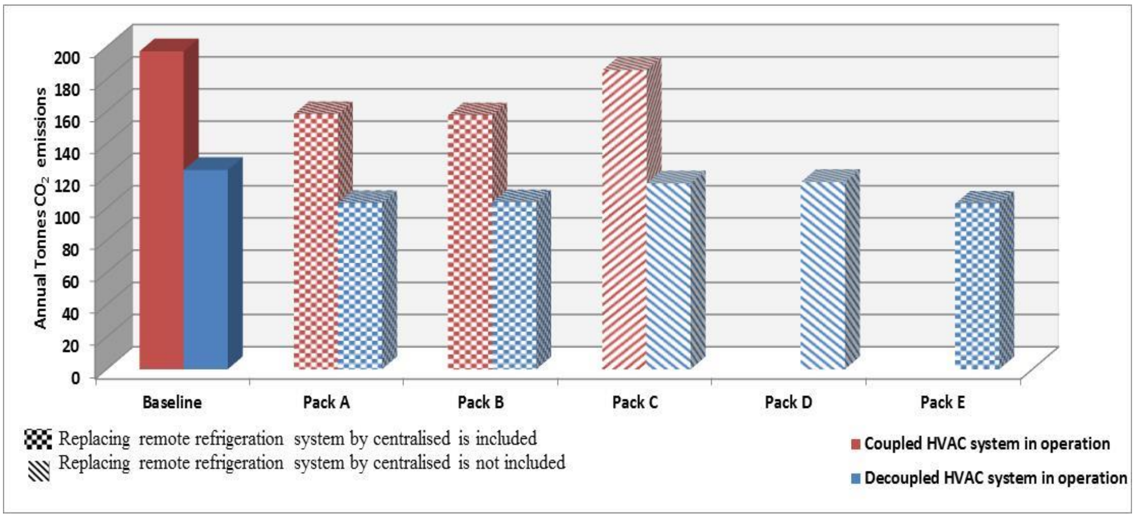


Figure 6-38: CO_2 emissions of the different applications

Chapter's summary

This chapter presented the work undertaken with the validated EnergyPlus model developed. Firstly, the energy performance evaluation of the stores which represent the coupled and decoupled HVAC systems were discussed and the interdependence of the subsystems with each other as well with temperature (external, internal) and indoor air conditions. Similarities and differences were identified. It was found that the frozen food stores have a high percentage of refrigeration energy use; 2.5 times higher. It was also clear as well the correlation of both HVAC systems with the external temperature. Although different designs are used in the stores (coupled HVAC and decoupled heating/cooling from ventilation), HVAC energy use was observed to have the same percentage in the total annual energy use breakdown.

However, control strategy is a key parameter for the HVAC energy use. It is also clear from sensitivity analysis of the HVAC in correlation with the external temperature that at around 10^oC external temperature, the daily HVAC energy use is at its lowest level and consequently the total energy use. Although 24h HVAC operation enables stable indoor conditions in the sales area for better operation of the refrigeration system, sophisticated controls that enable the night free cooling have potential to reduce the heating and cooling energy use as well as the fans energy use. Moreover, lower energy use of remote refrigeration cabinets is achieved by decreasing the temperature of the sales area during night time. However, optimised control strategy in terms of air flow rate, set point temperature and indoor temperature difference from outside temperature is required.

Furthermore, thermal mass of the buildings challenges the heating gains and losses which are strongly correlated with the cooling and heating demand. Changes on the fabric materials analysed thoroughly as this affects the operation of other sub-systems.

However, bigger impact on the total energy use reduction was observed by upgrading the lighting system with LED lamps and by implementing and optimising NC.

The energy use balance of the stores sub systems was also examined by changing the remote refrigeration system with centralised. Different centralised refrigeration systems were evaluated in terms of energy performance and environmental impact. Potential for bigger reduction promised the transcritical CO_2 booster system. Although heating and cooling requirements changed completely inside the sales area, the total HVAC energy use is not affected significantly.

A total reduction of 17%-20% was achieved by implementing all the energy efficient strategies referring to systems and buildings. The biggest reduction was due to the lighting systems upgrade and the change of the remote refrigeration system with a CO_2 transcritical booster. Without replacing the refrigeration system, a reduction of 6-7% of the total energy use is achieved which is equally separated by the effect of the LED upgrade and the optimised control strategy of the night ventilative cooling. It can been concluded that even with this small change in the annual energy use, a reduction of the running costs of the case studies could be achieved which consequently reduce significantly the food retailer’s annual energy running costs.

Chapter 7

Conclusions and Future Recommendations

7.1 Overview

The aim of the research project was to understand the energy use of frozen food supermarkets by identifying the factors influencing it and finding ways to identify opportunities for energy use reduction. This was achieved by detailed monitoring of two case study stores, development of calibrated thermal simulation model based on EnergyPlus and evaluation of energy efficiency improvements using the validated model.

The investigation was based on two different HVAC systems (coupled and decoupled), their operation and interdependence with all the subsystems of a frozen food supermarket. The extensive energy and environmental monitoring of two representative stores along with the computational EnergyPlus model enable the investigation.

Objectives set in the beginning of this research project were achieved as follows:

Objective 1: A comprehensive literature review of current trends in food retailing and frozen food market evolution is presented in Chapter 2. In the same chapter, literature review regarding energy use benchmarking for food retail stores was carried out. Available research projects and industry reports were reviewed and presented. In addition, literature review regarding energy use analysis and forecasting tools were reviewed and fall into two categories; i) tools that require past energy use data and therefore they have the ability to predict energy data with minimal set of adjustable inputs (data-driven or inverse models), ii) tools that by applying a given set of laws and based on buildings' characteristics can predict dynamic or steady state energy use predictions (law-driven or forward models).

The literature review revealed that supermarket building energy use and energy demand profile simulation is a difficult task due to the complexity of supermarket buildings and the interdependence of the operational systems. According to literature review, the most reliable and effective way to simulate the energy performance of supermarkets is to use software tools that incorporate the heat exchanges of refrigeration system with HVAC.

Objective 2: The selection of the two case study stores is presented in Chapter 3. The incentive for the selection of the stores is analysed and two stores who represent two different HVAC systems are chosen. A store with a coupled HVAC system in operation and a store with heating and AC decoupled from ventilation are described. Building description and their subsystems operational data are outlined.

Objective 3: The design of monitoring campaign for data acquisition along with the equipment used is thoroughly explained in Chapter 3. Acquired monitored data and their analysis are described in Chapter 4. It presents measured data of the long term energy use and environmental monitoring results. They refer to total energy use and subsystems energy use performance. Environmental results including temperature, RH, lighting levels and CO_2 levels within sales and temperature and RH within storage area are analysed. Moreover, temperature and RH of coldrooms as well energy use of lift up lid frozen food cabinet are described in detail. Their analysis contributes to understanding of energy and environmental performance of the stores as well as to develop and validate the computational building model.

Objective 4: The development of a new computational model for frozen food supermarket using EnergyPlus is described in detail in Chapter 5. The model is calibrated using the monitoring energy use and environmental data. As part of this objective, EnergyPlus software is used as it is particularly suited for this work focusing on dynamic energy and environmental analysis to solve simultaneously building, systems and plant considering a range of HVAC systems.

Objective 5: Improvements to the store design and operation are presented in Chapter 6. Using the validated against operational measurements EnergyPlus model and after evaluating the energy use performance of each system, a series of scenarios are used to investigate strategies for better energy performance in total without influencing each subsystem operation and maintaining satisfactory environmental conditions. These refer to

- Building construction amendments
- Lighting amendments and daylight control
- HVAC control operation and optimisation of night ventilative cooling
- Evaluation of different refrigeration systems

7.2 Key findings of the research

The key findings of the research can be divided to those derived from analysis of monitored data and those derived from simulation applications on the developed validated model.

7.2.1 Energy use and environmental conditions of frozen food retail stores

Key findings from monitored energy use can be outlined as follows:

- The high refrigeration load leads to higher energy use in comparison with a conventional supermarket.
- According to sub-metering of the systems in frozen food stores, the higher percentage is due to the refrigeration system (60%) and HVAC follows with 20%. Lighting and electrical equipment does not exceed 20%. Although not extensive sub-metering data were available, these results agree with the simulation results for energy use breakdown. Refrigeration system shares the 60-62%, HVAC comes second with 23-26% depending on the system and control strategy and with fans to be responsible for the half of this energy, and lighting system takes the 8% and electrical equipment the remaining share.
- The effect of outdoor conditions is significant in total energy use of supermarkets and especially on HVAC control strategy.
- Lighting system upgrade with LED resulted in average monthly energy use reduction of 5% to 12%.
- Frozen food lift up lid cabinet was monitored in terms of energy use and glass surface temperature for different ambient temperature. Daily energy use was observed to be reduced by 10-15% if lower ambient temperature is set. Consequently, air conditioning is of great importance not only for customers comfort but for efficient operation of refrigeration equipment as well. However, surface temperature of glass lid should be taken into account while condensation could be arosed. In that case, HVAC actions for dehumidification could counterbalance the energy savings in the energy use of the remote cabinets.
- Building design, construction date and thermal mass are key drivers for energy use intensity as it influences significantly the HVAC energy use.

Key findings from monitored indoor air environmental can be outlined as follows:

- Temperature patterns inside the sales area are highly affected by HVAC control set points and refrigeration systems operation. Moreover, areas that are not affected from the transient occupancy patterns (entrance-tills area) present more stable temperature patterns.
- Building orientation and design enhance daylighting which has energy saving potentials.
- The average temperature in the storage area was observed to be highly affected from the refrigeration equipment used for coldrooms. The use of mounted mono-block systems whose heat is exhausted in the storage area increases the temperatures within the storage areas. Relative humidity levels measured in storage area should be taken into consideration in combination with the temperature levels because it might affect the durability of the products.
- Temperature and relative humidity inside the coldrooms is significantly affected by the duration of the doors opening for products stocking. Peak in the temperatures is observed before and after the trading times when the staff is dealing with the restocking of the products from and to the display cabinets.
- Frozen food lift up lid cabinet monitoring showed that the mean lid opening duration was 14.1 seconds while the most frequent duration was 4 seconds. Approximately 4-8 times per hour occurs the lid opening and the highest frequency observed in busiest day and the day that the biggest number of sales is recorded.
- Higher numbers of transactions are taken place on Saturdays due to the customers' preference of doing vast shopping during non-working days.
- The location of the store plays important role for the sales' volume and customers' density in store. Central commercial areas near stations are in favour of bigger volume of sales while out of town area and nearby discounters or other food-dominant supermarkets could reduce the volumes of sales and the number of customers in store.

