Department of Mechanical and Aerospace Engineering

Exploring Low Carbon Options for Refrigeration in UK Supermarkets: Assessing the Impact of Doors on Refrigerated Display Cabinets

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Signed: Richard Faulkner Date: 31/08/2021

Abstract

As an industry, food retail is responsible for consuming 12.0 TWh of electrical energy in a year (Tassou *et al.*, 2011) equating to 3% of the UK's total consumption. In supermarkets the energy is divided through many areas such as lighting, HVAC, food preparation and offices. However, by far the main source of consumption is refrigeration, using 30-60% of the store's total energy (Tassou *et al.*, 2011). The refrigeration cycle in supermarkets is used to chill display cabinets for perishable food products and consists of four key components: compressors, condensers, expansion valves and evaporators (all of which are covered in the literature review). In this thesis the focus is specifically on the refrigerated display cabinets as there are many potential improvements that can be made to reduce electrical consumption. A substantial argument in the industry is the 'Doors Vs No Doors' debate where supermarkets appear to be reluctant to add doors to cabinets. Research has shown that customers strongly disregard the idea of having doors on cabinets as it is deemed "a barrier to shopping" (Adande Refrigeration, 2013). A supermarket's main goal is to generate revenue which means that unless there are significant savings, they will not implement any additional changes that would risk disrupting their customer's experience.

In this thesis two investigations were carried out to explore areas where supermarkets can lower their refrigeration energy demand. The first investigation used three case study locations where doors had recently been retrofitted to analyse if significant saving were possible. The results proved that in the three investigated locations, savings were present for all refrigeration units. In Edinburgh average savings across the shop were 37.78% ± 17.8%. In Hartlepool savings were less significant at 21.45% ± 9.59%, and in Middleton the store performed well where an average of 34.79% ± 16.3% was saved.

The second investigation used the University of Strathclyde's modelling software, Esp-r, to simulate a cross section of an aisle. Three test environments were created to simulate a quiet, regular, and busy supermarket. Simulations were carried out on each of the environments to assess if further savings could be made in cabinets with doors. Triple glazing was found to reduce consumption by a maximum of 9.66% but low emissivity glass was the recommended choice due to reduced installation costs and a maximum saving of 6.58%. Insulation thickness was then assessed which proved 30mm to be an optimum thickness for the side panels. Finally, introducing night infiltration of 2.5ac/h when the shop is unoccupied proved to save an average saving of 2.7% ± 1%.

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I would also like to thank my family and friends who have supported and encouraged me throughout my masters, and general university career. They have helped to keep me focused, inspired and motivated for the duration of this project.

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1.0 Introduction

In the UK there are over 87,000 retail stores accounting for 9% of total household expenditure (J. Vasquez, 2019). Shopping for food is the third largest expense, after housing and transport, and is a key driver for the rising number of shopping locations across the UK. Over 15% of retail food stores can be described as supermarkets, which vary dramatically in size depending on their purpose and location, with some supermarket's exceeding sizes of over 10,000m^2 (Tassou *et al.*, 2011). Subsequently this means that larger stores will experience a substantial increase in energy demand.

The food chain as a whole consumes 18% of the UK's primary energy use each year which including all stages from the production of food right through to the end use consumer (Tassou *et al.*, 2014).

As an industry, food retail is responsible for consuming 12.0 TWh of electrical energy in a year (Tassou *et al.*, 2011) which is roughly 3% of the UK's total consumption. In supermarkets the energy is divided through many areas such as lighting, HVAC, food preparation and offices. However, by far the main source of consumption is refrigeration, using 30-60% of the store's total energy (Tassou *et al.*, 2011). The percentage of energy consumed by the refrigeration cycle depends on the type of supermarket. Smaller stores are more energy intensive thus taking up a larger percentage. In larger stores a bigger proportion of the sales floor is dedicated to non-refrigerated products and often include aisles for technology and clothing resulting in refrigeration using less energy per m^2 of sales floor.

The refrigeration cycle in supermarkets is used to chill display cabinets for perishable food products and consists of four key components: compressors, condensers, expansion valves and evaporators. The cycle can be manipulated to suit the type of supermarket, but the end product remains constant, cold air being delivered to display cabinets which stock the refrigerated products.

Refrigerated display cabinets come in a variety of sizes and shapes suited to their primary role. An air curtain in the front of the cabinet is used to circulate cold air essentially forming a wall of cold air at the front of the cabinet. This air is collected at the bottom and recycled through the back of the unit to uniformly distribute the cold air. Customer interactions with products on the shelves disrupts the air curtain and causes an infiltration of hot air into the refrigerated cabinet resulting in an internal temperature rise which requires increased duty from the refrigeration plant and energy demand increases. Infiltration accounts for 70-80% of the cooling load (Tassou *et al.*, 2011). Another issue with conventional air curtains is that air can leak into the aisle thus reducing the ambient temperature and requiring more output from the HVAC system to maintain ambient aisle temperatures. Spillage into aisles can be caused by blockages in the return inlet for the air curtain or simply from older equipment that may not have a high enough air flow velocity to fully reach the bottom of the cabinet.

Adding doors to display cabinets has long been considered as an effective solution to reduce air spills and infiltration thus saving energy. Currently the frozen section is the most common place in which doors have been fitted to the display units, however many large chain supermarkets are still reluctant to add doors to the chilled cabinets because they believe it disrupts the customer experience. In research done by Adande Refrigeration (2013), over 50% of customers found glass doors inconvenient or difficult to open when holding a shopping basket. With the majority of customers describing cabinet doors as “a barrier to shopping” (Adande Refrigeration, 2013).

In Europe display cabinets are built to BS EN ISO 23953 standards (IOR, 2019) which requires the testing of doors for 10 openings per hour. Modelling the addition of doors has been found to lower energy demand by 20-35% for 20 openings per hour (Hill, Watkins and Edwards, 2014). Whilst 10 – 20 door openings an hour can generally be applied to quiet stores, busier stores can be in the range of up to 50-150 per hour (Månsson *et al.*, 2019).Testing of display cabinets, with doors built to BS EN ISO 23953 regulations, for 30 openings per hour showed that internal temperatures can rise by 5°C (Wood, 2019). The cabinets also failed to reduce the internal temperature back within the set points after 12 hours of being closed. Increased infiltration causes the evaporator to ice over which restricts the cabinets’ ability to control the temperature and the energy consumption rises.

A supermarket’s main goal is to generate revenue which means that unless there are significant savings, they will not implement any additional changes that would risk disrupting their customer’s experience. In this thesis investigations were conducted to evaluate the impact of two different methods that supermarkets can deploy to lower their energy demand and subsequently reduce their carbon footprint and ultimately save money.

The first investigation utilises data collected by City Facilities Management (UK) Ltd (City FM) in three supermarket locations in the UK. The data provided includes daily recordings of temperatures and energy consumption for various appliances in each of the retail premises. In these carefully selected sites, the refrigerated display cabinets had recently been retrofitted with glass doors in the meat, vegetable, and dairy aisles. The investigation focuses only on the energy consumption of the refrigeration units that supply the aisles where the retrofits took place. One year of data leading up to the installation was used to create a baseline equation from which consumption can be calculated. The actual consumption was then used to assess the energy being saved after the doors were installed.

In the second investigation, a computer model was created to simulate additional alterations that can be made to display cabinets to reduce energy consumption. Using the University of Strathclyde's modelling software, Esp-r, a cross section of a supermarket aisle was modelled featuring a small box area with two display cabinets facing each other. Once a baseline model was established, it was replicated and edited to simulate three test environments. The models were structurally identical; however, changes were made to internal gains and air flows to represent quiet, regular, and busy supermarkets.

For each test environment three sets of simulations took place where alterations were made to the model. One set of simulations investigated using different glazing on the doors and side windows. The second simulations examined how insulation thickness in the cabinets structure directly effects the energy consumption. The third set of simulations introduced night infiltration when the shop was unoccupied to investigate if the amount of cooling hours per year could be reduced.

2.0 Literature Review

2.1 Global Energy Consumption

Throughout history the worlds energy consumption has grown exponentially in line with increasing population and the development of new technology. Figure 1Figure 1 : Global energy consumption by source (Source: Our world in data), displays a graph detailing the world's energy consumption in the last century which has increased 8-10x (Ritchie, 2020). Notably, in recent years the growth of coal and oil use has slowed and is beginning to flatline.

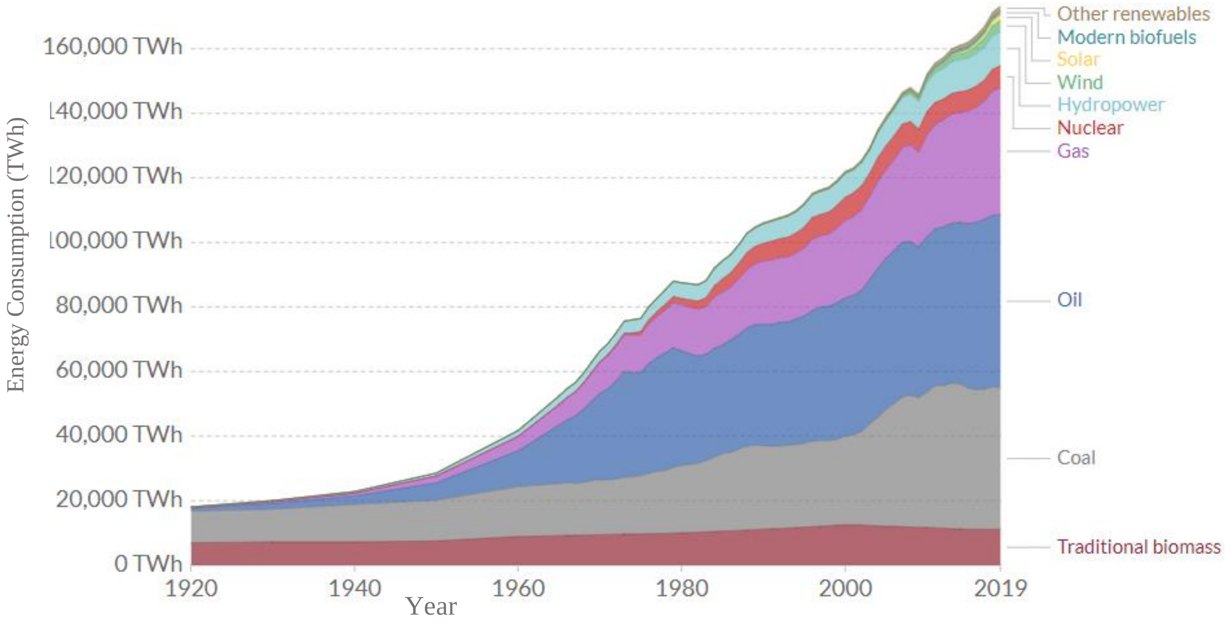


Figure 1 : Global energy consumption by source (Source: Our world in data)

Increased global concern about climate change has driven energy away from traditional fossil fuels and towards more renewable sources, such as hydropower, wind and solar. The Paris Agreement (UNFCCC, 2015) has also had an effect on global energy consumption where 195 countries agreed to collectively reduce carbon emissions. Targets were set to limit global warming to 1.5 - 2°C above pre-industrial levels which has driven exploration into low-carbon energy solutions. By 2020 participating countries were asked to submit long term plans to reduce carbon emissions which has undoubtably caused a significant uptake in renewable power over the last few years. Between 2018 and 2019 energy consumption from renewable sources had a record increase with a growth rate of 12.2% (BP, 2020a). Although using renewable energy is becoming more common a significant amount of energy is still consumed from fossil fuels.

Oil and natural gas consumption both experienced small growth of 0.9% and 2% respectively whereas use of coal declined by 0.6% to its lowest share of the world consumption in over 15 years (BP, 2020b). The small growth in oil and gas consumption is considerably less than previous years exponential growth and still signals a decline in consuming fossil fuels. Over the last decade global CO_2 emissions from energy use have grown at an average rate of 1.1% per annum (BP, 2020b). In 2019, growth of CO_2 emissions more than halved to 0.5% (BP, 2020b) suggesting that the large uptake in consuming renewable energy is salvaging the increase of emissions in recent years.

2.2 Supermarkets Energy Consumption in the UK

Between 2018 and 2019 the UK's total energy consumption decreased by 1.4 million tonnes of oil equivalent (mtoe) to 142mtoe (GOV.UK, 2019). As expected, the domestic and transport sectors take up a considerable 68% of the total. Services account for 15% of total consumption with a substantial 2.97mtoe (2% of total) being used in the food and beverages sector (GOV.UK, 2019).

'Supermarkets' fall under different classifications regarding the average sales floor area, for example:

- Convenience Store (< 280m^2)
- Supermarket (280m^2-1400m^2)
- Superstore (1400m^2-5000m^2)
- Hypermarket (5000m^2-10,000m^2+)

In order to give a fair assessment of energy use in supermarkets their consumption is specified in terms of sales floor area, generally kW/m^2, which is defined as an energy intensity (Tassou *et al.*, 2011). Considering energy intensity enables comparison of any individual supermarket ranging from convenience to hypermarket retail units.

In convenience stores, the average electrical energy intensity is around 1500 ± 350 kWh/m^2 per year which can be reduced through increased sales floor area. For example hypermarkets electrical intensity is 770 ±120 kWh/m^2 per year (Tassou *et al.*, 2011) which is significantly less than convenience stores considering the annual consumption is much larger. Figure 2 shows the variation of electrical energy intensity for 2570 UK supermarkets for an increasing sales floor area of 80m^2 to 10,000m^2. Moving from convenience stores to supermarkets exponentially reduces the energy intensity but when progressing to superstores and hypermarkets the reduction is less significant.

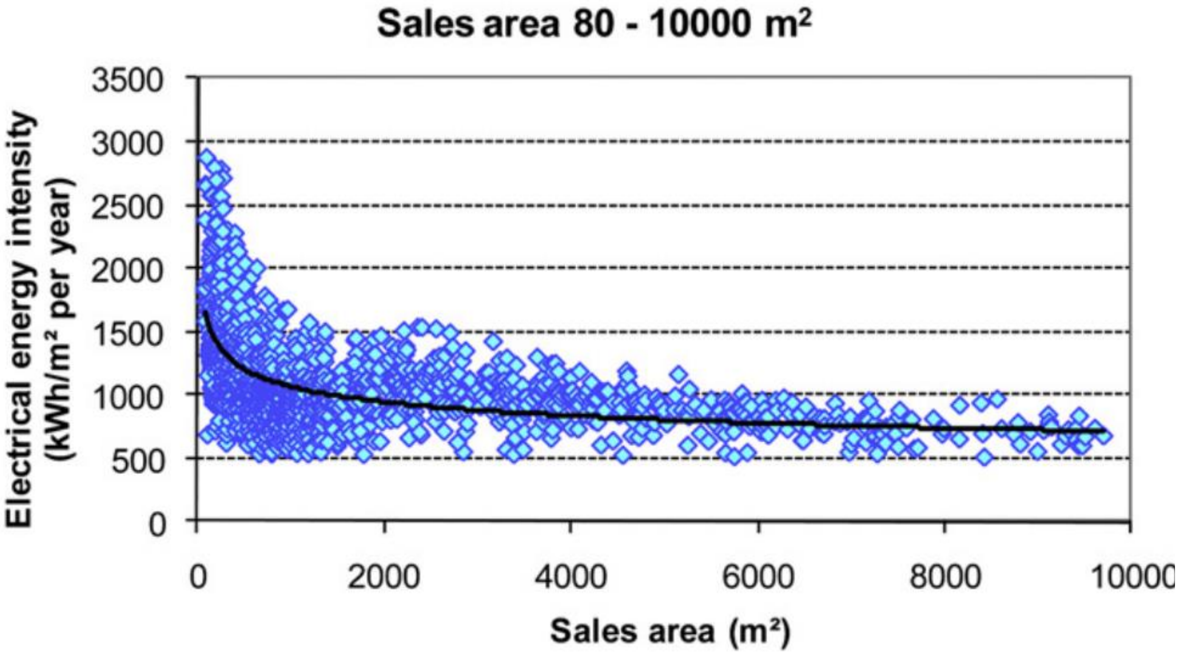


Figure 2: Variation of electrical energy intensity in 2570 UK retail food stores (80m2 ¬- 10,000m2) (Source:(Tassou et al., 2011))

One influential factor causing the exponential drop is that convenience stores mainly stock grocery products, requiring significant energy for refrigeration, whereas larger stores offer a wider variety of products such as clothing and other non-food products.

The food retail industry consumes 12.0 TWh of electrical energy each year which represents roughly 3% of the UK's total consumption (Tassou *et al.*, 2011). Figure 3 conveys how the electrical consumption is split between different areas in a hypermarket. A considerable 30% of the store's consumption is directly related to refrigeration which significantly increases up to 60% in smaller stores where the energy intensity is higher.

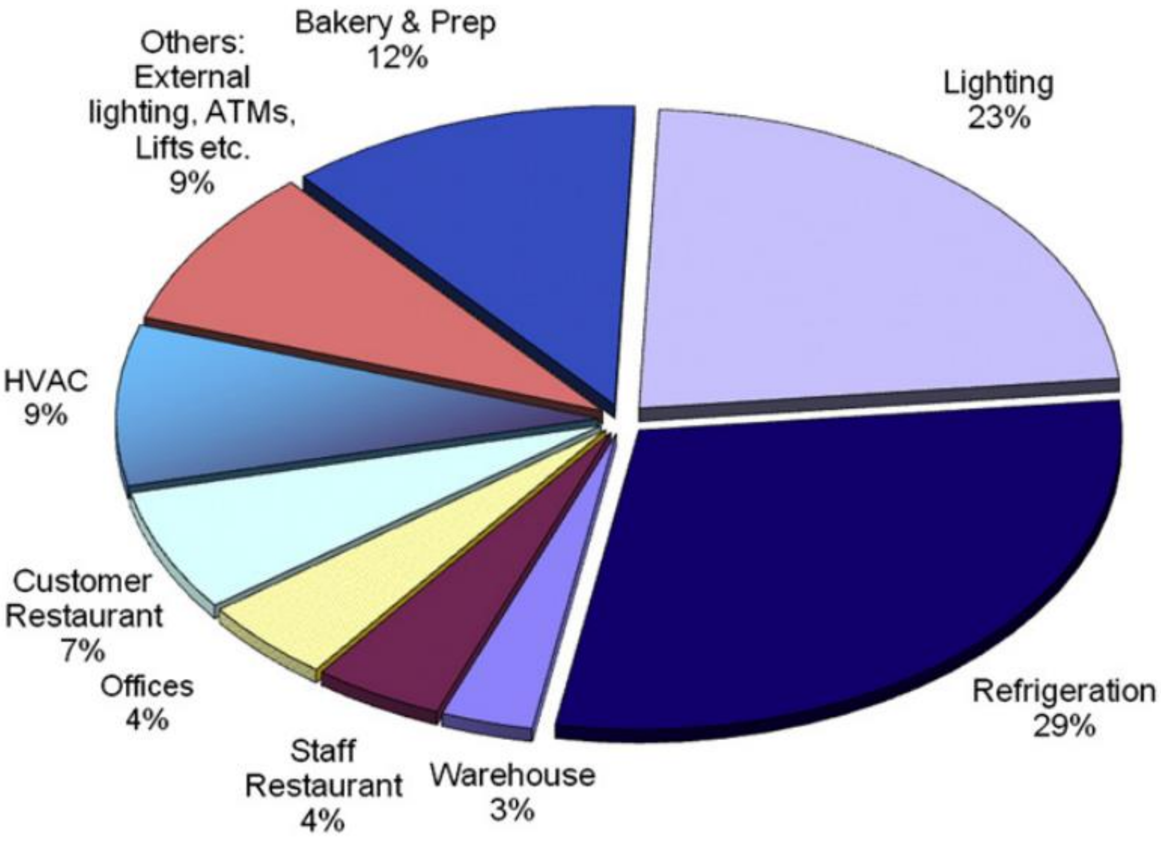


Figure 3: Energy consumption pie chart - hypermarket (Source: (Tassou et al., 2011))

2.3 Refrigeration in Supermarkets

In supermarkets, refrigeration is vital as the shops mainly supply food and beverages, many of which need to be stored at low temperatures to avoid spoiling. This means that refrigeration appliances are needed in both the warehouse, to store overstock, and on the sales floor, to be presented to customers. In a typical supermarket there will be at least two cold storerooms in the warehouse for refrigerated and freezer products. Additionally, on the shop floor display cases are required for fridge and freezers which can come in a selection of sizes with or without doors. Although the appliances being used can vary depending on store size or location the main components used in the refrigeration cycle remain the same:

- Compressor
- Condenser
- Expansion Valve
- Evaporator

Figure 4 gives an example of a common air-cooling vapour compression schematic that is widely used. Refrigerant is passed through the cycle where its state of matter changes between liquid and gas to form the cooling effect.

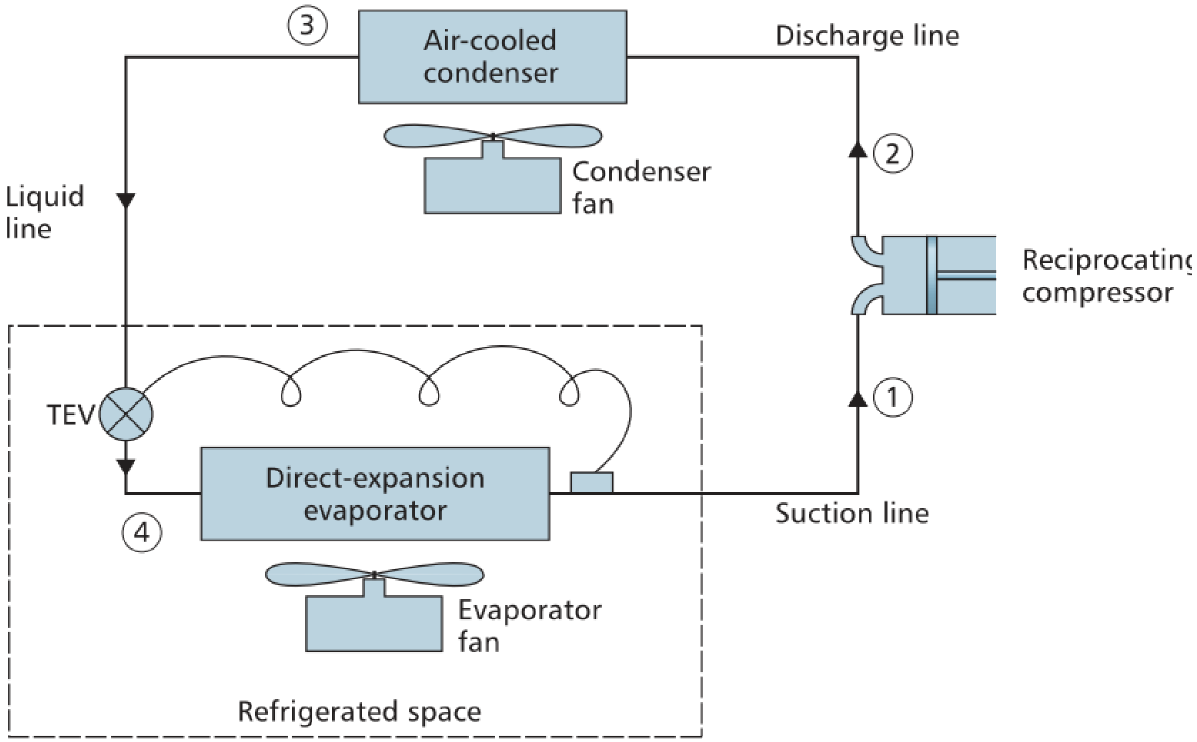


Figure 4: Air cooling vapour compression schematic (Source:(CBISE, 2008))

In its gaseous form, refrigerant from the evaporator flows into the compressor which reduces the volume creating a hot pressurised gas. Hot gas then passes through the condenser where a change of state occurs producing a warm liquid. Progressing through the expansion valve (TEV in Figure 4) rapidly decreases the temperature of the refrigerant due to pressure being released. Finally, the cold liquid refrigerant is passed through the evaporator tubing where a fan circulates the cold air in the refrigerated space. During this stage in the cycle the cold liquid refrigerant changes state to gas which is extracted and used as the inlet for the compressor (CBISE, 2008).

2.3.1 Compressor

When selecting which type of compressor to use in a refrigeration cycle there are five alternatives to choose from the following list.

- Reciprocating

- Rotary Vane
- Rotary Scroll
- Rotary Screw
- Centrifugal

Reciprocating compressors can be described as single acting piston compressors (Lin and Avelar, 2017). Pistons are contained within a cylinder which synchronise with compression and suction valves to increase the pressure and temperature of the refrigerant. A motor inside the compressor is connected to the piston through a crankshaft which transforms rotation into a linear piston motion. Figure 5 shows a cut- away view of a reciprocating compressor.

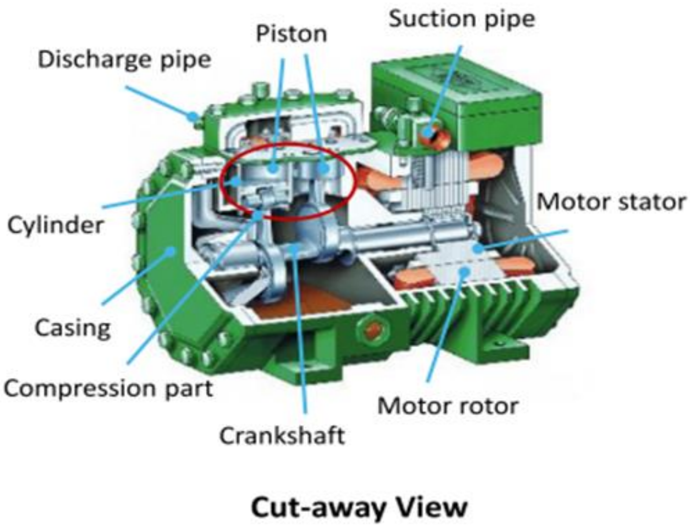


Figure 5 : Cut-away view of a reciprocating compressor (Source:(Lin and Avelar,2017))

A key feature of this type of compressor is its diversity as they can compress a variety of gases and can be built to specific capacities, even for residential fridges/ freezers. Unfortunately, they can have very low efficiencies due to losses from clearance volume, a proportion of compressed refrigerant that becomes trapped in the piston because of its shape (Lin and Avelar, 2017). Reciprocating compressor efficiency is also affected by gas leaks between the cylinder and compressors which can become a significant problem depending on which type of refrigerant is being used.

Rotary vane compressors are contained within a cylinder that is split into two sections with openings for discharge and suction. Volume of refrigerant in each section is increased and decreased by a rolling piston that moves in a circular motion to produce gas suction, compression, and discharge (Lin and Avelar, 2017). Figure 6 shows a cut away view of a rotary vane compressor. Compared to reciprocating compressors, the rotary vane will be more efficient because of its streamlined design which reduces clearance volume losses. They also are more reliable because there is no conversion from rotation to linear motion. One main limitation is their capacity which is restricted to a maximum of 18kW due to the structure of the compressor (Lin and Avelar, 2017).

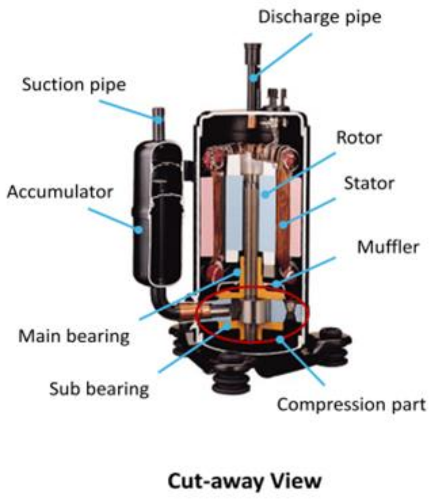


Figure 6: Cut-away view of a rotary vane compressor (Source:(Lin and Avelar,2017))

Rotary scroll compressors have one fixed scroll and one orbital scroll that rotates and creates a pocket of vapour refrigerant that compresses towards the centre of the fixed scroll. As the volume of gas is reduced it is discharged through the top of the compressor. An example of a rotary scroll compressor can be found in Figure 7 where the red circle highlights the fixed (grey) and orbital (yellow) scrolls.

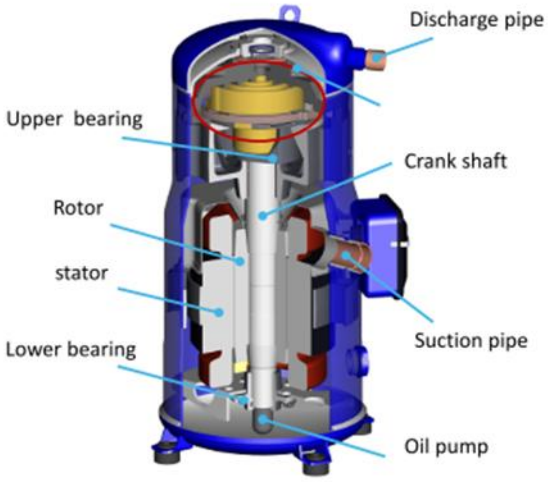


Figure 7 : Cut-away view of a rotary scroll compressor (Source:(Lin and Avelar,2017))

Compared to the previous two examples, rotary scroll compressors adopt a simpler design with less components thus increasing its reliability. They are also more efficient pieces of hardware as there will be no clearance volume and removing suction and discharge valves eliminates their losses too. Capacity can range between 18 – 35kW (Lin and Avelar, 2017) which is slightly better than rotary vane compressors.