7.2.2 Model development and its applications

A computational model was developed based on the characteristics of frozen food stores and monitored data. EnergyPlus was selected as the simulation software as it offers the possibility to simulate a supermarket as a 'whole building' taking into account the interactions of the building, HVAC and refrigeration systems. Furthermore, it allows dynamic simulation of the energy and environmental performance of the supermarkets and includes the required variety of HVAC and refrigeration systems used in the case of the frozen food stores. The main outcomes of the model development are:

- A thermal and energy model with coupled or decoupled HVAC system and remote refrigeration systems including walk-in coldrooms (freezer and chiller) was successfully developed.
- Two levels of model development and calibration were followed in order to capture firstly the as-built model (level 1) and the integrated model with the operating information (level 2).
- Plans, drawings, observations, interviews, surveys, technical characteristics of systems components and spot measurements of systems components used for the development of the model.
- The model was validated against operational measurements of total energy use, subsystems energy use and temperature levels inside sales area.
- Graphical and statistical process was followed for the model validation. The developed model has the ability to represent reliably the energy performance of frozen food stores. The model maintains a constant level of accuracy across the full range of predicted energy use values with an average error of 1-2 kWh per timestep. It can predict the hourly energy use of frozen food stores with the 95% of the errors to lie from -20 kWh to 22 kWh. However, extreme external weather conditions increase the error.
- The validated model's subsystem energy use was compared with metered data from stores with the same systems. Therefore, its ability to represent their energy performance accurately is confirmed.
- Environmental conditions validation completed the overall ability of the model to represent as close to reality as possible the thermal conditions of frozen food stores. If more accurate air temperature prediction in the tills area is required a more accurate model for air infiltration through the entrance door needs to be developed.

Analysis on the energy performance of the subsystems of frozen food stores was performed and the annual energy use breakdown created as well as the daily energy use demand profile. The main findings are:

- The HVAC energy use is at its lowest levels if outdoor temperature is 8-12^{o}C.
- Heating and cooling demand is lower if night ventilative cooling is in operation.
- A strong positive correlation is observed between the heat losses and heating demand due to the single glazed facades and slightly weaker for heat gains with the cooling demand.
- The high refrigeration load per sales area of frozen food stores using remote refrigeration system leads to significantly high cooling needs in comparison to a conventional supermarket. A strong correlation was found between the cooling demand required and the refrigeration energy use because it is remote type and the heat is released in the sales area. Also, reduced sales area temperature during nights results in reduced frozen food cabinet energy use.
- Night ventilative cooling leads to reduced fans energy use in colder days, taking advantage of the night cooling although fans operate with high air flow rates during the night.

According the above key outcomes, several applications were carried out in the building and systems in order to achieve the optimum energy savings for frozen food stores in total and without negatively loading the operation of the systems. The results are summurised below:

- The upgrade of the lighting system to LED reduces the total energy use by 2-2.5 % due to the 23.5% decrease in the lighting demand. Further reductions can be achieved if daylight controls are applied in store which can further reduce the lighting demand by more than 20%.
- Optimised control strategy for night ventilative cooling plays an important role for optimum energy savings in stores with high cooling requirements.
  - Longer operation period of night ventilative cooling leads to higher energy savings enabled by lower air flow rates which have a small impact on fans energy use but cool effectively.
  - Another key parameter for effective night ventilative cooling is the inside-outside temperature difference. Parametric analysis indicated that

optimum savings occurred if the air inside the stores has 5-7^{o}C difference with the outside air. The higher the air flow rate of the fans, the higher this difference should be for optimum energy savings.

  - By changing the conventional refrigerated cooling with ventilative cooling during night a reduction of 40.8 kWh/m^2/annum is achieved while optimised control strategy of night ventilative cooling a 3.6% reduction is gained. These savings are due to cooling energy demand drop with a positive influence in the remote type refrigeration system whose energy use is reduced with lower temperature inside the sales area.

- Building design amendments have insignificant impact in the total energy use but lead to energy reduction for the HVAC system mainly due to heating requirements changes. Heating demand is reduced due to higher insulation but frozen food stores with remote type refrigeration equipment has a unique nature and double glazed windows lead to a further increase in the high cooling demand due to the solar gains and reduced heat transfer through windows.
- Refrigeration equipment is very important for frozen food stores and inefficiencies or faults may cause significant spoilage or destructions in sales. The comparative analysis of different refrigeration systems showed that shifting towards low GWP refrigerants and more efficient refrigeration systems lead to reduction in the total annual energy use.
  - The CO_2 transcritical booster system was found to be the more energy efficient system not only in terms of energy performance but in carbon dioxide emissions as well. This system concluded to 18 % reduction in the total energy use.
  - Although the performance of the CO_2 booster system is reduced as the outdoor temperature increases, the London climate conditions are not restrictive as the majority of the time through the year the outdoor temperature does not exceed the 27^{o}C.
  - All R134a parallel centralised system and parallel cascade R134a/CO2 system also found to offer a good balance between emissions and refrigeration energy use but the TEWI was found to be only 16% lower than the baseline while the TEWI of CO_2 booster system dropped by 44%.

- HVAC system is affected the same by all the centralised systems and although the balance of heating/cooling requirements changed diametrically, the HVAC total annual energy use was found to remain almost stable.

Summarising, the biggest energy savings reduction in frozen food stores is due to the lighting systems upgrade and the change of the remote refrigeration system with a CO_2 transcritical booster. If there is no change in the remote refrigeration system, a reduction of 6-7% of the total energy use is achieved which is equally due to the effect of the LED upgrade and the optimised control strategy of the night ventilative cooling. It can be concluded that even with this small change in one store significant changes in the food retailer's annual energy running costs are achieved.

7.3 Impact on the research field

The findings of the research project can be summarised as three contributions to the research academia.

Contribution 1:

Monitored data for energy use and power demand profile of frozen food stores are in the public domain. Even though many retailers have been monitoring food retail stores, data for their energy efficiency performance are scarce. Within this project, research papers have been published based on this data and provided insights for frozen food retail stores which can be used for the design and retrofit of small supermarkets or convenience stores. Customers' behaviour in the use of refrigeration cabinets is an important factor; data on how customers use the refrigeration data in store operation were missing. The monitoring of refrigeration equipment in store operation carried out provide useful data for the analysis of energy demand profile.

Contribution 2:

Environmental conditions profiles were derived from data of detailed and extensive environmental monitoring of two operational food retail stores. Analysis of key drivers which influence internal conditions have been published including sales and storage areas.

Contribution 3:

A validated computational energy and thermal model of small size, food dominated, high refrigeration load supermarket in EnergyPlus was created. The model includes coupled and decoupled HVAC systems, building design and operation schedules as well as refrigeration equipment. It allows whole system thermal simulation including subsystem interactions. In general, the model can be used to future predictions or for different systems application for energy saving and reductions in carbon footprint of food retail stores. Most published work on energy efficient refrigeration system is focused on system's energy use and not in integration within a supermarket daily operation with coupled interactions of HVAC, refrigeration system and building. This developed model enables the comparative analysis of different refrigeration systems taking into account the interaction of all the subsystems and the building. One example is the optimisation of night ventilative cooling control strategy. This technique is used for reasonably high thermal mass buildings and most published work focuses on domestic buildings and offices. A supermarket with high cooling requirements is also a suitable case for night ventilative cooling to be installed.

7.4 Impact on the food retail contributor/industry

The project was conducted in collaboration with a frozen food retail chain which provided access in two case study stores chosen to represent different HVAC systems, energy use data in total, sub-metering data and transactions data. The validated model created can be used for evaluation and analysis of energy efficiency performance of all the frozen food stores of the chain which are planned to be retrofitted or even for decisions in the design phase. In general, this project provided a tool and the confidence to the energy manager to use the data and make data driven decisions. This model will probably not represent stores of different food retail chains but the method used for model development can be used. However, the environmental conditions data or even the same model can give insights for conditions inside similar stores (food oriented stores, convenient stores).

More specifically, contributions to the industry can be summarised as follow:

- The findings from this project could influence the energy team in order to evaluate the energy use performance of the stores in comparison with national benchmarks and helps in identifying energy use baselining across the chain's stores.

- ➢ The environmental monitoring enable the visualisation of internal environmental conditions inside the sales area of the stores which is further affect the design layout of the refrigeration equipment location. Moreover, these results enable the evaluation and the redefining of the HVAC control strategy if needed.
- ➢ Results from frozen food display cabinet monitoring in the laboratory also gave insights for the optimisation of control strategy for night ventilation with lower sales area temperature set points than the current strategy the engineering team uses. It was proven that there is no effect on the operation of the cabinet or on the products display due to possible glass condensation which could further influence the customers' preferences.
- ➢ Simulation results for the control strategy optimisation of night cooling enables the redefining of the setting parameters in the stores that they have already implemented night cooling and to consider implemented night cooling in the forthcoming stores.
- ➢ Results from comparative analysis on different refrigeration systems will influence decisions of the engineering team for refrigeration equipment replacements which normal have 10 years lifetime. F-Gas regulation by phasing out high GWP pushes for refrigeration systems upgrade and the analysis given in Chapter 6 gives insights for different systems and the impacts in the heating/cooling requirements. Environmental impacts analysis robust the above insights for better evaluation of choices.
- ➢ Building design amendments could be used for better evaluation of building fabric for refurbishments or new constructions. Moreover, daylight control strategies when the stores location enables it could save significant amounts of lighting energy.

7.5 Suggestions for future work

The field measurements and the validated model presented in this research project provide a platform for future studies about energy performance in food oriented supermarkets. The following are suggested as further work related to this research:

- Sub metering of specific case study stores would lead to more detailed results regarding the energy performance profile of the two case study stores. Moreover, sub metering monitoring data could also improve even more the accuracy of the model as calibration according to them would lead to even more realistic representation of each subsystem.