Rotary screw compressors use a combination of male and female rotors to increase the refrigerants pressure and temperature. Cold gas is drawn in through the suction port and pushed through the threads of the rotors that rotate and reduce the volume of gas (Lin and Avelar, 2017). Hot gas with high pressure exits through the discharge port and moves on to the next stage in the cycle. Figure 8 shows a cut away view of a rotary screw compressor.

Out of the above-mentioned compressors, the rotary screw has the largest capacity and is most efficient due to its simple structure and limited components. One problem with the design is that it is impractical to design a capacity of less than 70kW (Lin and Avelar, 2017) and is therefore more common in large projects.

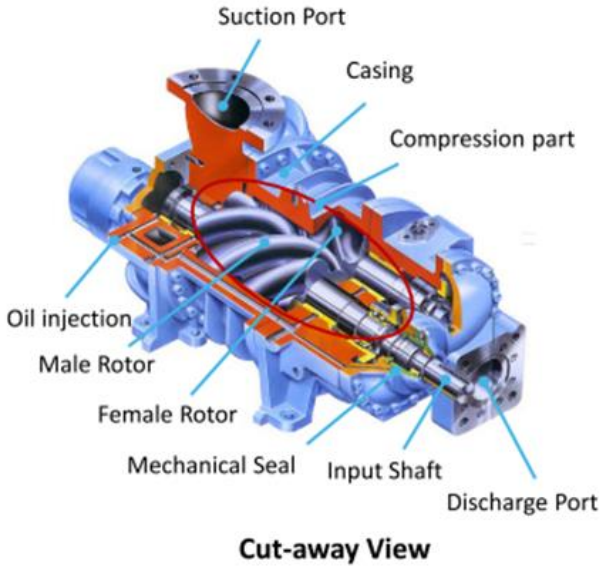


Figure 8 : Cut-away view of a rotary screw compressor (Source:(Lin and Avelar,2017))

Centrifugal compressors use kinetic energy from two stages of rotating impellers to increase the refrigerants pressure and temperature (Lin and Avelar, 2017). Cold vapour is sucked into the first impeller where it is spun up to a high speed. The fast-moving gas is then passed through a diffuser that slows it down simultaneously causing the gas to expand. Figure 9 shows a cut away view of a centrifugal compressor.

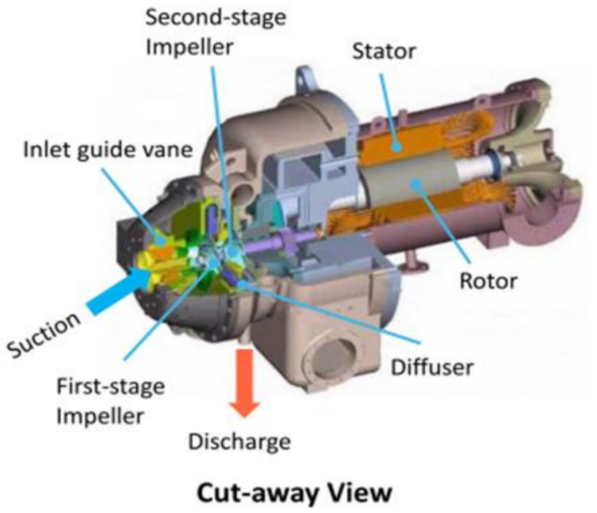


Figure 9 : Cut-away view of a centrifugal compressor (Source:(Lin and Avelar,2017))

They have the largest capacity rising as high as 35,000kW for a single unit (Lin and Avelar, 2017). They are also the most efficient and much more reliable as they have the least number of components. Out of all the alternatives they are the lightest, weighing 80- 90% less than reciprocating compressors and the carbon footprint is halved (Lin and Avelar, 2017). Centrifugal compressors have a high start-up cost but increased efficiency and decreased operating costs make it a worthy investment. Similar to the rotary screw compressors it is impractical to design them with a capacity of less than 70kW and manufacturing small diameter impellers is difficult. When operating at smaller loads the system is at risk of surging where the gas flow is reversed from the discharge side to the suction leaving it in an unstable condition.

2.3.2 Condenser

In a refrigeration cycle the condenser is used as a heat exchanger to cool the hot gas into a warm liquid. For commercial and industrial purposes two main types of condensers can be used:

- Air Cooled
- Water Cooled

Air cooled condensers have the cheapest initial start-up cost due to their simple design, but they generate high running costs and require a large surface area (CBISE, 2008). They have higher operating costs due to greater power requirements to keep the condensing temperature

15-20°C above the ambient air temperature (Hosoz and Kilicarslan, 2004). Figure 10 shows an example of an air-cooled condensing unit where hot gas is drawn from the compressor into the condensing tubes. Cold ambient air then passes over the condenser coil which reduces its temperature turning the hot gas into a liquid. In supermarkets these condensing units are generally found outside to the rear of the building or on the rooftop because of their size. Leaving the unit in direct sunlight on a flat roof can raise the temperature by 10°C which may affect the performance (IOR, 2019). To minimise solar gains, screens can be used to protect the units.

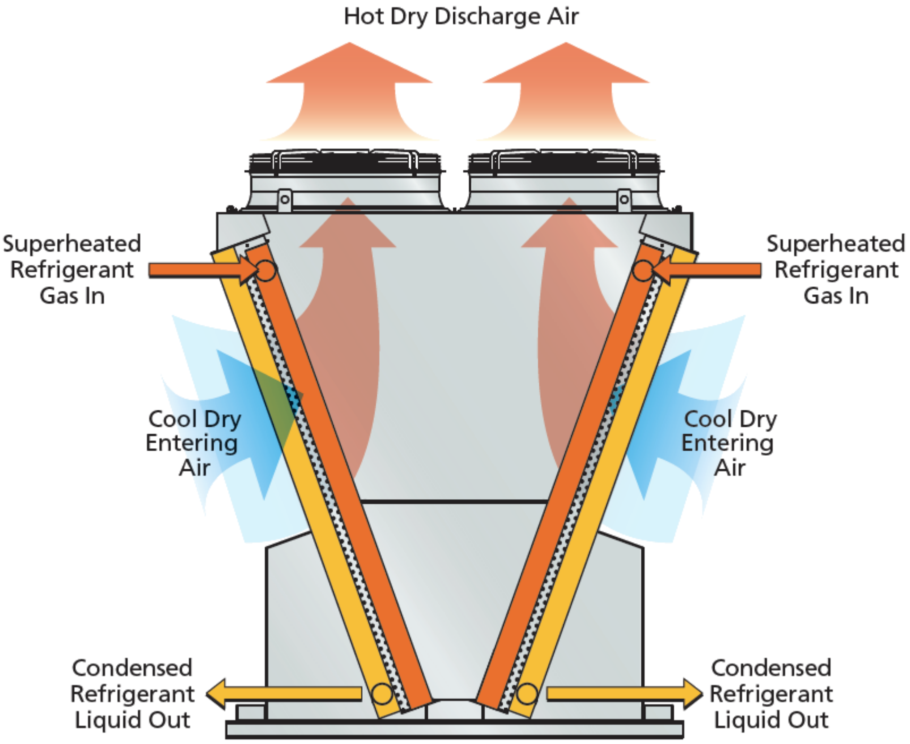


Figure 10 : Air cooled condensing unit

Water cooled condensers use water instead of air in a shell and tube heat exchanger. Figure 11 shows a diagram of a water-cooled condenser where cold water enters the tube and the hot gas from the compressor flows over the tubes causing condensation. Eventually the condensation drips off the tubes into a hot well of liquid refrigerant ready to be passed into the next stage of the cycle. The heat from the refrigerant gas is absorbed by the cold water that exits to the ambient air through a cooling tower (Hosoz and Kilicarslan, 2004). Cooling towers use fans to circulate air through the hot excess water consequently lowering the temperature before being returned to the start of the heat exchanger process (Smith and Parmenter, 2016). They tend to have higher start-up costs than air cooled condensers and require frequent treatment and supervision as there is risk of legionella growing if the temperature in the cooling tower is between 20-55°C (Rogers et al., 1994). An opportunity for legionella growth to be eliminated would be to use a dry air cooler instead of a cooling tower (CBISE, 2008). This method of cooling is however less efficient as the water temperature cannot be reduced enough.

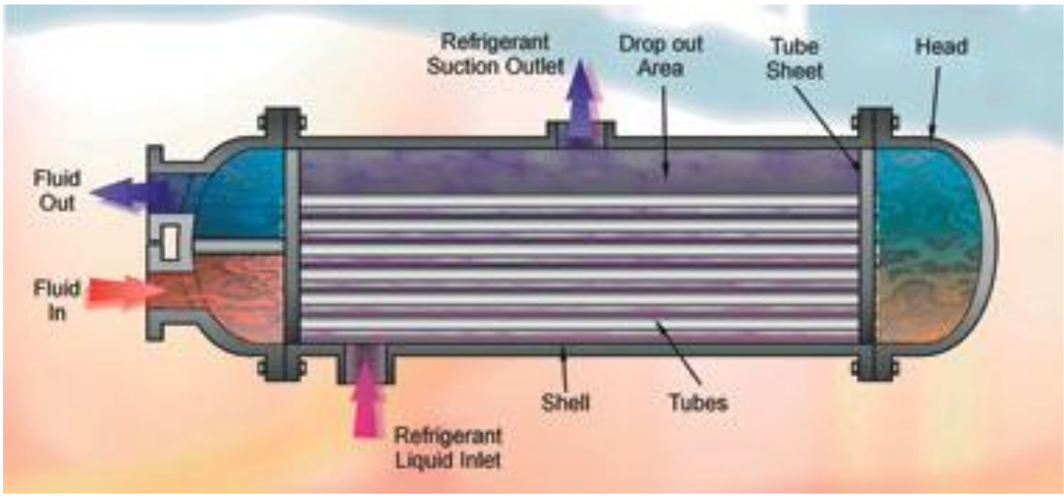


Figure 11 : Diagram of a water-cooled condenser

Comparing the two condensers, water cooled have about a 45% larger capacity than air cooled condensers (Hosoz and Kilicarslan, 2004). Additionally, water cooled condensers have a higher coefficient of performance (COP) by 25% (Hosoz and Kilicarslan, 2004).

2.3.3 Expansion Valve

Refrigerant leaving the condenser flows into an expansion valve which reduces the pressure and creates the cooling effect. This is also used to control the volume of refrigerant that will pass on to the evaporator. In general, either a thermostatic expansion valve or an electronic expansion valve would be used in commercial refrigeration systems (CBISE, 2008).

Thermostatic expansion valves use a temperature measurement from the evaporator outlet and a measurement of the evaporator pressure to determine how much refrigerant is required (Aprea and Mastrullo, 2002). The controls feature a feedback loop that regulates the evaporator superheat at a constant value. The simple nature of the control mechanism results in a limited range of flow conditions that the valve will correctly operate at.

Electronic expansion valves were designed to overcome limitations of thermostatic valves. They use electronic controls that can react quicker to changes in the operating conditions (Aprea and Mastrullo, 2002). The controller is set up for the selected refrigerant and valve type. This receives information about the temperature and pressure at the evaporator outlet that defines the superheat (IOR, 2019). A motor then is used to open the valve to supply refrigerant to the evaporator.

In steady state condition both types of expansion valves perform almost identically (Aprea and Mastrullo, 2002). Transient testing has however proven electronic expansion vales to be superior as they reduce oscillations of the superheat away from the fixed values (Aprea and Mastrullo, 2002). Control of the superheat is important in both the efficiency and the longevity of the cooling system. If the superheat is too high, the system will be inefficient and if the superheat is too low there is a risk flooding and damaging the compressors.

2.3.4 Evaporator

An evaporator is another heat exchanger where a fan circulates air over an extended surface or finned design to reduce the temperature. The liquid refrigerant moves through the tubing of the evaporator at a lower temperature than the air (CBISE, 2008). The low refrigerant temperature is achieved through two key principles. Refrigerant entering the evaporator must be in its saturated liquid state which evaporates due to heat from the air. Adding heat to the refrigerant takes place at a constant temperature until all the liquid evaporates. Secondly the evaporation temperature can be adjusted by increasing or decreasing the pressure of the refrigerant to ensure that the liquid is fully vaporised and slightly superheated when it enters the compressor (CBISE, 2008).

In a supermarket the desired temperature of the food cabinet will be specified depending on what kind of product is being displayed. For example, fresh fruit and vegetables dehydrate quickly and thus must be kept at 3°C compared to other refrigerated products that would be kept at 5°C (IOR, 2019). Many factors can affect the efficiency of the evaporator for example, fin spacing, air velocity and method of defrosting.

Fin spacing can be anywhere between 3mm and 12mm with larger spacing being used to account for the formation of frost at low evaporating temperatures. Small fin spacing can increase the heat transfer surface area and thus improve efficiency but will require frequent defrosting to ensure the equipment does not fail.

Air velocity will depend on the function of the evaporator. Low air flow is typically used for cooling delicate produce whereas high velocity flows are more common for blast freezing

(IOR, 2019). Increasing air velocity increases the capacity of the evaporator but if it is too high it can remove moisture from the products.

Defrosting is crucial in evaporators because if frost is left to build up it can impact the performance of the unit. Evaporators in the same vicinity must be defrosted simultaneously because moisture released during the defrost will migrate to the other units.

2.3.5 Refrigeration System Overview

The most typical refrigeration system set up in the UK retail sector is reciprocating or scroll compressors with air cooled condensers and either thermostatic or electronic expansion valves. On the refrigeration system side of things there are many initiatives underway in the retail sector to both improve the environmental impact of refrigerants and to drive the energy efficiency of the systems. The efficiency of refrigeration systems is a very broad subject area, so for the purpose of this thesis it was assumed that the actual refrigeration system is efficient and therefore the focus is towards the actual refrigeration loading at an operational level and how this can be improved to lower the amount of energy needed to run the systems in the first place. The refrigeration loading is largely driven by the design of the display cabinets on the shop floor and the interaction of customers with these cases, together with the temperature of the air in the aisle.

2.4 Refrigerated Display Cabinets

Refrigerated display cabinets are used in supermarkets to display chilled and frozen food products. The refrigeration cycle previously mentioned fuels the display cases with cool air to maintain the cabinet at pre-determined temperatures. There are legal requirements to reduce the growth of micro-bacteria in chilled display cabinets that require temperatures of under 8°C (GOV.UK, 1995). To eliminate any risk of bacteria growing, supermarkets generally have set points within 2-5°C. Legally there are no restrictions for freezer temperatures but –18°C is widely adopted as a standard set point.

Cold air can be delivered to the display cabinets in a variety of different ways. One method is for integral refrigerated display cases where the refrigeration hardware, as previously mentioned, is contained within the display cabinet, and provides cold air directly to the cabinet. Essentially these cabinets only need to be plugged into an electrical source to start operating.

Another method of cooling is remote refrigeration which is the most common type of refrigeration in larger supermarkets. In this type of cooling system, the condenser and compressors are contained within the one unit to limit the number of refrigeration lines as displayed in Figure 12

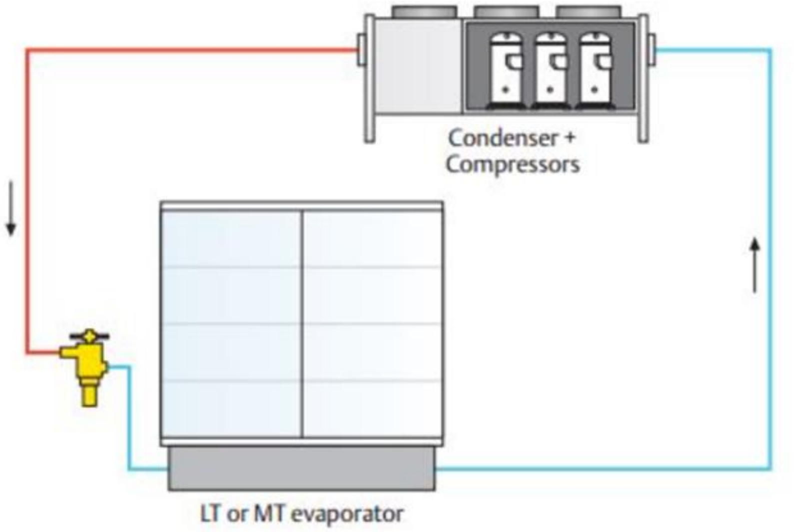


Figure 12 : Remote refrigeration schematic (Source: Koolmax)

Typically, the condensing units, known as ‘packs’, are located on the roof of stores above the cabinets to once again reduce the number and length of refrigeration lines and the number of welded joints to minimise refrigeration leaks. This type of cooling is most effective where there are several connected cabinets forming an aisle and there will be different packs on the roof to feed each individual aisle.

Air flowing into the display cabinets can take two paths to cool the products. The first path is where cold air is passed over a honeycomb opening at the top of the display cabinet which flows directly down to the air return at the bottom of the cabinet, causing an air curtain. The cold air is collected at the bottom and fed through a cold exchanger (evaporator coil) via a fan, and then back up through the rear of the cabinet thus evenly distributing the air from each side of the cabinet. The second path is where the cold air is distributed through the back panel of the unit onto the shelves. Figure 13 shows a diagram of air flow within a display cabinet. Notably in the ‘blocked return’ diagram, the air return point is being blocked causing the cold air to spill into the aisle. Spillage of cold air into the aisle causes a phenomenon known as ‘cold feet’ (Foster and Quarini, 2001) which is essentially making the customers feet cold. To minimise customer complaints about aisle temperatures, the supermarket will increase the aisle heating load consequently increasing the supermarkets overall energy consumption.

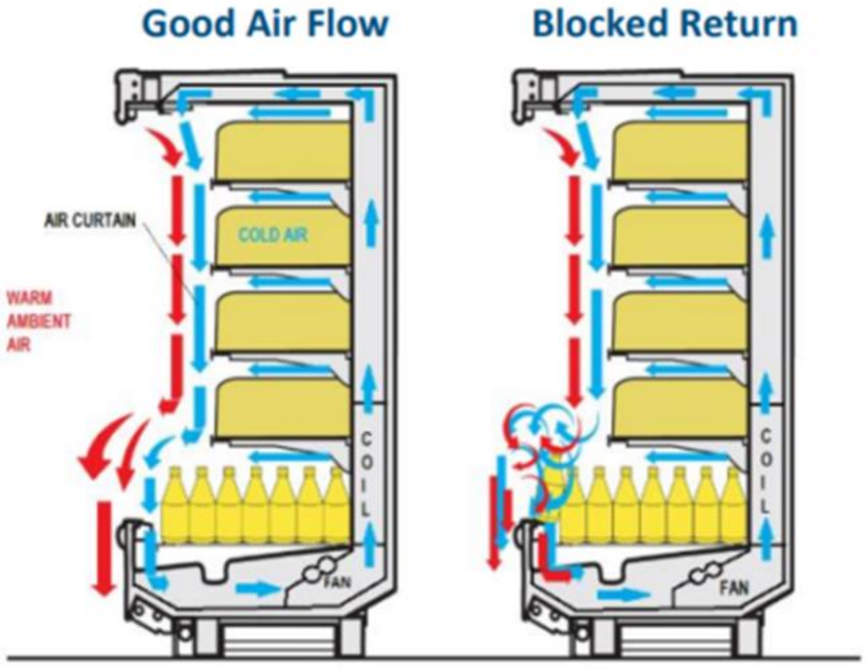


Figure 13 : Air flow in display cabinets

In supermarket refrigeration systems, the air curtain is the main factor that influences the performance of display cases and is a main driver in energy consumption (Cui and Wang, 2004). Many factors can influence the energy performance of air curtains such as the velocity of the curtain and the temperature difference between the ambient aisle temperature and the cold curtain. The main factor that accounts for 70-80% (Lindberg et al., 2008) of the cooling load is infiltration where the air curtain is disrupted and hot ambient air enters the refrigerated cabinet. This causes an increase to the internal temperature of the cabinet thus requiring more energy to reduce the temperature back to the set points. Infiltration happens when a customer puts their hands through the air curtain to select a product or when the store employees are re-stocking the shelves. If the air curtain is weak on disrupted, infiltration occurs.

2.4.1 Cabinet Doors

One method that can be used to reduce air infiltration and air spills is to add glass doors onto the front of the display cabinets. Adding a door to the display cabinet can reduce the electrical demand for refrigeration by 20-35% (Hill, Watkins and Edwards, 2014). Adding doors doesn’t only affect the refrigeration load but it impacts the whole indoor climate of the entire store. Retrofitting doors has been found to reduce the electrical demand from refrigeration by 26%, however the total consumption of the store was only reduced by 6% (Lindberg, Axell and Fahlén, 2010). This may be due to the ambient temperature rising too high (or falling too low) without spillages helping to cool the aisle and thus the HVAC demand will increase on warmer days. In Europe, display cabinets are built to BS EN ISO 20953 standards (IOR, 2019) which require testing of doors for 10 openings per hour. This represents a relatively quiet supermarket, and it has been found that door openings can rise to as high as 250 per hour for busy stores. Testing of display cabinets, with doors built to BS EN ISO 20953 regulations, for 30 openings per hour showed that internal temperatures can be raised by 5°C (Wood, 2019). The cabinets also failed to reduce the internal temperature back to within the set points after 12 hours of being closed. Increased infiltration causes the evaporator to ice over which restricts the cabinets’ ability to control the temperature and energy consumption rises.

One of the main drawbacks to the installation of doors on display cases is that it can disrupt the customer’s experience. Generating revenue is the main focus of supermarkets which means that unless significant savings can be made from retrofitting doors, they will not implement them at the risk of upsetting customers. A survey across three leading supermarket retailers found that 88% of the customers felt that a clear display of the products was essential to their shopping experience (Adande Refrigeration, 2013). Over half of the customers expressed that browsing products in closed cabinets would be “very inconvenient” and they would struggle to open the doors whilst holding a shopping basket. The general responses were negative towards adding doors and issues such as condensation on the glass doors disrupting their shopping experience were raised. A very small minority of 12% stated that they would prefer to shop from cabinets with doors (Adande Refrigeration, 2013).

Low emissivity glass coatings (Low-E) can be used to reduce radiative heat transfer through the glass doors with the objective of lowering the cooling load. They are manufactured using very thin layers of metal oxides which allow high transmission throughout the visible spectrum whilst reflecting infrared waves (Schaefer, Bräuer and Szczyrbowski, 1997). Retrofitting chilled display cases with Low-E coatings on doors was investigated in Thailand where the power consumption dropped by 40% for the analysed period (Saengsikhiao *et al.*, 2020). Figure 14 compares the transmittance of waves through multiple layers of Low-E glass. Normal glass allows a large amount of radiation to pass through compared to each of the tested Low-E windows where the amount of reflected radiation increases from layer to layer. It should be noted that for all types of windows a substantial amount of the visible spectrum (light) is transmitted through the glass meaning that adding Low-E glass with multiple layers will not restrict the ability to see through the glass. Fitting Low-E glass on display case doors can therefore increase the energy efficiency of the cabinets while avoiding any further disruption to the customers experience. Whilst Low-E coatings help to suppress radiative heat transfer through glass doors, spillage and infiltration still allow major heat transfer into refrigerated display cases.

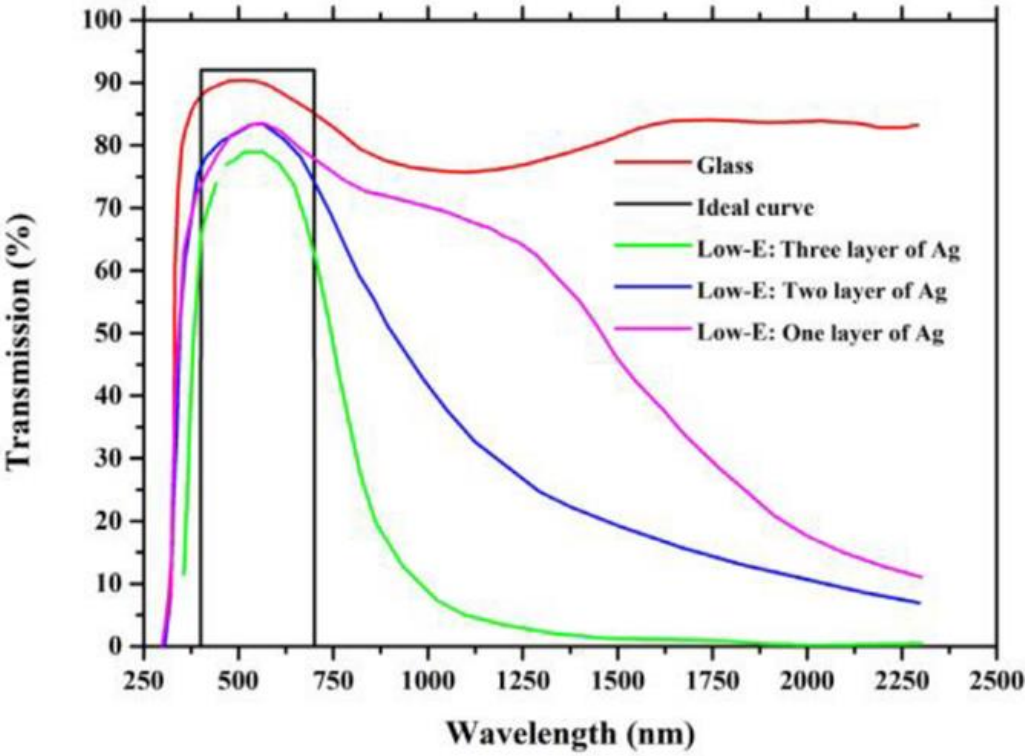


Figure 14 : Transmittance of waves through different glass (Source: (Saengsikhiao et al., 2020))

2.4.2 Alternatives To Doors

As the debate between doors and no doors continues within the supermarket industry, engineers have been working towards alternative energy saving solutions that minimise disruption to the customers experience.

In 2018 trials started in 187 ASDA stores where Formula One technology from the front and back wings of race cars was applied to existing display cabinets (Garsten, 2018). The device is an aerofoil that attaches to the shelf ends to reduce air spillage into aisles and encourage air flow into the display cabinet. CFD comparisons of open display cabinets and ones with guiding strips similar to the aerofoil device proved that the cooling capacity consumption can be reduced by 34% (Sun, Tsamos and Tassou, 2017). Additionally, the average food temperature on the shelves was reduced by 5°C. Both results are strongly influenced by the guiding strips accelerating the cold air generating a stronger air curtain. This minimises hot air infiltration from the aisle and spillage the other way.

Alternative airflows have also been considered. Typically inside a display case, 70% of the air should be directed to the air curtain and only30% distributed through the back panel of the unit to maximise performance (Gray *et al.*, 2008). This has resulted in a focus on alternative air curtain designs. One hypothesised solution was to reduce the flow rate of the air curtain to 50% and circulate the other 50% through the back panel, however this resulted in a weak air curtain that was not strong enough to resist air infiltration. This has led to the development of Aircell® cabinets as shown in Figure 15 that utilise short air curtains. The technology works by dividing the singular air curtain into separate air flow managed cells that create low pressure air columns. Testing using short air curtains on open display cabinets exhibited a 28.3% reduction in heat gain and a 35.9% reduction in energy consumption (Hammond, Marques and Ketteringham, 2016).

Figure 15 :Aircell ® short air curtain design (Source: (Hammond, Marques and Ketteringham, 2016))

2.5 Heating Ventilation and Air Conditioning (HVAC)

In supermarkets HVAC plays a vital role in maintaining store temperatures and removing excess heat from shops. Generally found on roofs of large supermarkets, the central HVAC unit uses a fan to draw in fresh air and circulate it through the shop via large ductwork that hangs from the internal roof. Some of these units also can remove ‘dirty’ air out of the supermarket and pass it through a filter to remove dust and other particles. The clean air can be directed through a heat exchanger where it can reach its desired temperature before returning to heat or cool the store. In HVAC systems that provide heating and cooling, the cooling coil is connected to a refrigeration unit and the heating coil is connected to gas or electrical heating. In systems with both sometimes a heat pump is used.

In supermarkets as much as 40% of the full stores heating load is extracted by the chilled display cabinets (Hill, Edwards and Levermore, 2014). HVAC is then required to replace the heat that is lost to the cabinet although this extraction of heat has been found to significantly reduce the required cooling load. Heat transfer between the cabinets and the shop aisles can have a substantial effect on the overall building’s performance. It was shown that by halving ventilation rates and doubling insulation, savings of 25% can be made in the whole store (Hill, Edwards and Levermore, 2014).