- As food retail stores are used by customers who do not have either professional or personal attachment to the building itself, predictions and changes are further complicated. For that reason, data from operational behaviour of customers and staff and monitoring of their presence inside the sales area are crucial in order to reduce as much as possible the error inserted from their transient profile.
- Similar data (total annual and sub metering) from as many as possible frozen food stores of the chain could establish an energy use benchmark and an analysis for identifying parameters affecting the total energy use of the stores could further help the evaluation of energy use of frozen food stores. These parameters could contain the building construction materials and age of construction, location and weather conditions.
- Although multi-zone EnergyPlus simulation with air flow between zones can have similar results to those of Computational Fluid Dynamics (CFD) (L. Phan, C-X. Lin, 2014), further steady state CFD analysis could help to establish in more detail the temperature in the sales area and the effect of hot and cold aisles which could lead to better investigation for energy saving solutions.
- Implementation of several applications after the modelling process for taking results while in store operation could further enhance the power of the simulation results. Only lighting system upgrade was possible during this research project. However, changing in the control strategy of the HVAC systems and especially in the night ventilative cooling settings in store where it is it already in operation and monitoring for significant amount of period could boost the results and give insights for further investigations.
- As refrigeration systems technology is moving fast and pressure from regulations for natural refrigerants, lower refrigerant leakage and more efficient systems, investigation of the latest trends in refrigeration systems is apparent. For this research purposes only comparison between remote and centralised systems was carried out but due to the size and the requirements of frozen food stores, waterloop systems for plugged-in cabinets is a very promising solution and requires further investigation.

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Appendix A:

Information for environmental monitoring process for the two case study stores:

Environmental monitoring equipment (type of sensors, name and height of installation)

CS1

	Name	Height
	Sales area	
Column 1	1 Gr 1 (HOBO U12-012)	0.3m
	1 Gr 2 (HOBO U12-012)	1.1m
	1 Gr 3 (HOBO U12-012)	2 m
Column 2	2 Gr 1 (HOBO U12-012)	0.3 m
	2 Gr 2 (HOBO U12-012)	1.1 m
	2 Gr 3 (HOBO U12-012)	2 m
Column 3	3 Gr 2 (HOBO UX100-003)	1.1 m
Column 4 In front of the door and near to trolleys	4 Gr 1 (HOBO UX100-003)	0.3 m
	4 Gr 2 (HOBO UX100-003)	1.1 m
	4 Gr 3 (HOBO UX100-003)	2 m
Column 5 In front of the Electric Cupboard	5 Gr 1 (HOBO UX100-003)	0.3 m
	5 Gr 2 (HOBO UX100-003)	1.1 m
Column 6	6 Gr 2 (HOBO UX100-003)	2 m
Column 7	7 Gr 1 (HOBO UX100-003)	0.3 m
	7 Gr 2 (HOBO UX100-003)	1.1 m
	7 Gr 3 (HOBO UX100-003)	2 m
1 HOBO U12-012+TELAIRE 7001	Gr 10	Above the cabinet and connected to the available plug
	Groundfloor-Storage	
2 HOBO UX100-003	Gr St 1	1.1 m
	Gr St 2	1.1 m
	1st floor-Storage	
2 HOBO UX100-003	FF St 1	1.1 m
	FF St 2	1.1 m
	Coldrooms	
1 HOBO UX100-003	Gr C1 (Chiller)	1.1 m
1 HOBO UX100-003	FF C3 (Freezer)	1.1 m
	Diffusers	
		Comments
1 HOBO UX100-003 & i-button	Gr D1	#8 (Figure 3-9)
1 HOBO UX100-003 & i-button	Gr D2	#15 (Figure 3-9)
1 HOBO UX100-003 & i-button	Gr D3	#4 (Figure 3-9)
1 HOBO UX100-003 & i-button	Gr D4	#6 (Figure 3-9)
1 HOBO UX100-003 & i-button	Gr D5	#12 (Figure 3-9)
Gr=Groundfloor, FF=First Floor, St=Storage area, C=Coldroom, D=Diffuser		

CS2

	Name	Height
Sales area		
Column 1	1 SA 1 (HOBO UX100-003)	0.3m
	1 SA 2 (HOBO U12-012)	1.1m
	1 SA 3	Adjusted on a till 1.1m
Column 2	2 SA 1 (HOBO UX100-003)	0.3m
	2 SA 2 (HOBO U12-012)	1.1m
	2 SA 3 (HOBO U12-012)	2m
Column 3	3 SA 1 (HOBO UX100-003)	0.3m
	3 SA 2 (HOBO UX100-003)	1.1m
	3 SA 3 (HOBO U12-012)	2m
1 HOBO U12-012 +TELAIRE 7001	SA 1	Above the cabinet and connected to the available plug
Storage Area		
Coldrooms		
1 HOBO UX100-003	St1	1.1m
1 HOBO UX100-003	St C1 (Chiller)	1.1m
1 HOBO UX100-003	St C2 (Freezer)	1.1m
Cassettes		
		Comments
1 HOBO UX100-003 & i-button	D1	#1 (Figure 3-14)
1 HOBO UX100-003 & i-button	D2	#2 (Figure 3-14)
1 HOBO UX100-003 & i-button	D3	#3 (Figure 3-14)
1 HOBO UX100-003 & i-button	D4	#4 (Figure 3-14)
1 HOBO UX100-003 & i-button	D5	#5 (Figure 3-14)
1 HOBO UX100-003 & i-button	D6	#6 (Figure 3-14)
1 HOBO UX100-003 & i-button	D7	#7 (Figure 3-14)
1 HOBO UX100-003 & i-button	D8	#1 (Figure 3-14)
SA=Sales area, St=Storage area, C=Coldroom		

CS1

Environmental monitoring period

Name	Monitoring period	Comments
1 GR 1	14/3/14 to 24/4/15	
1 GR 2	7/3/14 to 24/4/15	
1 GR 3	9/4/14 to 24/4/15	
2 GR 1	7/3/14 to 24/4/15	
2 GR 2	14/3/14 to 24/4/15	
2 GR 3	7/3/14 to 24/4/15	
3 GR 2	21/3/14 to 19/6/15	
4 GR 1	21/3/14 to 10/10/15	Lost
4 GR 2	21/3/14 to 24/11/15	Lost
4 GR 3	21/3/14 to 19/6/15	
5 GR 1	21/3/14 to 19/7/15	Broken
5 GR 2	21/3/14 to 13/2/15	Lost
6 GR 2	21/3/14 to 19/6/15	
7 GR 1	21/3/14 to 19/6/15	
7 GR 2	21/3/14 to 19/6/15	
7 GR 3	21/3/14 to 19/6/15	
FF C3	21/3/14 to 13/2/15	Broken
FF ST 1	21/3/14 to 13/2/15	Lost
FF ST 2	21/3/14 to 19/6/15	
GR 10+ TELAIRE 7001	7/3/14 to 28/6/14	
GR 11	21/3/14 to 19/6/15	
GR C1	21/3/14 to 19/6/15	
GR ST1	21/3/14 to 24/11/14	Lost
GR ST2	21/3/14 to 19/6/15	

Monitoring period of diffusers

Hobos' name	Monitoring period	Comments
D1	21/3/14 to 15/7/14	
D2	-	Not installed
D3	-	Didn't record anything
D4	21/3/14 to 15/7/14	
D5	21/3/14 to 15/7/14	
I-buttons' name	Monitoring period	Comments
D1	29/3/15 to 19/6/15	
D2	29/3/15 to 19/6/15	
D3	29/3/15 to 19/6/15	
D4	29/3/15 to 19/6/15	
D5	29/3/15 to 19/6/15	

CS2

Environmental monitoring period

Name	Monitoring period	Comments
1 SA 1	8/4/14 to 3/6/15	
1 SA2	8/4/14 to 24/12/14 and 16/2/15 to 3/6/15	Missing period due to lack of memory: 24/12/14 to 16/2/15
1 SA 3	8/4/14 to 3/6/15	
2 SA 1	8/4/14 to 3/6/15	
2 SA 2	8/4/14 to 24/12/14 and 16/2/15 to 3/6/15	Missing period due to lack of memory: 24/12/14 to 16/2/15
2 SA 3	8/4/14 to 24/12/14 and 16/2/15 to 3/6/15	Missing period due to lack of memory: 24/12/14 to 16/2/15
3 SA 1	3/4/14 to 26/7/14	Lost
3 SA 2	8/4/14 to 3/6/15	
3 SA 3	8/4/14 to 24/12/14 and 16/2/15 to 3/6/15	Missing period due to lack of memory: 24/12/14 to 16/2/15
SA 1 + TELAIRE 7001	8/4/14 to 14/11/14 and 16/2/15 to 3/6/15	CO_2 measurements until 14/11/14 Missing period due to lack of memory: 24/12/14 to 16/2/15
St 1	8/4/14 to 20/10/14 and 14/11/14 to 3/6/15	Missing period for not specified reason: 20/10/14 to 14/11/14
St C1 Freezer	8/4/14 to 29/5/14	Lost
St C2 Chiller	8/4/14 to 28/6/14	Broken

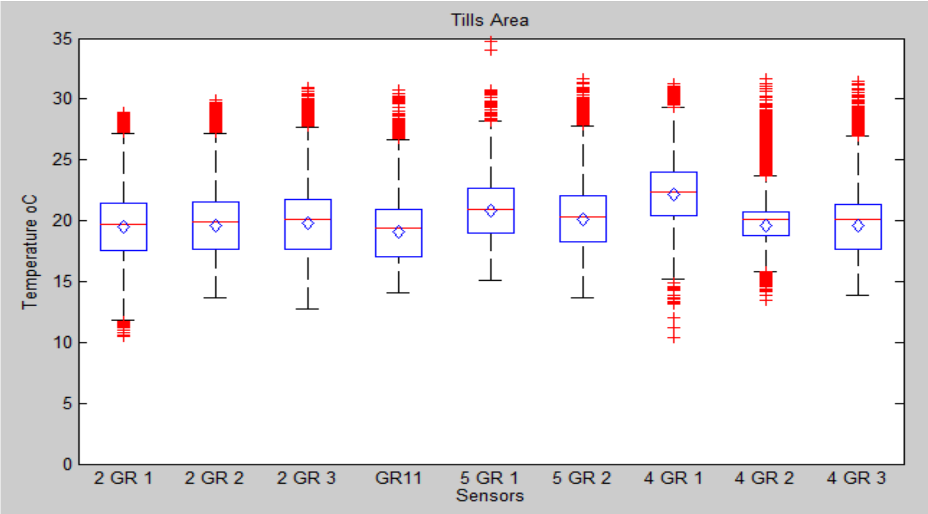
<u>Monitoring period of diffusers</u>

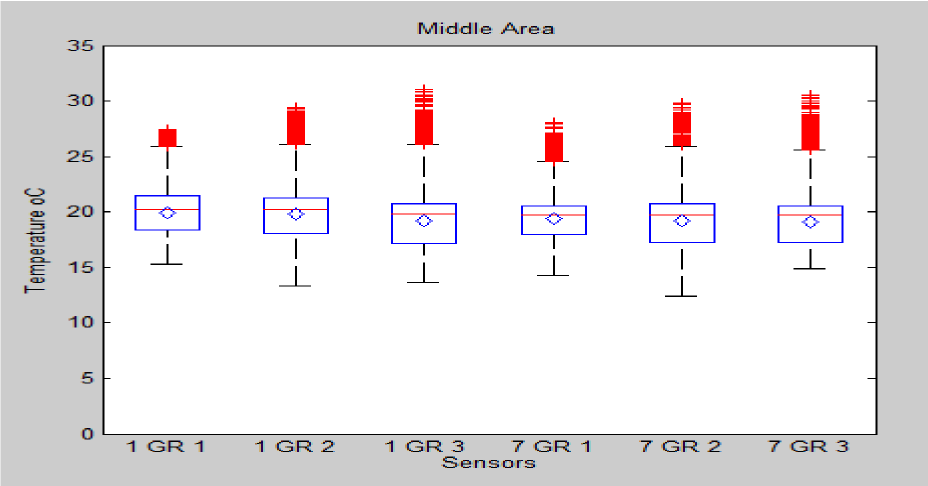
HOBO diffusers	Monitoring period	Comments: All the sensors installed in the air outlet facing the west side
D1	29/5/14 to 23/7/14	In the same cassette (#1) with the D8 but in opposite air outlet (east side)
D2	29/5/14 to 23/7/14	
D3	29/5/14 to 23/7/14	
D4	29/5/14 to 23/7/14	
D5	29/5/14 to 23/7/14	
D6	29/5/14 to 23/7/14	
D7		Didn’t record anything
D8	29/5/14 to 23/7/14	In the same cassette (#1) with the D1 but in opposite air outlet
ibuttons diffusers	Monitoring period	Comments: All the sensors installed in the air outlet facing the west side
1	15/3/15 to 3/6/15	In the same cassette (#1) with the D8 but in opposite air outlet (east)
2	15/3/15 to 3/6/15	
3	15/3/15 to 3/6/15	
4	15/3/15 to 3/6/15	
5	15/3/15 to 3/6/15	
6	15/3/15 to 3/6/15	
7	15/3/15 to 3/6/15	In the same cassette (#1) with the D8 but in opposite air outlet (east)

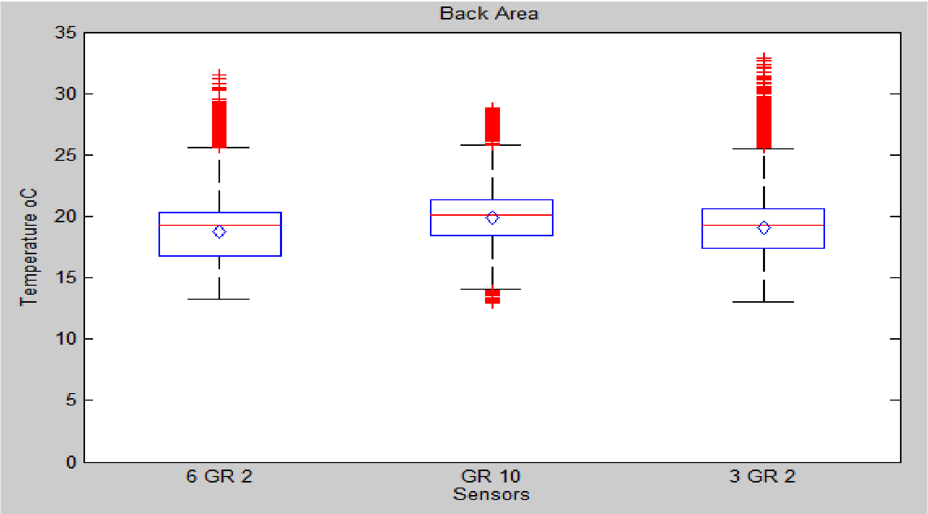
Appendix B:

Temperature monitoring data by sensor during the whole monitoring period.