As well as heat transfer, moisture is also exchanged between the display cases and the aisle environment during operation. Moisture being exchanged leads to an increase in energy demand for the display cases and maintaining low relative humidity in the store can minimise exchanges. Investigations into environmental conditions in supermarkets and the effect on refrigeration loads have shown that a 5% reduction in a stores relative humidity can reduce display case loads by 9.25% (Bahman, Rosario and Rahman, 2012). Additionally, the whole stores energy demand was lowered by 5% for the same reduction in relative humidity.

When supermarkets are closed overnight, and the shop is unoccupied there is a good opportunity for supermarkets to save money on HVAC. Night infiltration is a method of passive cooling that has been found to reduce energy consumption in supermarkets by 3kWh/m^2 (Wu, Zhao and Wang, 2006). The main issue with current HVAC systems is the amount of active cooling hours throughout the year, night infiltration reduces this by lowering the internal temperature in the shop. In turn this reduces the temperature difference between the display cabinets and the aisle and thus the fridges don’t need to use as much active cooling. Throughout the year this offsets the amount of active cooling hours when the shop is open and in turn can reduce annual cooling by 17% (Mylona, Kolokotroni and Tassou, 2018).

3.0 Methods

With an ever-growing number of supermarkets being built annually and with pressures to meet climate change targets by 2030, supermarkets need to work hard towards lowering their significant energy demand. Refrigeration and HVAC are two areas that take up a considerable amount of the supermarkets total energy consumption and are therefore the focus of this project.

Two approaches were used to investigate potential areas where supermarkets can reduce their consumption:

1. Investigate the energy savings where doors have recently been retrofitted on existing open refrigerated display cabinets in three case study supermarkets.
2. Modelling to investigate if additional alterations to display cabinet construction or indoor environment can reduce energy consumption in supermarkets.

3.1Retrofit Doors – Case Study

The first approach focused on investigating the energy saving potential of retrofitting doors to existing open refrigerated display cases. On site interviews were conducted with the project management team at City FM who provide services such as refrigeration, HVAC, maintenance, cleaning, integrated systems, and energy management to over 600 retail locations across the UK (CityFM, 2017) including Asda, Sainsbury, Marks & Spencer, and The Co-operative. A particularly interesting service that City FM offer is their Energy and Technical Bureau, where they monitor the operation and energy efficiency of multiple assets in each of their customers retail locations. Individual assets involving refrigeration, HVAC and lighting are fitted with electrical sub-meters that can be remotely accessed, monitored, and controlled. Interviews with City FM revealed that retrofitting doors to existing display cases was an ongoing project, and they were able to provide detailed pre and post project sub-meter data for supermarkets where the installations had been completed.

The criteria used when selecting which stores to investigate required locations where the doors had been installed within the last 3 months and where data had been recorded after the installation for at least 4 weeks. Locations where other refurbishments were ongoing were excluded from the investigation as these results could potentially be contaminated by other energy efficient initiatives. Therefore, three preferred supermarkets were identified for investigation in Edinburgh, Hartlepool, and Middleton. Figure 16 displays the maximum and minimum ambient temperatures for each of the selected supermarkets. Middleton (the furthest south store) recorded the highest outdoor temperature of 23.5°C. Slightly further north, Hartlepool recorded the lowest temperature of -4.35°C with highs of 20°C in the summer months. The coastal location of Hartlepool leaves it vulnerable to more severe weather fluctuations than the inland location, of Middleton. As expected, Edinburgh (the furthest north store) recorded the lowest peak temperature of 18°C. The minimum temperature recorded in Edinburgh was similar to Hartlepool, at -3.9°C. In total the three locations are 360km apart and thus were determined to be suitable case studies to represent supermarkets in multiple UK locations.

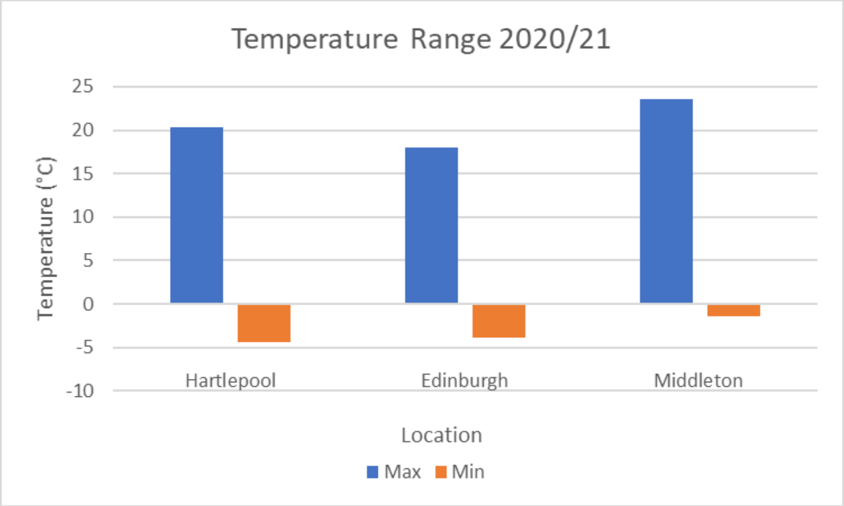


Figure 16: Ambient temperature ranges for each store investigated

In each supermarket there are multiple roof top packaged compressor and condenser units, referred to as packs, that supply the shops with refrigeration and HVAC. Packs can be classified as either High Temperature (HT) or Low Temperature (LT) where HT mainly supply chilled display cases and LT supply freezer display cases. The recent retrofitting of doors only applies to the chilled display cases and therefore only the energy consumption of the HT packs was considered during the investigation. HT packs were only investigated if there had been doors fitted to the connected cases and if the packs were not connected to multiple cold rooms in the warehouses. Therefore, Table 1 shows the packs that were selected during the investigation.

Table 1: Packs to be considered at each supermarket

Store	**Packs suitable for investigation**			
Edinburgh	HT-D	HT-E	HT-F	HT-J
Hartlepool	HT-D	HT-F	HT-G	HT-H
Middleton	HT-C	HT-D	HT-E	

3.1.1 Establishing Baseline Equations

City FM provided one years’ worth of consumption data for each of the stores being investigated. The recorded data for each day of the year showed the average recorded temperature throughout the day and the relevant packs daily consumption. Table 2 provides a sample of the data that was recorded in Edinburgh over the last year.

Table 2: Sample of data provided by City FM

Edinburgh					
Date	**Temperature (°C) (Average)**	**PACK HT- D (kWh)**	**PACK HT-E (kWh)**	**PACK HT-F (kWh)**	**PACK HT- J (kWh)**
27/07/2020	12.625	308	331	464	300.8
28/07/2020	13.41666667	284	296	435	272.9
29/07/2020	13.95833333	285	294	443	279.4
30/07/2020	12.22916667	299	313	459	297
31/07/2020	16.08333333	388	415	554	362.2
01/08/2020	16.3125	345	369	500	328.3
02/08/2020	14	310	321	463	303.4
03/08/2020	13.08333333	283	301	444	285.3

For each day leading up to the installation, average temperature and total electrical consumption for each day was plotted on a scatter graph. Outdoor temperatures can affect the energy consumption inside supermarkets and therefore a regression analysis was used to relate the two variables. Regression analyses were performed for individual packs and polynomial trendlines were applied to the plots. The resultant polynomial equation was therefore adopted as the baseline equation to be used later in the investigation. The baseline equation will be in the form: $Y= Ax^2 +Bx +C$ where Y represents the electrical consumption and x is the average outdoor temperature. An R^2 value was also calculated for each of the baseline equations which determined their correlation. It was decided that a correlation of over 0.8 was acceptable for the investigation although greater than 0.9 was preferred.

3.1.2 Estimating Consumption

Using the baseline equations calculated in the previous section, daily electrical consumption was estimated. Excluding one day following the installation of doors, the average temperature recorded (x) was used in the baseline equation to give an estimate of what the consumption would be based on the previous year's data. The R^2 value at this stage was particularly important as it directly relates to the accuracy of the baseline equation. For example, if the R^2 value was at the lower end of the acceptable values (0.8) 20% of data points do not correlate with the baseline equation and thus results may be inaccurate.

3.1.3 Energy Savings

To calculate the energy savings where doors had been installed the estimated consumption and recorded consumption for each day were assessed. The following formula was used to calculate a percentage of how much energy had been saved:

$$\frac{Estimated\ Consumption - Actual\ Consumption}{Estimated\ Consumption} \times 100$$

Retrofitting doors to the open display cases is an ongoing project and therefore the amount data recorded after installation varies between stores. Middleton was the first store to complete installing doors and thus 14 weeks of calculations were completed. The Edinburgh retrofit was completed next where 12 weeks' worth of data was available for calculations. Finally, Hartlepool's retrofit was completed most recently and only 4 weeks' worth of data had been collected for calculations. In Figure 17 the maximum and minimum recorded ambient temperatures after installation are shown. As the Edinburgh and Middleton projects were completed first, the gathered data provides a 16°C range of temperatures to be used in calculations. Hartlepool however was only completed during the summer months and thus the temperature range is only 6.75°C. Considering these factors proved that the Edinburgh and Middleton savings can represent almost all outdoor temperatures whereas the Hartlepool savings only represent savings for the summer period.

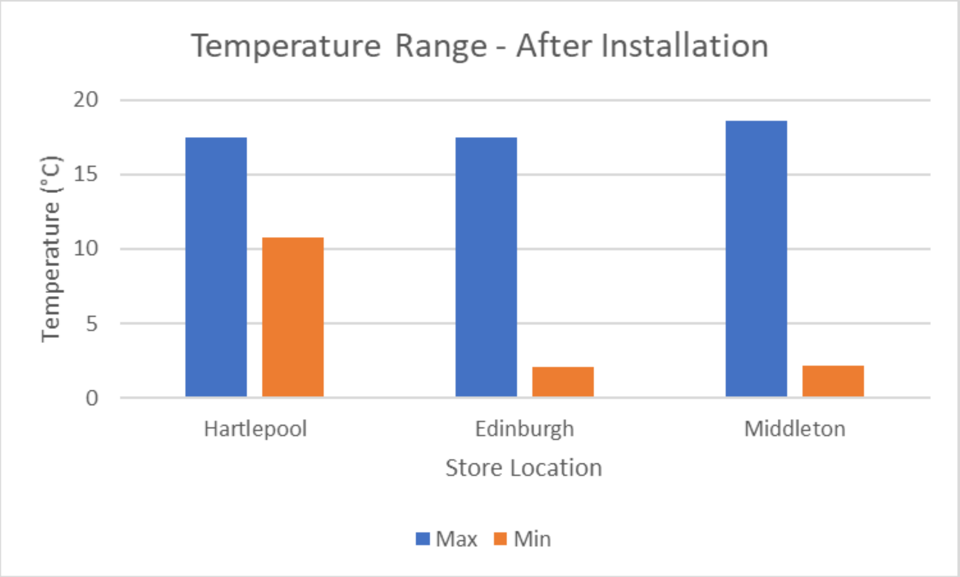


Figure 17: Ambient Temperature range recorded for each store after installation

3.2 Refrigeration Modelling

The second approach focused on investigating other possible alterations that could be made to a display cabinet's construction or the indoor environment in order to reduce a supermarkets annual energy consumption. Esp-r is a modelling tool designed by the University of Strathclyde which can be used to assess a buildings performance. For the purpose of this investigation, Esp-r was used to simulate an aisle section of a supermarket where multiple energy demand reduction strategies were tested.

Several UK locations were considered for the model from an extensive list of weather profiles on Esp-r. The chosen profile, found in Figure 18, was from Aughton in 1995 (a small village outside of Liverpool). Aughton was selected as the model location as the ambient temperature variation throughout the year correlated the most with the three locations investigated in Section 3.1. For example, the maximum temperature in Aughton was 24.8°C which is very similar to Middleton's maximum temperature of 23.5°C. Likewise the lowest temperature recorded in Aughton was -3.8°C which is comparable to Edinburgh's -3.9°C and Hartlepool's -4.35°C.

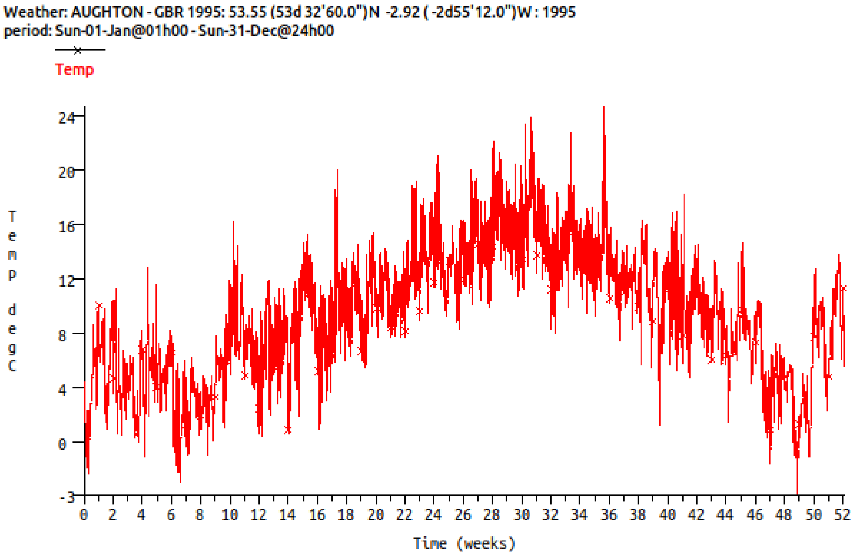


Figure 18: Weather profile used in Esp-r model - Aughton 1995

The objective of the modelling was primarily to investigate the display cabinet's construction in relation to its energy demand and therefore a choice was made to only model a small cross section of the supermarket's total refrigerated floorspace. As shown in Figure 19, the model consists of a 4.85m x 9.4m x 8m box with two fridges inside facing each other to simulate part of an aisle. On one of the external walls there is also a 3.9m x 2.45m window to introduce an element of natural light to the zone.

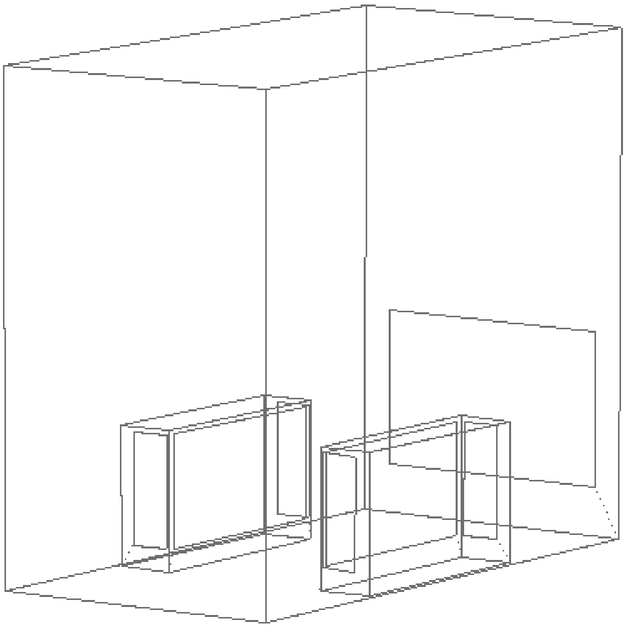


Figure 19: Esp-r model representing a supermarket aisle scenario

All four external walls are constructed using the same materials with a U-Value of 0.387 W/m^{2}K. A design value of 0.25W/m^{2}K was recorded from a case study supermarket (Hill, Edwards and Levermore, 2014) although the range of 0.1 – 0.47W/m^{2}K is acceptable for modelling. The model's roof is crucial for controlling radiant gains and losses and therefore it was assumed there would be a polished aluminium finish on the surface. The window is constructed from double glazed glass and Table 3 shows the composition by layer of each surface in more detail. Heating and cooling set points within the zone were 18°C and 25°C respectively.

Table 3: Model geometry's surface composition by layer

Surface	**Composition By Layer**	**Layer Thickness (mm)**
External Walls	1. Lt Brown Brick 2. Glasswool 3. GAP 4. Breeze Block	1. 100 2. 75 3. 50 4. 100
Floor	1. Lt Brown Brick 2. Glasswool 3. GAP 4. Breeze Block	1. 100 2. 75 3. 50 4. 100
Roof	1. Aluminium 2. Glass Fibre Quilt 3. Aluminium	1. 3 2. 100 3. 3
Window	1. Plate Glass 2. GAP 3. Plate Glass	1. 6 2. 12 3. 6

Inside the aisle zone there are 2 main contributors to casual gains. The first is lighting of 25W/m^2 that will be present between 6am and 12.30am assuming lights are turned off at night 30mins after the shop closes. The second contributor is number of occupants which varies throughout the day and also differs at weekends. On surveying various supermarket chains, the peak shopping times are between 12pm-2pm during the week with other busy periods coming between 8am-10am and 4pm-7pm (Davis, 2021). At the weekends supermarkets also tend to be busier with peak occupancy coming between 11am-6pm on Saturday. Morrisons average around 24,000 customers per week in their stores (Statista, 2021). Assuming the supermarket is relatively small (2,400m^2), it was determined that throughout the day an average of 3.6 customers would be in the aisle zone every hour. Figure 20 shows how occupants varied within the zone where busy times had as many as 7 customers at one time and quieter times only 1 or 2 customers. Additionally infiltration of 0.36 ac/h was applied to simulate the air change throughout the day when customers enter and leave the supermarket (Hill, Edwards and Levermore, 2014).

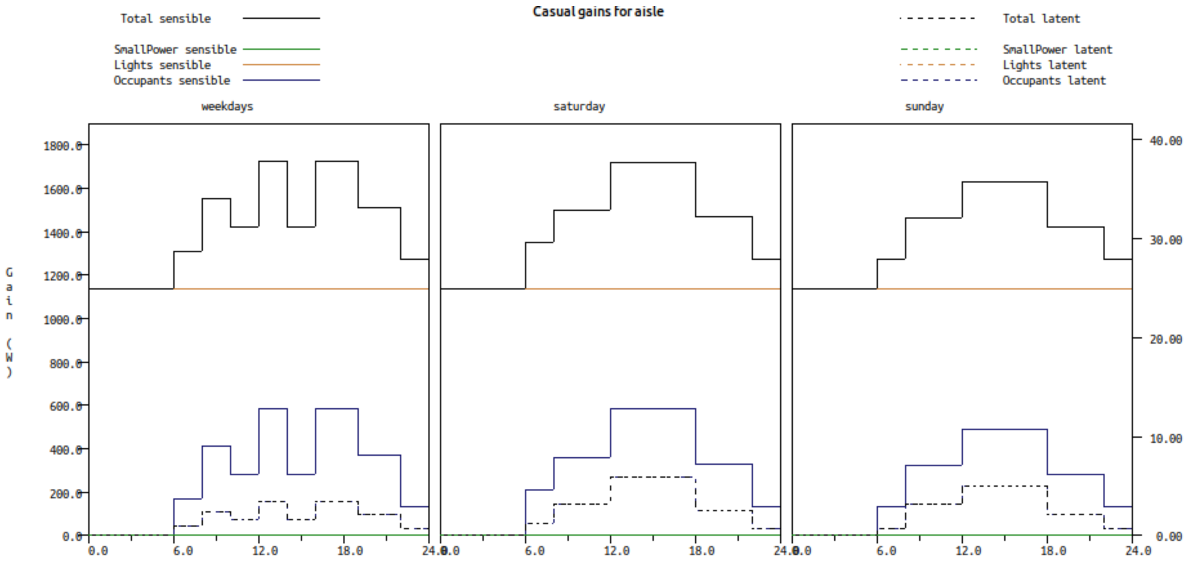


Figure 20: Occupancy and lighting casual gains within the zone for each day type

Both refrigerated display cabinets modelled inside the zone were composed identically. Each fridge was 0.9m x 3.75m x 2.2m. A single display unit is 1.25m in length although the chosen 3.75m long case represents a section of a meat and dairy aisle where units will be connected in groups of two or three to form the aisle. A large window facing the aisle was modelled to represent doors on the cabinet and was raised 0.35m from the base. Two smaller side windows were modelled that would usually connect to another fridge in the aisle allowing customers to view products through side walls. Figure 21 shows a closer image of the fridge structure within the aisle zone.

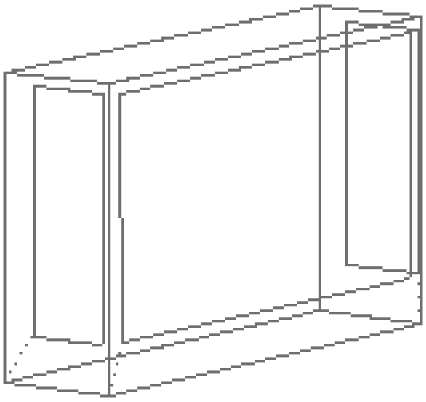


Figure 21: Display cabinet geometry on Esp-r

Glass in each of the side windows and on the front door was double glazed. The roof and side walls were insulated with Polyurethane foam insulation sandwiched between two 1mm thick galvanised steel panels (Getu and Bansal, 2007). Thickness of the insulation was 10mm, density was 30kg/m^3 and conductivity was 0.018 W/mK (Fangareggi and Bertucelli, 2018). Full composition by layer of the display cabinets construction can be found in Table 4.

Table 4: Composition by layer of Fridge 1 & 2

Surface	**Composition By Layer**	**Layer Thickness (mm)**
Side Walls & Roof	1. Steel 2. Polyurethane Foam 3. Steel	1. 0.4 2. 10 3. 0.4
Side Windows & Door	1. Plate Glass 2. GAP 3. Plate Glass	1. 6 2. 12 3. 6
Base	1. Steel 2. Polyurethane Foam 3. Steel	1. 0.4 2. 10 3. 0.4

Inside the cabinet zones there is a cooling capacity that represents cooling to maintain the zone within the 2-5°C temperature set points. There is a legal requirement to keep fridge temperatures below 8°C to stop the growth of micro bacteria although in industry a range of 2-5°C is expected (GOV.UK, 1995). Due to the fact refrigerated display cabinets are being studied, there was no heating inside the fridge zones. Display cabinets are fitted with undershelf LED lights which can account for 25W/m^2 internal gains in the cases (Hill, Edwards and Levermore, 2014). At night when the store is closed, the fridge lights are turned off therefore internal gains are only between 6am and midnight.

Customers opening and closing doors to get products out had to be factored into the simulation as the air infiltration during openings has a significant effect on the refrigeration consumption (Chaomuang *et al.*, 2019). Across Europe refrigerated display cabinets are tested for 10 openings per hour (IOR, 2019) although further investigation has showed that in busier stores it can be raised to as high as 60 openings per hour (Wood, 2019). Given the variety of door openings per hour depending on how busy the supermarket is, three models will be used to simulate stores with 10 (Quiet), 25 (Regular) and 50 (Busy) openings per hour. Analysing door openings in supermarkets revealed on average each opening lasts 10s and every second 2% of the total volume is exchanged with the aisle zone (Månsson *et al.*, 2019). It was therefore assumed that for every door opening 20% of the air was exchanged. For 10 openings per hour this results in 2 ac/h, 5ac/h for 25 openings and 10 ac/h for 50 openings. Coinciding with busy times in the aisle, air changes throughout the day in the fridges were varied slightly as shown in Figure 22.

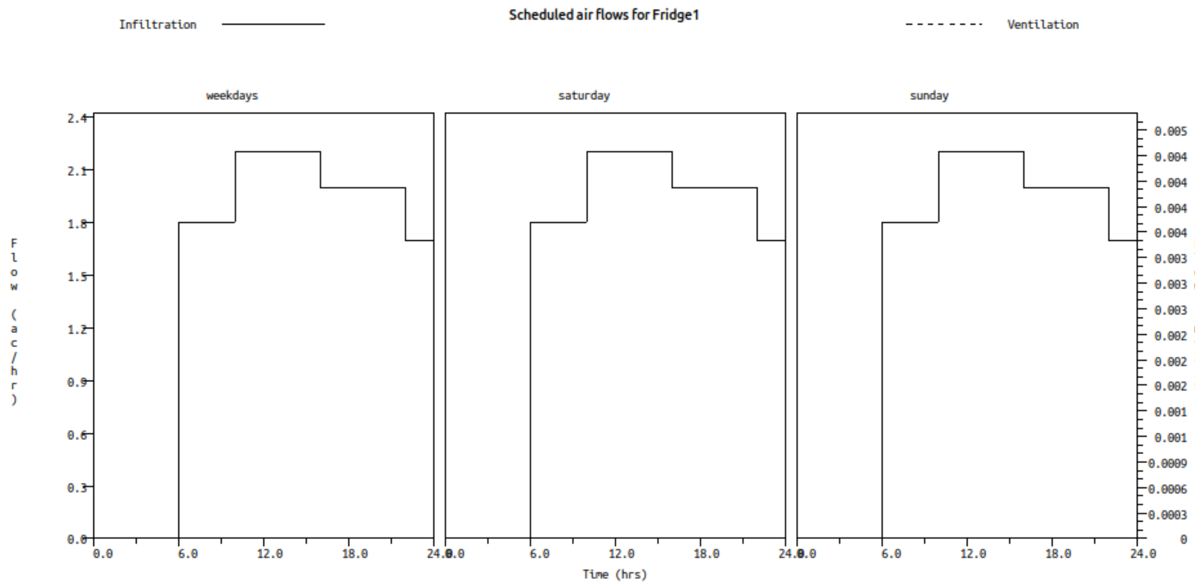


Figure 22: Air changes throughout the day in both display cabinets

3.2.1 Door Alterations

Investigating altering the door design was the first set of simulations to be carried out. For each test environment (Quiet, Regular, Busy) two alterations were made to the door constructions in an attempt to reduce energy demands.

The first simulation involved upgrading the glass used for the doors and side walls. Originally double glazing with a 12mm gap was assumed where the U-Value was 2.81W/m^{2}k. This U-value was considered to be relatively high and therefore the first approach looked at upgrading the glazing to triple glazed with a 12mm gap. Upgrading to triple glazing more than halves the U-Value to 1.08W/m^{2}k indicating that the display cabinet will retain its temperature better than double glazing. Triple glazing does however come at a greater cost and thus, when looking at the three test environments, this was considered when analysing the results.

Secondly, Low-E coatings were applied to the model to investigate if savings are achievable. Low-E coatings are a good alternative to triple glazing due to reduction of costs and has been observed to reduce consumption by 40% in foreign countries (Saengsikhiao *et al.*, 2020). Adding the thinly layered metal oxide coatings to windows and doors reduces the amount of infrared transmission into the cabinet whilst maintaining high visibility. Window and doors originally used in the model had an emissivity of 0.83 although optical measurements show that emissivity should be in the range of 0.19 – 0.30 to improve efficiency (Giovannetti *et al.*, 2014). To simulate Low-E coatings, alterations were made to the glass to reduce the emissivity to 0.19 and then simulations were done for each test environment.

3.2.2 Improving Cabinet Insulation

Section 3.2.1 assesses adjustments that can be made to the display cabinets glass to improve insulation. This section focused on investigating altering the cabinet side wall insulation to further increase the efficiency. In the original model, 10mm of Polyurethane insulation was modelled between two thin steel panels. Insulation thickness can rise to 90mm for commercial refrigeration (Fangareggi and Bertucelli, 2018) and generally varies between products. Simulations were therefore completed to carry out a sensitivity analysis for increasing insulation thickness. Simulations were done to represent an increasing insulation thickness from 1mm to 90mm and plotted against the total energy delivered to the display cabinet zones.

3.2.3 Night Infiltration

The final set of simulations involve introducing night infiltration to the supermarket zone. Although the supermarket is only open from 6am to midnight, appliances in the store are running all throughout the night. Lights and smaller appliances may be turned off overnight but the driving factor for energy consumption lies with the refrigeration cycle. As discovered in the literature review, heat transfer between the cabinet and shop aisle can significantly affect the overall buildings performance (Hill, Edwards and Levermore, 2014). Introducing night infiltration when the shop is unoccupied can help to reduce the aisle temperature and therefore the temperature difference between aisle and cabinet will not be as significant. In theory this will reduce the overall consumption and active cooling hours of the cabinet zones.

Currently in the aisle model there is only infiltration of 0.36 ac/h representing people entering and leaving the store. To investigate the effects of night infiltration additional infiltration from 12:00am – 4.00am was applied to the model when the store is empty. In the base model heating and cooling is fixed throughout the day. Between 12:00am-5.30am the heating set points within the zone was changed to 10°C and cooling capacity was set to 0 to allow simulation of only passive cooling. Heating was set at 10°C to prevent condensation building up on the glass cabinet doors (Mylona, Kolokotroni and Tassou, 2018). During the 12:00am-4.00am infiltration period, air changes of 2.5, 5 and 10 ac/h were tested in the store environments to determine an optimum amount of infiltration.

4.0 Results and Discussion

4.1 Retrofit Doors – Case Study Results

4.1.1 Baseline Equations

Figure 23 shows an example regression analysis for one pack in the first store analysed. Notably the supermarkets consumption exponentially increases when the outdoor temperature rises. The correlation of the regression model is 0.9366 meaning that 93.66% of the data points fit the model. Regression analyses for individual packs at each of the stores can be found in Appendix 1.