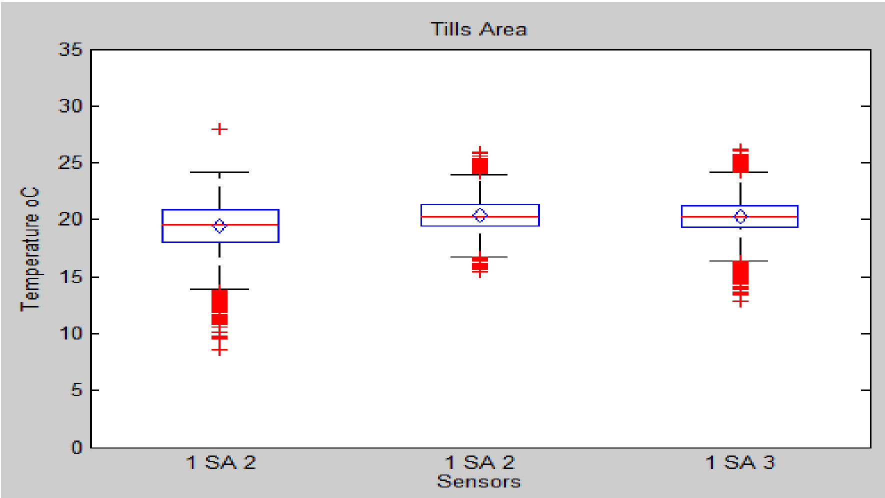
CS1



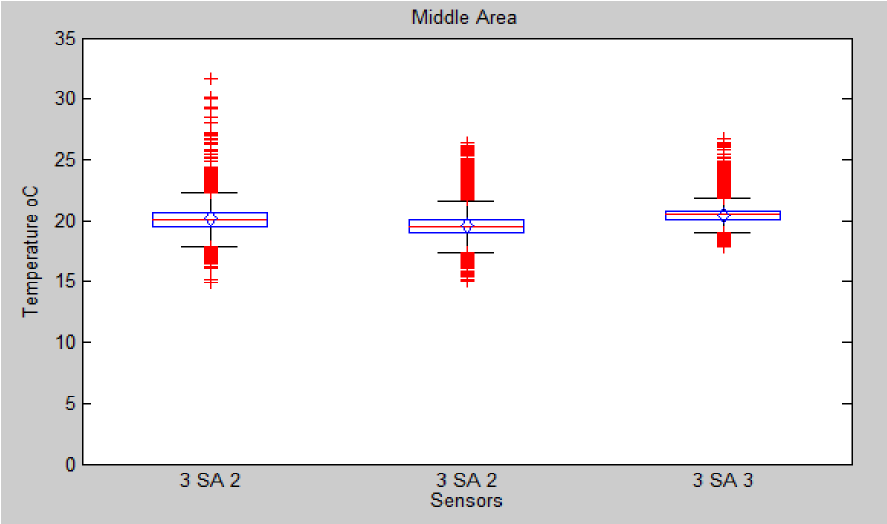




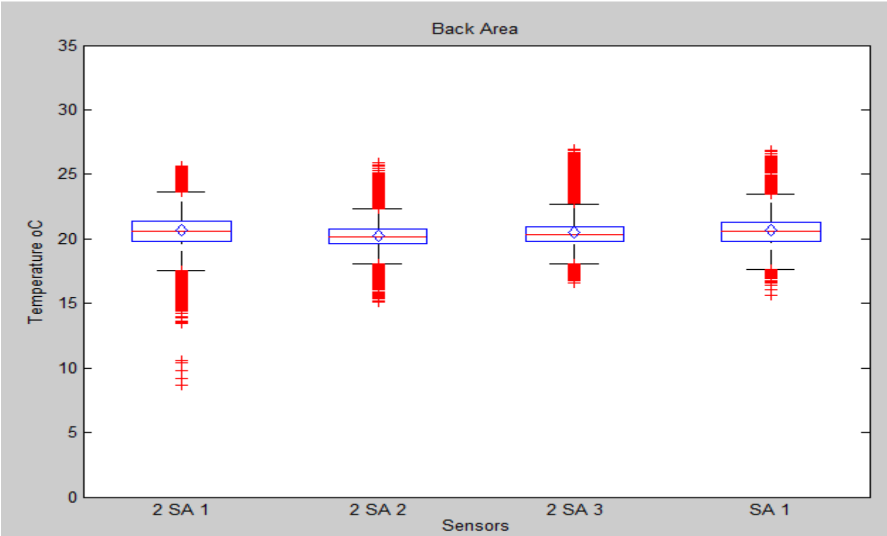
CS2



Tills Area
Temperature oC
35
30
25
20
15
10
5
0
1 SA 2
1 SA 2
1 SA 3
Sensors



Middle Area
Temperature oC
35
30
25
20
15
10
5
0
3 SA 2
3 SA 2
3 SA 3
Sensors

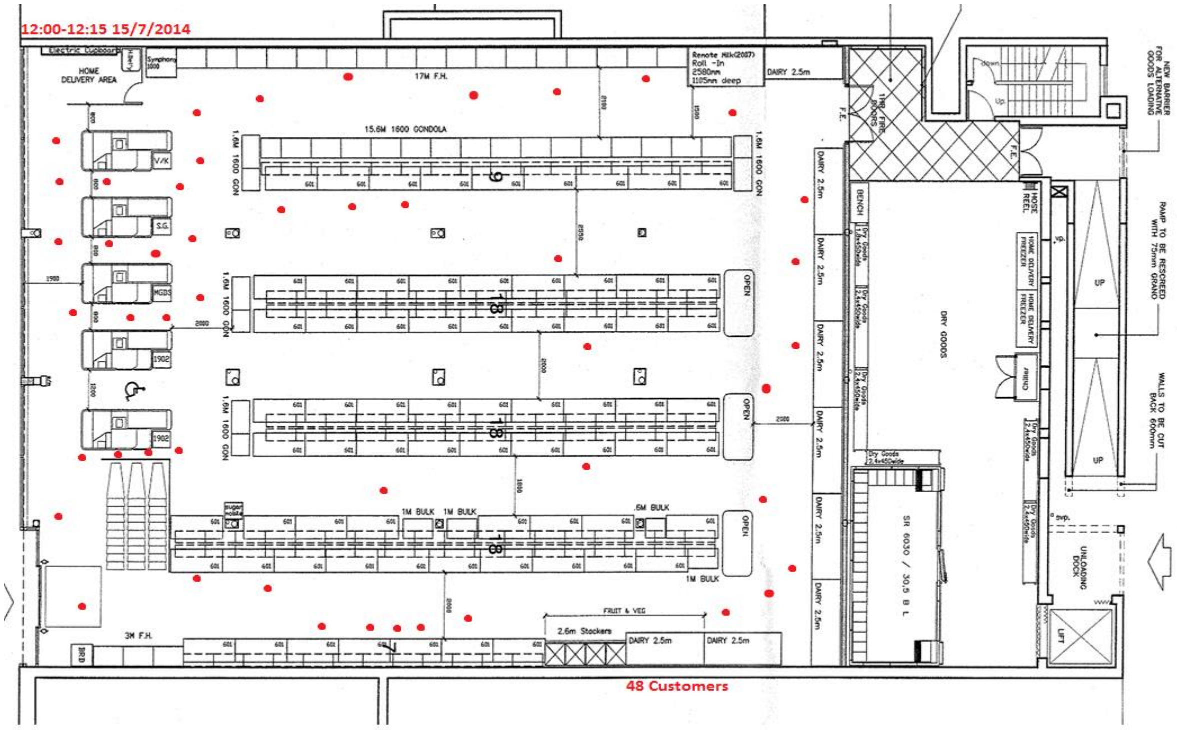


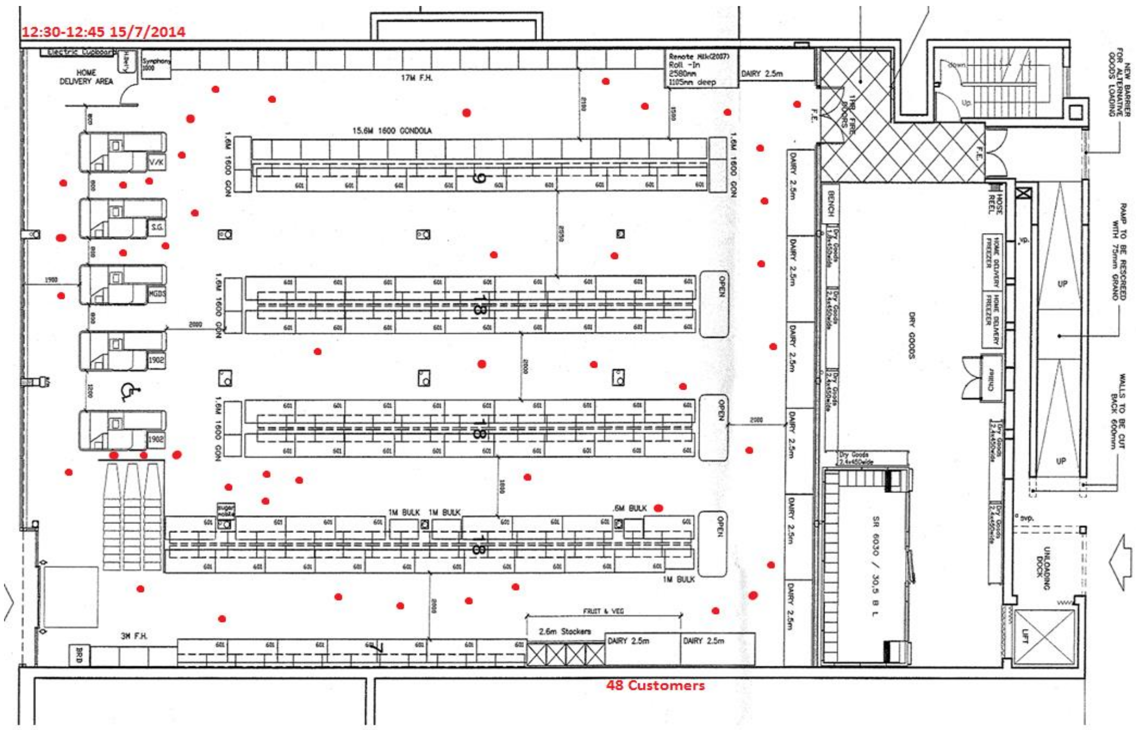
Back Area
Temperature oC
35
30
25
20
15
10
5
0
2 SA 1
2 SA 2
2 SA 3
SA 1
Sensors

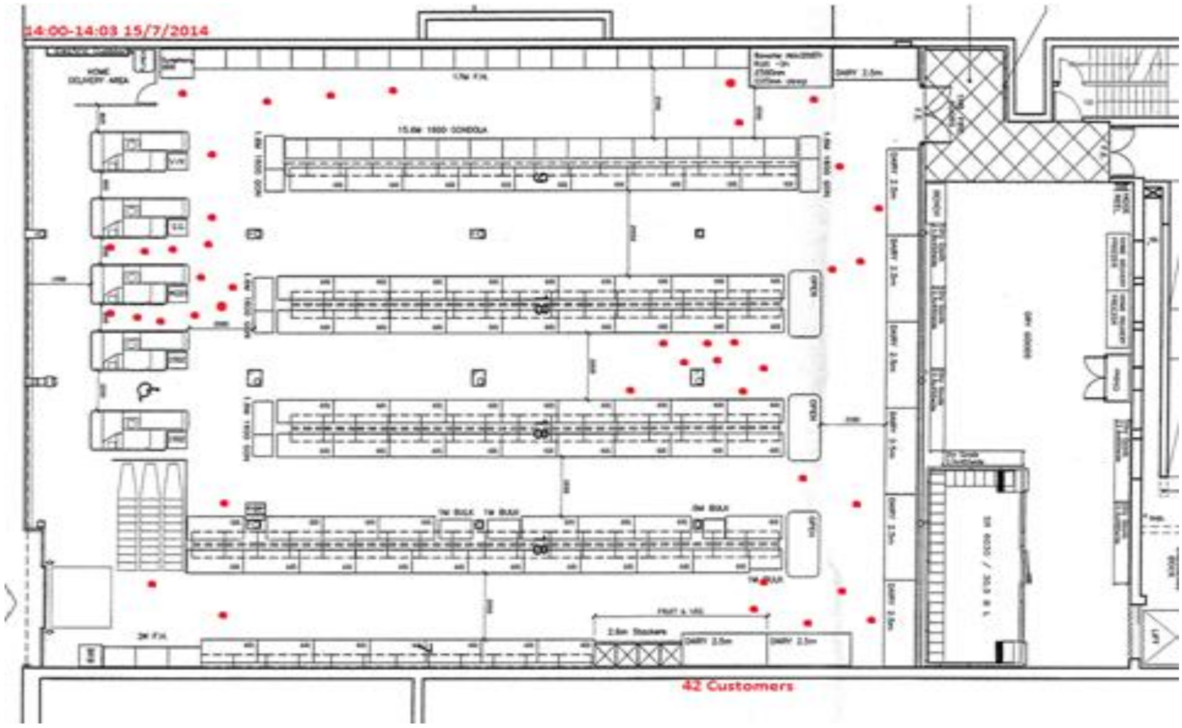
Appendix C:

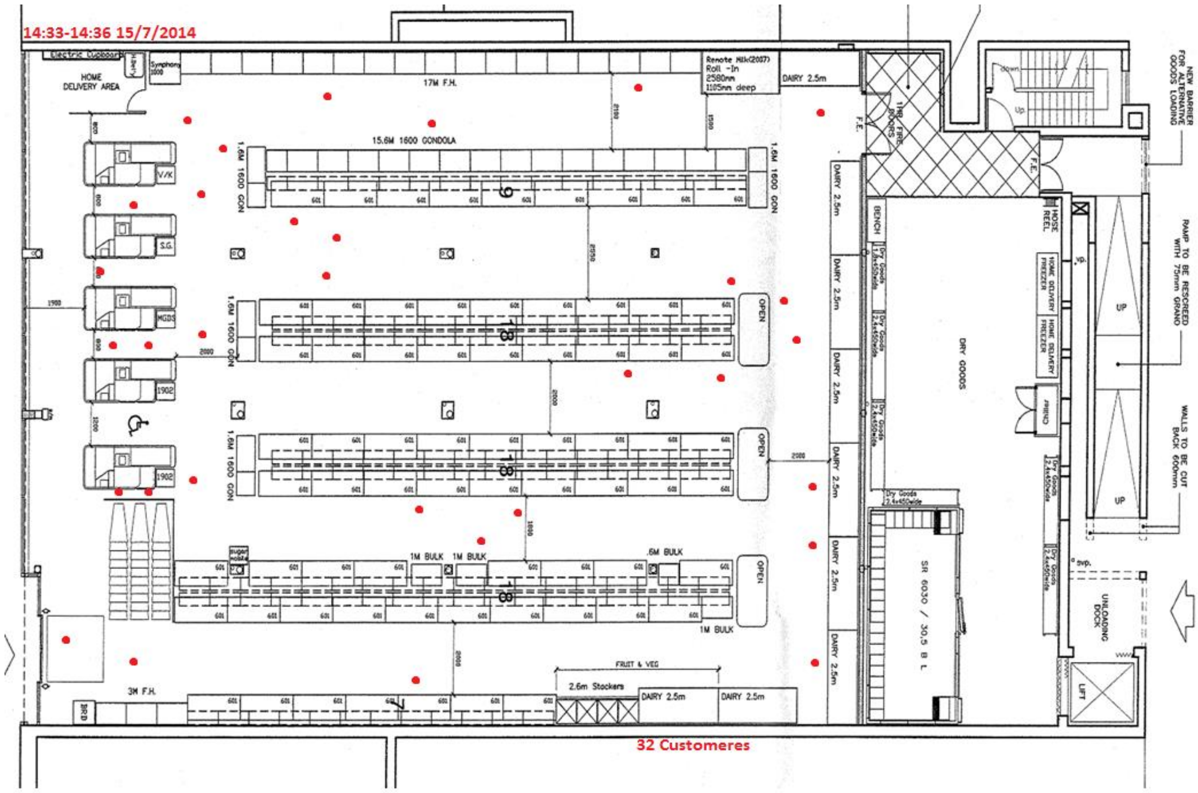
Examples of spot observations for customers in sales area.