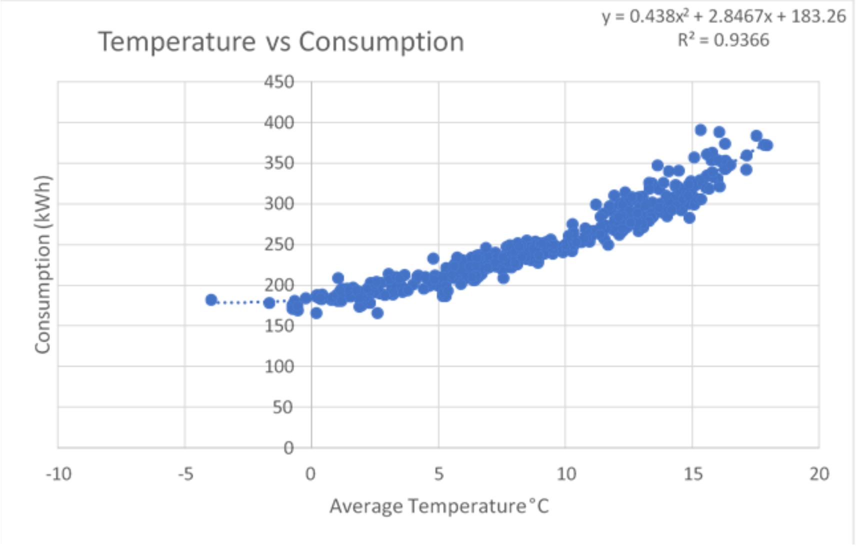


Figure 23: Regression analysis example - Edinburgh Pack HT-D

Table 5 displays the resulting baseline equations for each pack in Edinburgh. The correlation of the baseline equations is above 0.8 across all assets. As per a previous meeting with City FM, a correlation of 0.8 or greater was discussed to be an acceptable correlation for this investigation (Cameron, 2021). Baseline equations and correlations for Hartlepool and Middleton can be found in Table 6 and Table 7 respectively, where correlations are all above the 0.8 threshold.

Table 5: Baseline equation and correlation for each pack in Edinburgh

Edinburgh		
Pack ID	**Baseline Equation**	**Correlation (R^2)**
HT-D	$y= 0.438x^2 + 2.8467x + 183.26$	0.9366
HT-E	$y = 0.5546x^2 + 3.7909x + 164.62$	0.9309
HT-F	$y = 0.4242x^2 + 5.9528x + 287.92$	0.8571
HT-J	$y= 0.2684x^2 +3.2405x +200.73$	0.8196

Table 6: Baseline equation and correlation for each pack in Hartlepool

Hartlepool		
Pack ID	**Baseline Equation**	**Correlation (R^2)**
HT-D	$y= 0.0296x^2 + 9.9733x + 122.05$	0.933
HT-F	$y= 0.1169x^2 + 7.9144x +236.28$	0.8771
HT-G	$y= 0.2327x^2 + 3.6878x + 92.086$	0.9415
HT-H	$y= = 0.3153x^2 + 4.549x + 117.51$	0.9329

Table 7: Baseline equation and correlation for each pack in Middleton

Middleton		
Pack ID	**Baseline Equation**	**Correlation (R^2)**
HT-C	$y= 0.9517x^2 - 6.3329x + 149.92$	0.8994
HT-D	$y= 0.8755x^2 - 5.3537x + 142.96$	0.9132
HT-E	$y= 0.8417x^2 - 6.9179x + 121.96$	0.8902

4.1.2 Estimated Consumption

In Figure 24 an example of the actual and estimated consumption has been plotted against outdoor temperature for Hartlepool pack HT-H. As the regression model has a 0.9329 correlation it can be assumed that the estimated consumption for every considered temperature is comparable to what it would have been before the doors were installed. In the shown example, Hartlepool, doors have only recently been fitted onto the display cabinets and therefore a limited number of temperatures were available. This meaning that the data presented here could be less accurate than some of the other cases shown in Appendix 2, due to the difference in sample sizes. In each of the other locations doors have been installed for long enough to ensure all possible temperatures have been accounted for. More examples of the collected data regression analyses can be found in Appendix 2.

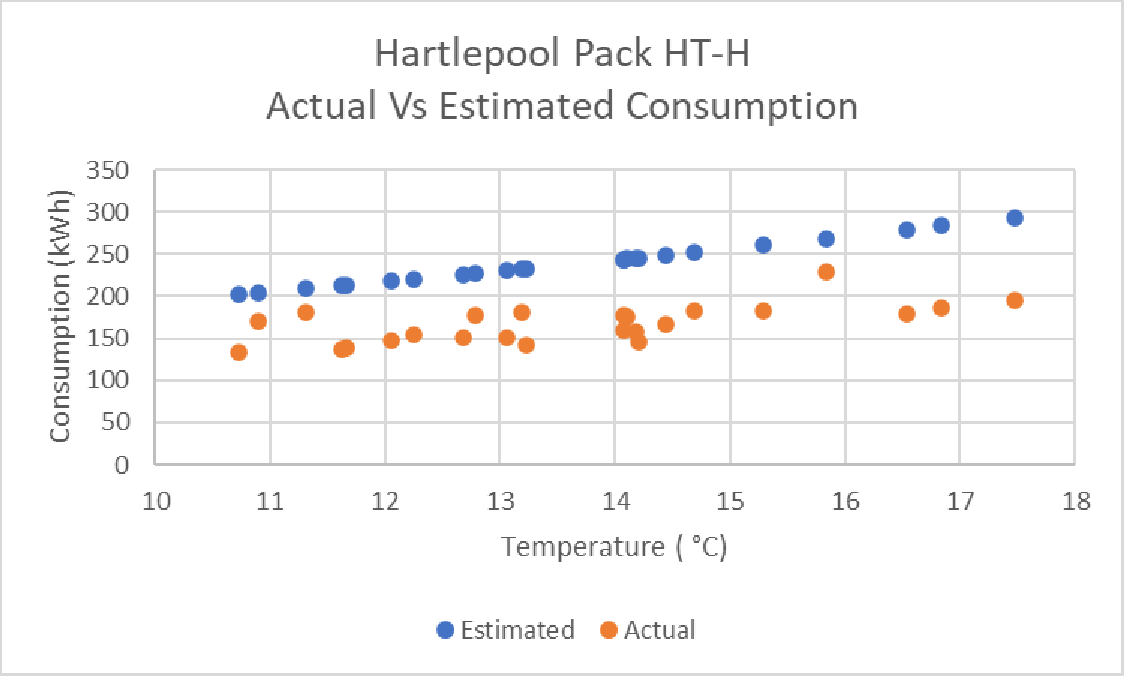


Figure 24: Actual vs estimated consumption example - Edinburgh Pack HT-D

4.1.3 Energy Savings

In Figure 25 the maximum and minimum savings for Edinburgh have been plotted for each pack that fuels the cabinets where doors have been fitted. In packs HT-D and HT-E consumption has been reduced by a maximum of 56.92% and 60% respectively, in the assessed 12-week period after the retrofit. Minimum savings for pack HT-D were 20.98% although this only occurred on 5 of the days where the rest all noticed similar savings to the maximum. Pack HT-E performed exceptionally well following the retrofit and the lowest recorded savings were as high as 46.83%. A significant saving of almost half the consumption. In pack HT-F the maximum savings are slightly less impressive at 24.29% and in the first week following the installation the consumption was higher than the predicted baseline. This may be due to a range of different factors that cannot be commented on due to a lack of information. After disregarding the first few days after installation, due to the inconsistencies discovered in the first week, the minimum savings in pack HT-F was 9.5%. Pack HT-J performed well following the retrofit where maximum and minimum savings of 41.87% and 30.02% respectively, were recorded.

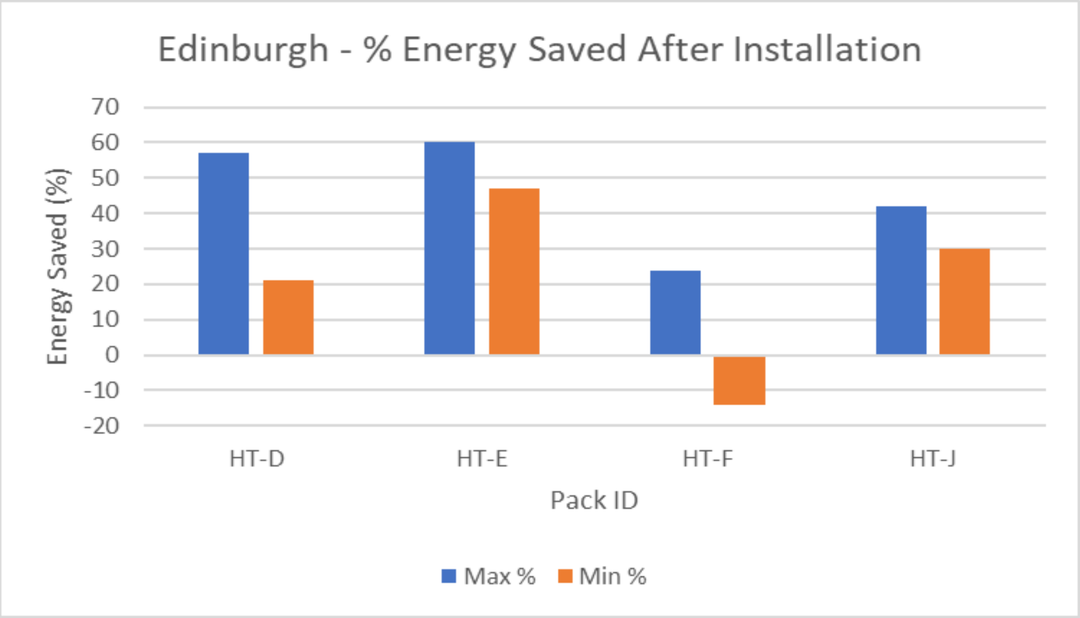


Figure 25: Energy savings results in Edinburgh after door installation.

Table 8 displays the average recorded savings across all packs in Edinburgh alongside the standard deviation of the results. For every analysed rooftop unit, it is clear that since the door installation, the supermarket is saving energy. Although energy savings are widely distributed between 9.5% and 60% it has been proven, in Edinburgh, that on average the supermarket can expect to save 38% on energy if doors are retrofitted to cabinets.

Table 8: Edinburgh average saving % and standard deviation

Pack ID – Edinburgh	**Average Saving (%)**	**Standard Deviation (%)**
HT-D	50.33	6.88
HT-E	53.01	3.15
HT-F	14.58	6.64
HT-J	33.19	2.78

In Figure 26 the maximum and minimum energy savings for each pack in Hartlepool have been plotted. For pack HT-D maximum savings of 23.81% were witnessed whilst the minimum amount of energy saved was 14.41%. In pack HT-F there were high maximum savings of 36.22%. However, unfortunately there were 5 days where savings were close to the minimum, 11.77%, and therefore the average consumption saved was restricted. Overall, it was observed that pack HT-G performed the worst after the installation, but energy was still saved during the analysis period. The maximum amount of energy saved was 17.85%. This was however a rare occurrence as savings of above 15% were only met on that one day. Similarly, the minimum recorded savings of 3.26%, only occurred on two days of the analysis, the majority of the data was evenly distributed between 6.5%- and 14.5%. The best performing pack post installation was HT-H which frequently provided a reduction of energy close to the 40.44% maximum. The majority of the data did however sit close to the 27.22% minimum, but the average energy saved was still higher than the maximum recorded at HT-D and HT-G.

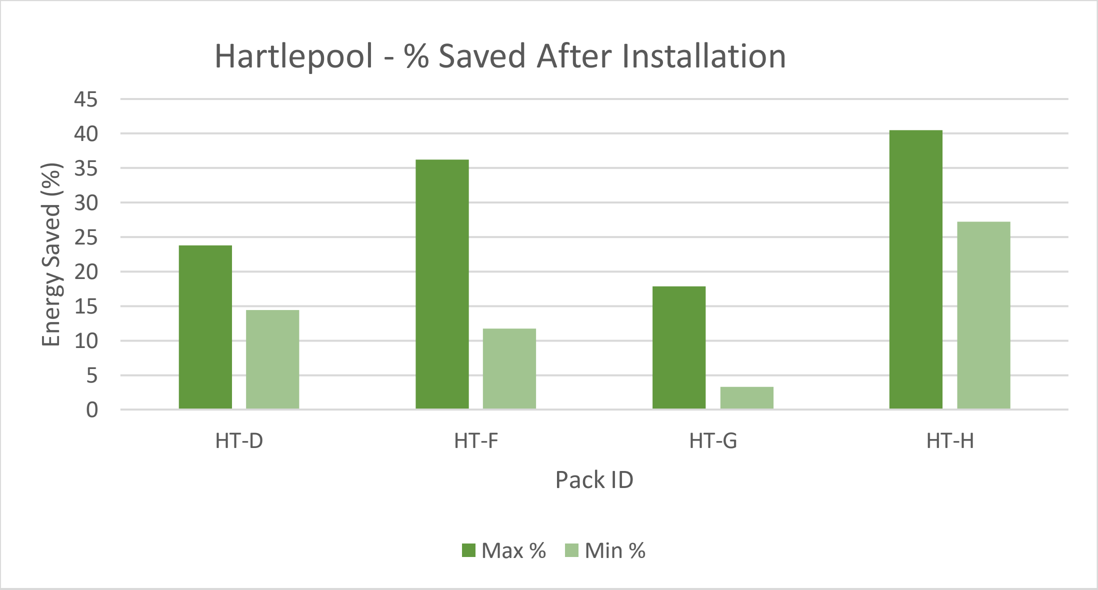


Figure 26: Energy savings results in Hartlepool after door installation.

Table 9 lists the average savings that were recorded across all packs in Hartlepool with the associated standard deviation for each set of results. The best performing pack, HT-H, averaged 32.17% ± 4.37% compared to HT-G that provided only 10.96% ± 5.52%. Taking into consideration all packs observed during the analysis, an average of 21.45% ± 9.59% can be saved across Hartlepool's display cabinets where doors were retrofitted.