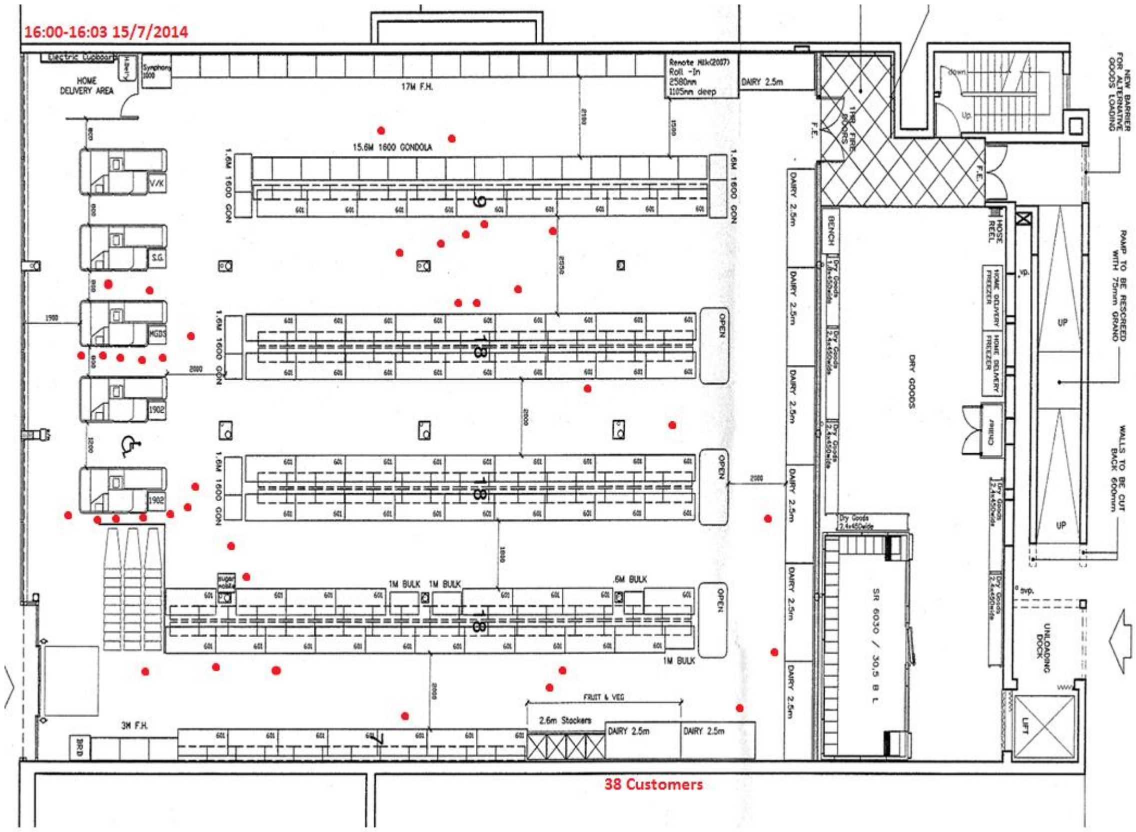
CS1 (Tuesday 15/7/2014)

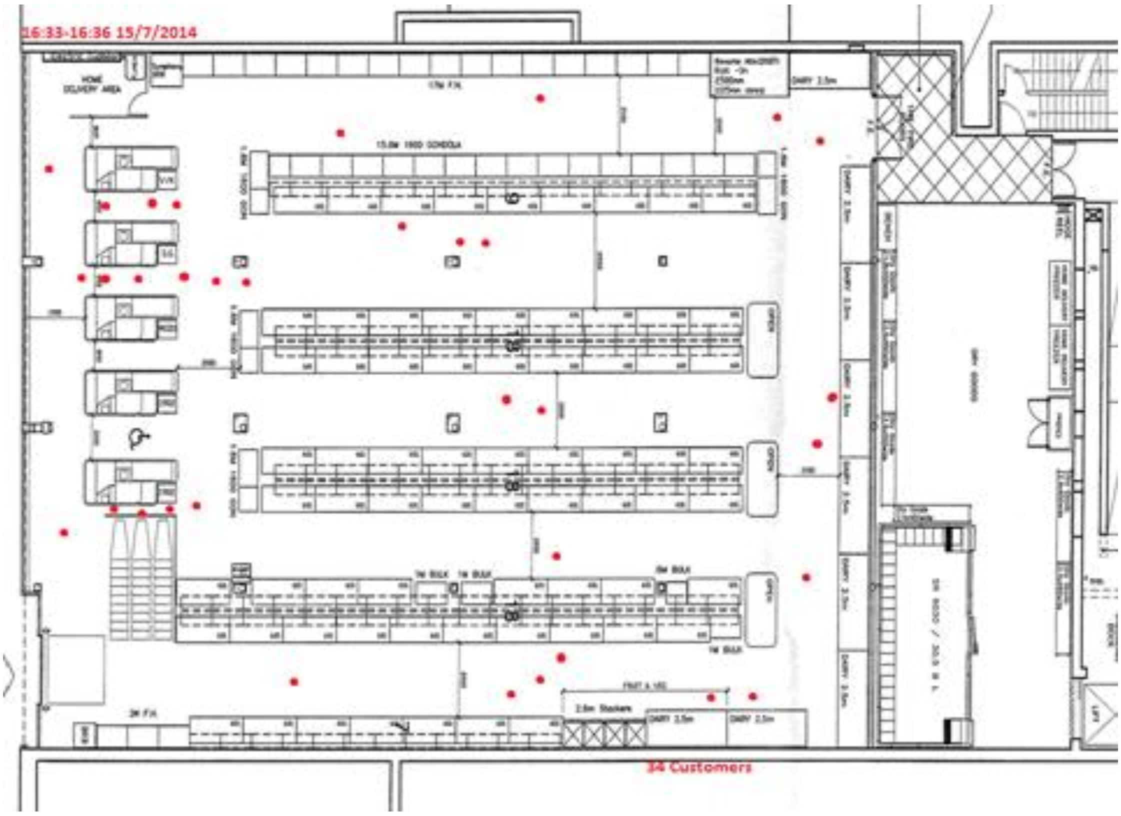




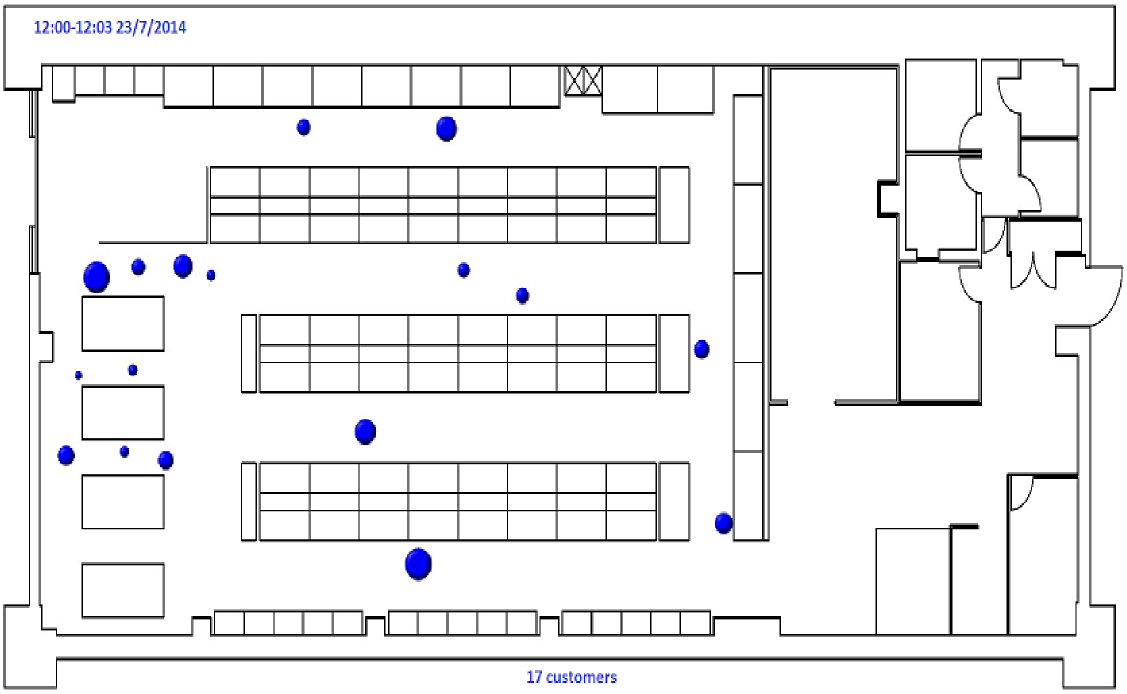

14:00-14:03 15/7/2014
HOME DELIVERY AREA
15.6M 1600 GONDOLA
DAIRY 2.5m
DRY GOODS
42 Customers

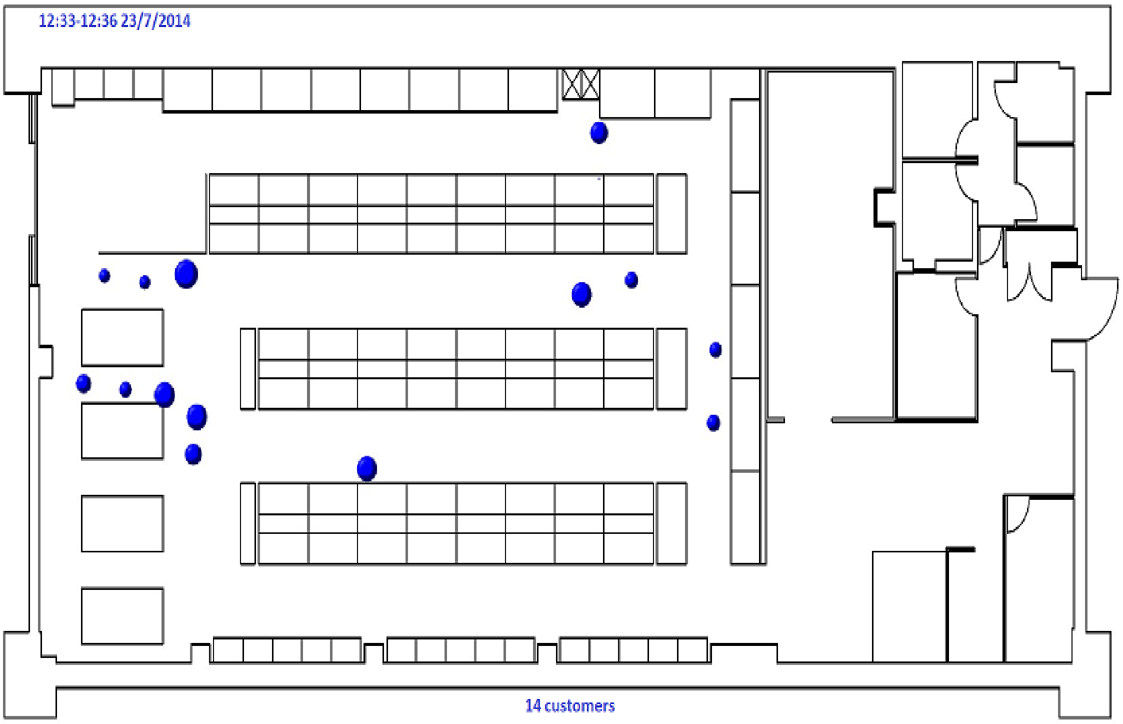

14:33-14:36 15/7/2014
Electric Cupboard
HOME DELIVERY AREA
17M F.H.
15.6M 1600 GONDOLA
Renote Milk(2007) Roll -In 2580mm 1105mm deep
DAIRY 2.5m
DRY GOODS
SR 6030 / 30.5 B L
2.6m Stockers
FRUIT & VEG
3M F.H.
UNLOADING DOCK
LIFT
32 Customeres

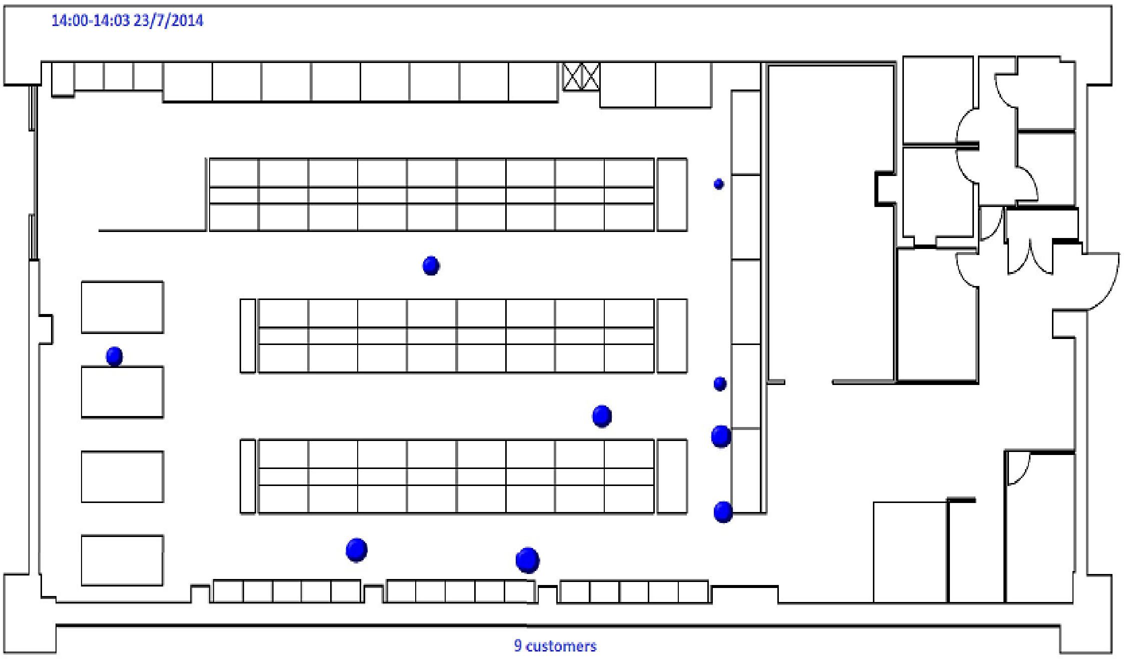

16:00-16:03 15/7/2014
HOME DELIVERY AREA
17M F.H.
15.6M 1600 GONDOLA
DRY GOODS
UNLOADING DOCK
FRUIT & VEG
2.6m Stockers
3M F.H.
38 Customers

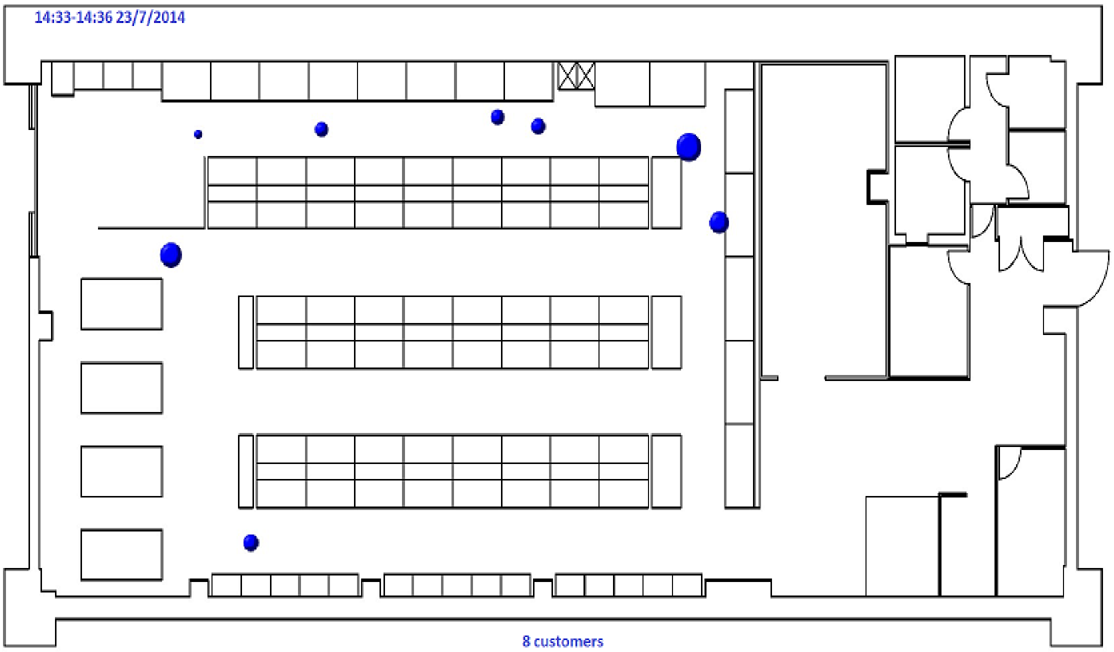

16:33-16:36 15/7/2014
HOME DELIVERY AREA
17M F.H.
15.6M 1600 GONDOLA
DRY GOODS
FRUIT & VEG
2.6m Stockers
3M F.H.
34 Customers

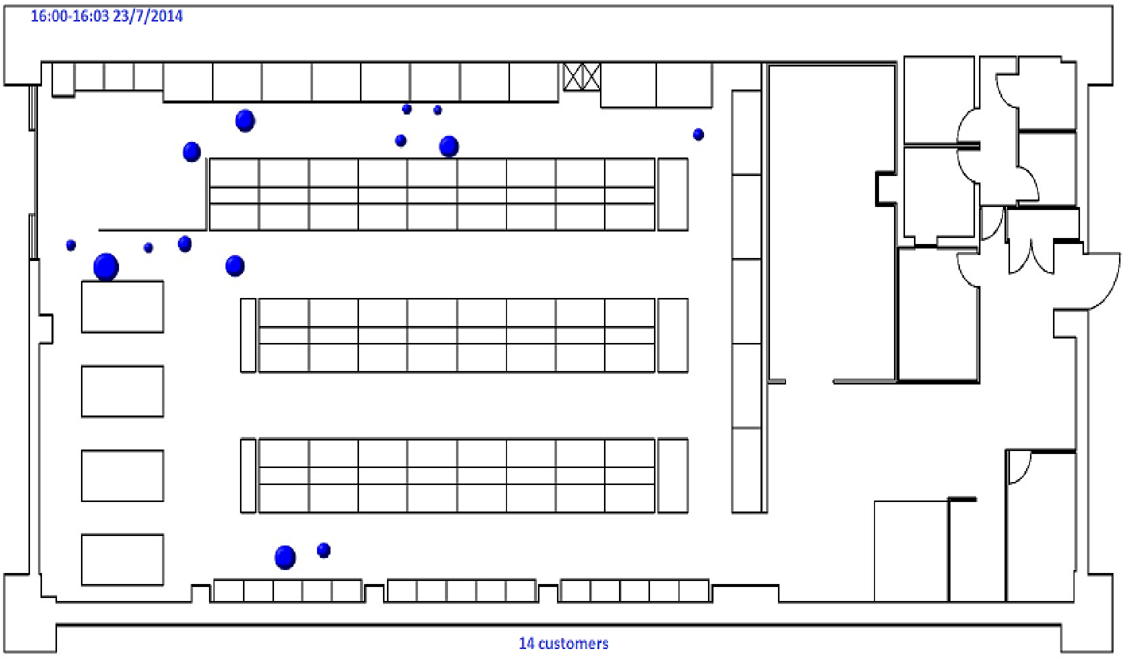
CS2 (Wednesday 23/7/2014)

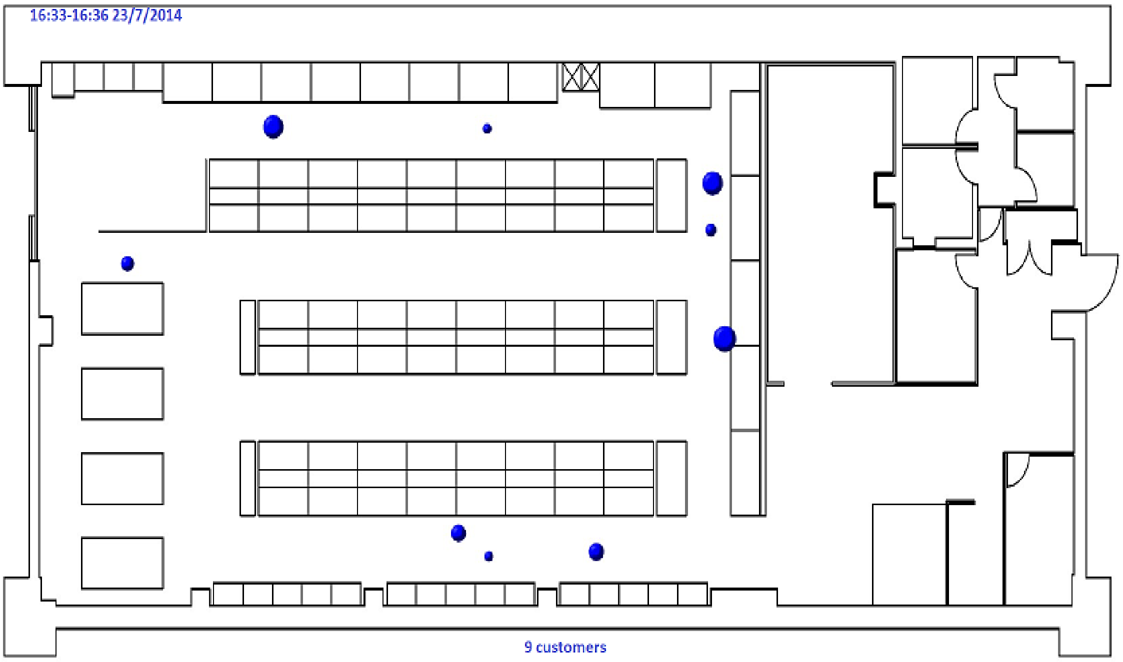





14:00-14:03 23/7/2014
9 customers


14:33-14:36 23/7/2014
8 customers


16:00-16:03 23/7/2014
14 customers


16:33-16:36 23/7/2014
9 customers

Appendix D:

Performance curves' coefficients data for HVAC systems modelling

	Cooling Capacity Function of Temperature Curve & Low Speed Total Cooling Capacity Function of Temperature Curve	Cooling Capacity Function of Flow Fraction Curve	Energy Input Ration (EIR) Function of Temperature Curve and Low Speed Energy Input Ratio Function of Temperature Curve	Energy Input Ration (EIR) Function of Flow Fraction Curve	Part Load Fraction Correlation Curve
a	0.942587793	0.800000000	0.342414409	1.155200000	0.850000000
b	0.009543347	0.200000000	0.034885008	-0.180800000	0.150000000
c	0.000683770	0.000000000	-0.000623700	0.025600000	0.000000000
d	-0.011042676		0.004977216		
e	0.000005249		0.000437951		
f	-0.000009720		-0.000728028		

Cooling Capacity Function of Temperature Curve: $a + b*wb + c*wb^2 + d*edb + e*edb^2 + f*wb*edb$
wb = entering wet-bulb temperature (^oC), edb = dry-bulb temperature seen by the condenser (^oC)

Cooling Capacity Function of Flow Fraction Curve: $a + b*ff + c*ff^2$
ff = fraction of the full load flow (actual air flow rate/rated air flow rate)

Energy Input Ration (EIR) Function of Temperature Curve: $a + b*wb + c*wb^2 + d*edb + e*edb^2 + f*wb*edb$
wb = entering wet-bulb temperature (^oC), edb = dry-bulb temperature seen by the condenser (^oC)

Energy Input Ration (EIR) Function of Flow Fraction Curve $a + b*ff + c*ff^2$
ff = fraction of the full load flow

Part Load Fraction Correlation curve: $a + b*PLR + c*PLR^2$
part load ratio (cooling load/steady state capacity)

	Cooling Capacity Ratio Modifier Function of Low Temperature Curve	Cooling Capacity Ratio Boundary Curve	Cooling Capacity Ratio Modifier Function of High Temperature Curve	Cooling Energy Input Ratio Modifier Function of Low Temperature Curve	Cooling Energy Input Ratio Boundary Curve	Cooling Energy Input Ratio Modifier Function of High Temperature Curve	Cooling Energy Input Ratio Modifier Function of Low Part-Load Ratio Curve	Cooling Energy Input Ratio Modifier Function of High Part-Load Ratio Curve	Cooling Combination Ratio Correction Factor Curve	Cooling Part-Load Fraction Correlation Curve
C1	0.576882692	25.73473775	0.6867358	0.989010541	25.73473775	0.143515	0.462812	1	0.618055	0.85
C2	0.017447952	-0.03150043	0.0207631	-0.02347967	-0.03150043	0.0186	-1.04024	0	0.381945	0.15
C3	0.000583269	-0.01416595	0.0005447	0.000199711	-0.01416595	-0.0004	2.17491	0		0
C4	-1.76324E-06	0	-0.0016218	0.005968336	0	0.024852	-0.59748			
C5	-7.47E-09		-4.259E-07	-1.0289E-07		0.000163				
C6	-1.30E-07		-0.0003392	-0.00015686		-0.00062				

Cooling Capacity Ratio Modifier Function of Low Temperature Curve : represents full load cooling capacity ratio as a function of outdoor dry-bulb temperature and load-weighted average indoor wet-bulb temperature

Cooling Capacity Ratio Boundary Curve: this is used to allow separation of low and high cooling capacity ratio performance curves. This curve represents a line passing through the points where performance changes. The curve calculates outdoor dry-bulb temperature given weighted average indoor wet-bulb temperature

Cooling Capacity Ratio Modifier Function of High Temperature Curve: is used to describe the high outdoor temperature performance curve used to describe cooling capacity ratio

Cooling Energy Input Ratio Modifier Function of Low Temperature Curve: represents cooling energy ratio as a function of outdoor dry-bulb temperature and indoor wet-bulb temperature

Cooling Energy Input Ratio Boundary Curve: is used to allow separate low and high cooling energy input ratio performance curves. This curve represents a line passing through the points where performance changes. The curve calculates outdoor dry-bulb temperature given weighted average indoor wet-bulb temperature

Cooling Energy Input Ratio Modifier Function of High Temperature Curve: describe the high outdoor temperature performance curve used to describe cooling energy ratio

Cooling Energy Input Ratio Modifier Function of Low Part-Load Ratio Curve: represents cooling energy ratio as a function of part-load ratio for part-load ratios less than or equal to 1

Cooling Energy Input Ratio Modifier Function of High Part-Load Ratio Curve: represents cooling energy ratio as a function of part-load ratio for part-load ratios greater than 1

Cooling Combination Ratio Correction Factor Curve: defines how rated capacity changes when the total indoor terminal unit cooling capacity is greater than the Gross Rated Total Cooling Capacity

Cooling Part-Load Fraction Correlation Curve: defines the cycling losses when the heat pump compressor cycles on and off below the Minimum Heat Pump Part-Load Ratio specified

	Heating Capacity Ratio Modifier Function of Low Temperature Curve	Heating Capacity Ratio Boundary Curve	Heating Capacity Ratio Modifier Function of High Temperature Curve	Heating Energy Input Ratio Modifier Function of Low Temperature Curve	Heating Energy Input Ratio Boundary Curve	Heating Energy Input Ratio Modifier Function of High Temperature Curve	Heating Energy Input Ratio Modifier Function of Low Part-Load Ratio Curve	Heating Energy Input Ratio Modifier Function of High Part-Load Ratio Curve	Heating Combinati on Ratio Correction Factor Curve	Heating Part-Load Fraction Correlatio n Curve
C1	-3.91E-01	-7.60009	1.161135	0.874655	-7.60009	2.504005	0.140009	2.429436	0.96034	0.85
C2	2.62E-01	3.0509	0.027479	-0.0132	3.0509	-0.05737	0.6415	-2.23589	0.03966	0.15
C3	-1.30E-02	-0.11628	-0.00169	0.001103	-0.11628	4.07E-05	0.133905	0.806452		0
C4	1.78E-04	0	0.001783	-0.01331	0	-0.1296	0.084586			
C5			2.03E-06	0.00089		0.001358				
C6			-6.9E-05	-0.00013		0.00317				

Heating Capacity Ratio Modifier Function of Low Temperature Curve: represents full load heating capacity ratio as a function of outdoor dry-bulb temperature and indoor dry-bulb temperature. Outdoor dry-bulb temperature may be used if wet-bulb temperature data is unavailable
Heating Capacity Ratio Boundary Curve: is used to allow separate low and high heating capacity ratio performance curves. This curve represents a line passing through the points where performance changes. The curve calculates outdoor dry-bulb or wet-bulb temperature given weighted average indoor dry-bulb temperature.
Heating Capacity Ratio Modifier Function of High Temperature Curve: is used to describe the high outdoor temperature performance curve used to describe heating capacity ratio
Heating Energy Input Ratio Modifier Function of Low Temperature Curve: represents heating energy ratio as a function of outdoor dry-bulb temperature and indoor dry-bulb temperature Outdoor dry-bulb temperature may be used if wet-bulb temperature data is unavailable
Heating Energy Input Ratio Boundary Curve: is used to allow separate low and high heating energy input ratio performance curves. This curve represents a line passing through the points where performance changes. The curve calculates outdoor dry-bulb or wet-bulb temperature given weighted average indoor dry-bulb temperature
Heating Energy Input Ratio Modifier Function of High Temperature Curve: is used to allow separate performance curves for heating energy.
Heating Energy Input Ratio Modifier Function of Low Part-Load Ratio Curve: represents the heating energy input ratio for part-load ratios less than 1
Heating Energy Input Ratio Modifier Function of High Part-Load Ratio Curve: represents the heating energy input ratio for part-load ratios greater than 1
Heating Combination Ratio Correction Factor Curve: defines how rated capacity changes when the total indoor terminal unit heating capacity is greater than the Gross Rated Heating Capacity
Heating Part-Load Fraction Correlation Curve: defines the cycling losses when the heat pump compressor cycles on and off below the Minimum Heat Pump Part-Load Ratio specified

	Piping correction factor for Length in cooling mode curve	Piping correction factor for Length in heating mode curve	Cooling capacity ratio modifier function of Temperature curve	Cooling capacity modifier curve function of flow fraction	Heating capacity ratio modifier function of Temperature curve	Heating capacity modifier curve function of flow fraction
C1	0.618055	0.96034	0.504547274	0.8	-0.390708928	0.8
C2	0.381945	0.03966	0.028889127	0.2	0.261815024	0.2
C3			-0.0000108194187	0	-0.0130431603	0
C4			0.0000101359395		0.000178131746	
Piping correction factor for length in cooling/heating mode curve: $C1+C2*P_{length}$ P_{length}: Piping length (m^2)						
Cooling/Heating Capacity Function of Temperature Curve: $C1 + C2*wb + C3*wb^2 + C4*wb^3$ wb = entering wet-bulb temperature (^oC)						
Cooling/Heating Capacity Function of Flow Fraction Curve: $C1 + C2*ff + C3*ff^2$ ff = fraction of the full load flow (actual air flow rate/rated air flow rate)						