Table 9:Hartlepool average saving % and standard deviation

Pack ID – Hartlepool	**Average Saving (%)**	**Standard Deviation (%)**
HT-D	16.3	3.15
HT-F	26.4	7.64
HT-G	10.96	5.52
HT-H	32.17	4.37

Maximum and minimum savings by each pack in Middleton have been plotted in Figure 27. Pack HT-C performed similar to packs at other locations where consumption was reduced by a maximum of 23.68%. On its worst performing day, the pack only saved 7.37%. Overall, around 10%-20% savings was observed on most of the days. Packs HT-D and HT-E witnessed the highest amount of energy saved equalling 61.34% and 60% respectively. In pack HT-D more than half of the analysed days provided a reduction in consumption of over 48%. The lowest recorded saving was 18.93% but the amount of energy being saved each day only dropped below 33% on 10 days out of the 12-week period. This meaning the average savings were still substantially higher. Pack HT-E on the other hand had a minimum saving of 10.54% and the energy consumption dropped below 33% twice as often as pack HT-D, resulting in a lower average saving over the full analysed period.

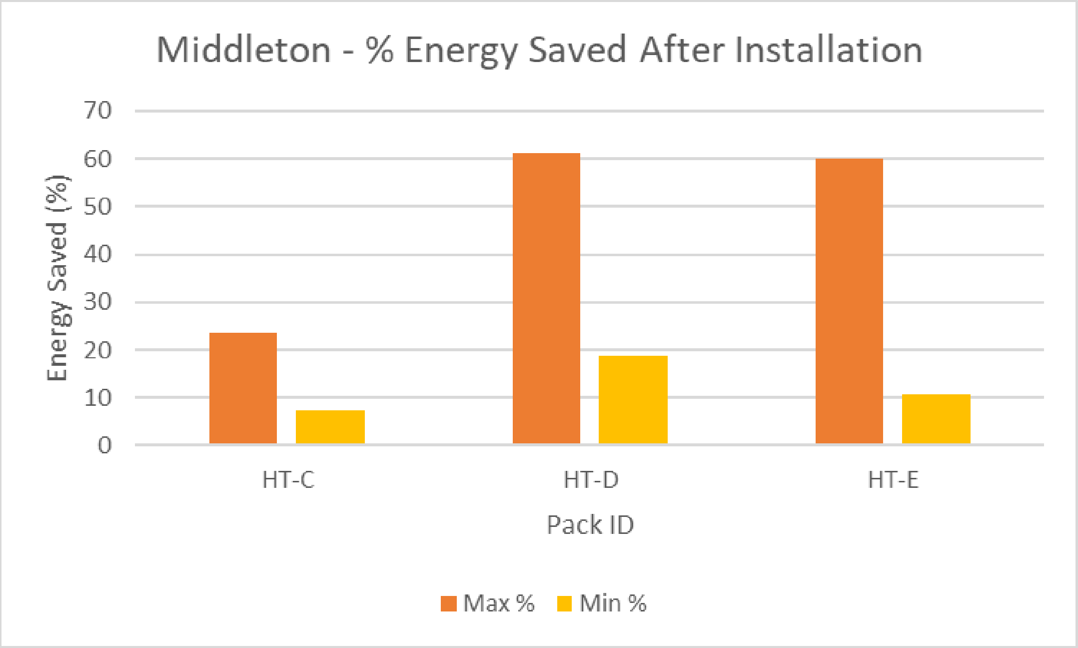


Figure 27: Energy savings results in Middleton after door installation.

The average percentage of energy saved across every pack in Middleton is listed in Table 10 alongside the accompanying standard deviations. Across the full analysis period pack HT-C saved an average of 16.4% ± 6.19%. Even though packs HT-D and HT-E recorded the maximum amount of energy saved in one day, their averages were significantly lower than the best performing Edinburgh location. HT-D had the highest average in Middleton of 47.5% ± 9.52%. Pack HT-E also produced a high average of 40.46% ± 10.09% which could have been closer to the savings observed in HT-E if the savings were denser near the maximum.

Table 10:Middleton average saving % and standard deviation

Pack ID – Hartlepool	**Average Saving (%)**	**Standard Deviation (%)**
HT-C	16.4	6.19
HT-D	47.5	9.52
HT-E	40.46	10.09

Overall, using a regression analysis to predict a baseline consumption for each pack's energy consumption has been established as an effective way of investigating energy reduction in supermarkets. Across all the analyzed stores a significant reduction in energy was observed with some packs consuming over 60% less energy than before the doors were retrofitted. Although these savings were not present throughout the whole analysis, the average amount of energy consumed across each store was reduced vastly. In Edinburgh the four packs witnessed consumption being reduced by an average of 37.78% ± 17.8%, - the highest of all the investigated locations. Hartlepool's results were compromised slightly, due to the fact that it was the most recent location to undergo the retrofit. The limited data that was available for Hartlepool only covered warmer periods of the year where refrigeration systems tend to consume more energy than the winter. Although its slightly less than the other locations, an average of 21.45% ± 9.59% was saved across all packs. Middleton presented interesting findings like Edinburgh where the energy consumption across all packs was reduced by an average of 34.79% ± 16.3%.

Investigations into modelling display cabinets with doors was proven to reduce the electrical demand by between 20%-35% (Hill, Watkins and Edwards, 2014). This investigation has proven that in real supermarket locations in the UK the expected savings from modelling can be surpassed. Comparing the Hartlepool results, that falls towards the lower end of the literature's predicted savings, to the other locations at similar high temperatures the same trend can be noticed where savings are reduced. Taking this into consideration it's safe to assume that if Hartlepool was analyzed for more temperatures, the overall average would be higher.

4.2 Refrigeration Modelling Results

This section presents the findings from the simulations that took place in each test environment. In Table 11 the baseline energy consumption for each environment is listed which was used to calculate savings in later simulations. All test environments have similar heating requirements. However, a notable difference that must be discussed is the cooling demand of the zone. The cooling mainly supplies the display cabinets and therefore there was a significant increases of 8.4% when moving from quiet to regular periods, followed by further increases of 11% when the store is busy.

Table 11: Base model heating and cooling requirements

	Sensible Heating			**Sensible cooling**		
Test Environment	kWh	kWh/m2	hrs	kWh	kWh/m2	hrs
Quiet	4947.9	94.5	4719	6112.5	116.8	15794
Regular	4978	94.9	4722	6626.6	126.6	15663
Busy	5013	96.2	4723	7393.3	141.2	15519

In Figure 28 the temperature inside each zone has been plotted for 1 year of simulations. To maintain the environment's temperature within the set points, a heating and cooling capacity of 3.5kW was sufficient in each zone. At certain points in the winter heating of just over 3kW is needed to raise the internal temperature of the aisle compared to the display cabinets that only use 1.5kW of the cooling capacity. In the summer this acts in reverse as there is no heating requirement for the aisle and a small amount of cooling arises that wasn't needed in winter. Similarly, the cooling requirements in the cabinet's double to 3kW in the summer. Figure 28 is an example for the quiet (2ac/h) environment. All followed similar trends with 3.5kW being sufficient for the capacity.

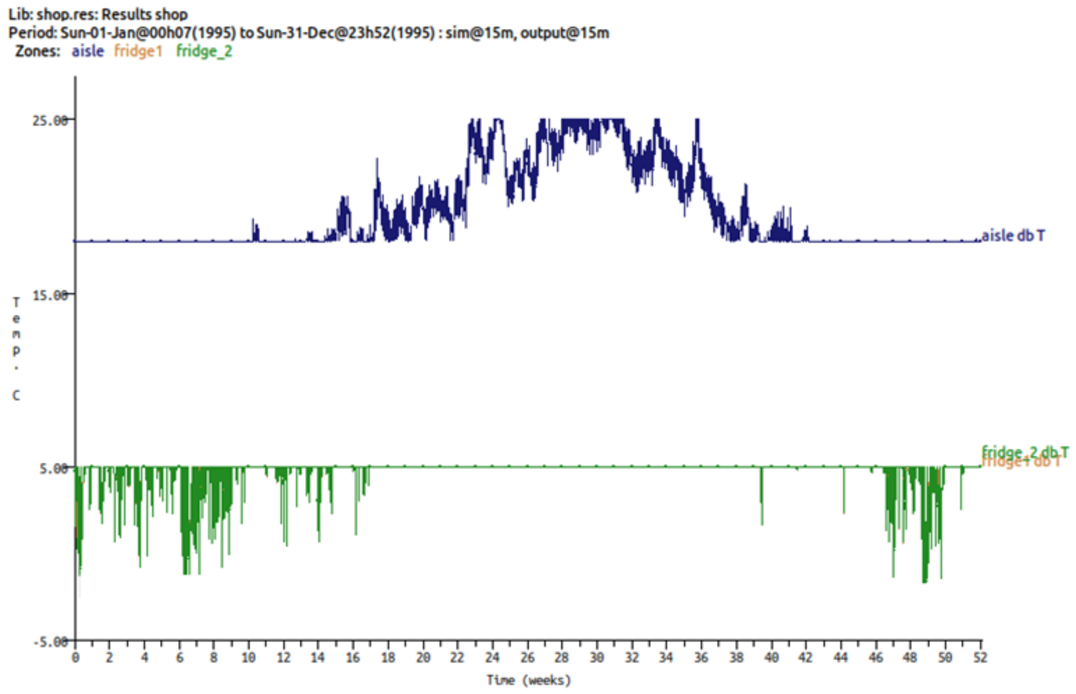


Figure 28:Temperature in zones for 1 year (Quiet Environment)

4.2.1 Door Alterations

Improving the type of glazing in each test environment highlighted an opportunity to reduce the energy consumption of the display cabinets. Figure 29 shows the change in consumption when the doors and side windows in the fridge were upgraded from the base double-glazing model. Compared with the base model, upgrading to triple glazing was found to save a maximum of 9.66%. For all test environments triple glazing consistently provided the best opportunity for savings. In the regular populated store 7.73% could be saved and 9.47% in the quiet store. Interestingly when the cabinets air changes are doubled to 5ac/h for the regular store, savings are much less than the quiet environment but, are maximised when the number of air changes are doubled again.

Compared with double glazing again and adding a Low-E coating to the windows and doors, proved to lower the stores consumption. Maximum savings were found in the regular the environment of 6.58%. In the quiet store 4.85% was saved and 5.91% in the busy. For both glass improvements that were made, savings were evident in all environments although in the quiet store, where cabinets were opened and closed less frequently, savings were restricted. Triple glazing can generate about 2x the savings of the Low-E glass but at a much greater cost. For every window, upgrading from two panes of glass to three can cost between £80-£100 (TradesmenCosts, 2021). In the model there are 6 windows that were upgraded totalling a cost of around £480. In the busy store when savings were at a maximum of 713.42kWh, the cost saved by the install was found to be £102.51, using the UK's average cost of 14.37p/kWh (SwitchPlan, 2021). Considering the install would cost an extra £480 compared to double glazing, it would take almost 5 years to recover the initial investment. Low-E glass as an alternative is actually cheaper than double glazing by about £15 per m^2 (RefreshRenovations,

2021) and is therefore an attractive alternative to be used. For the model being investigated about £130 could be saved by installing Low-E instead of double glazing. In the busy store when energy savings are at a maximum, £62.7 can be saved every year on top of the initial £130 that was saved by changing the glass. This demonstrates that although triple glazing can save the highest amount of energy each year, Low-E coatings are a more suitable investment in the short term.

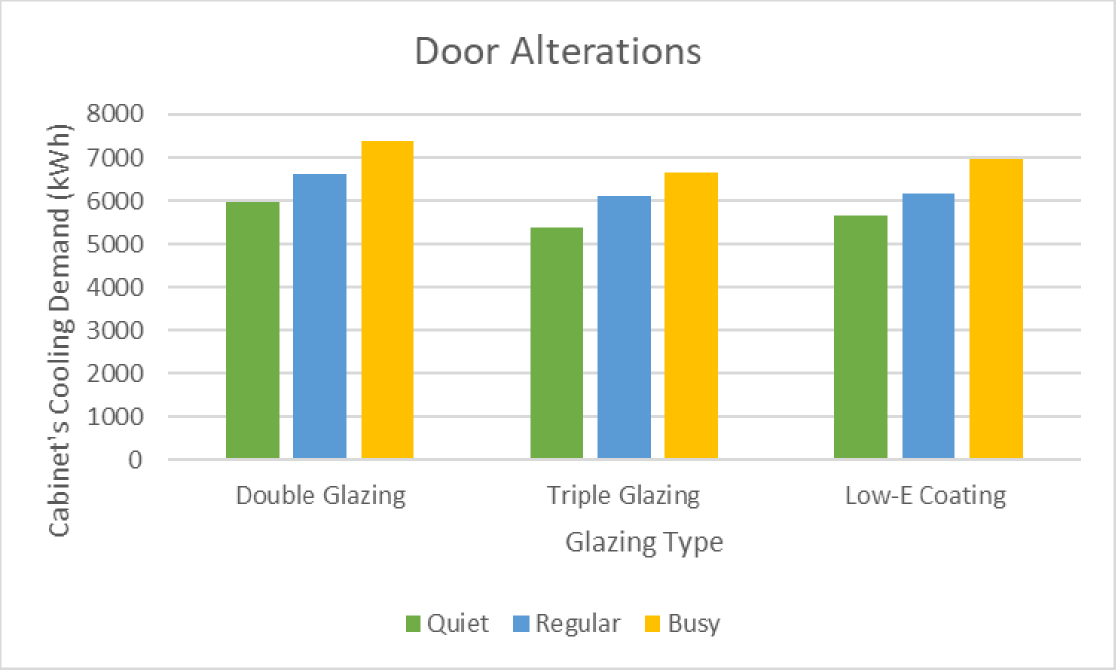


Figure 29: Energy consumed by cabinets when glazing is changed in each test environment

4.2.2 Improving Insulation

Figure 30 displays results from the sensitivity analysis carried out on the display cabinet's insulation. Each environment follows a similar exponential reduction in consumption as insulation thickness is increased. Notably the dramatic drop in consumption over the 1-10mm increase emphasizes the requirement for insulation inside refrigerated display cabinets. The initial drop in each environment reduced consumption by an average of 10.11% ± 0.83%. As the insulation continued to be increased the rate of savings began to slow, where insulation between 10mm-30mm saved on average 5.7% ± 0.49%.

Progressing past 30mm, the energy saving potential becomes limited. Between 30mm-50mm savings are reduced to 1.86% ± 0.15% on average and moving from 50mm-90mm only a further 1.43% ± 0.11% decrease is observed. Hence it can be concluded that the energy savings begin to yield at thicknesses greater than 30mm. In total across the three test environments 18% savings were observed with a standard deviation of ± 1.4%. The quiet environment witnessed the highest percentage saved of 19.3% compared to the busy environment where consumption was reduced by 16.54%. Analysis has therefore revealed that the initial 10mm of insulation is still relatively inefficient which can be improved by a small increase to 30mm. Due to the rate of savings being considerably reduced when insulation is increased past 30mm, it can be seen as an optimum thickness for the cabinets. Advancing past 30mm will only continue to increase costs and thus the already limited savings would be even smaller.

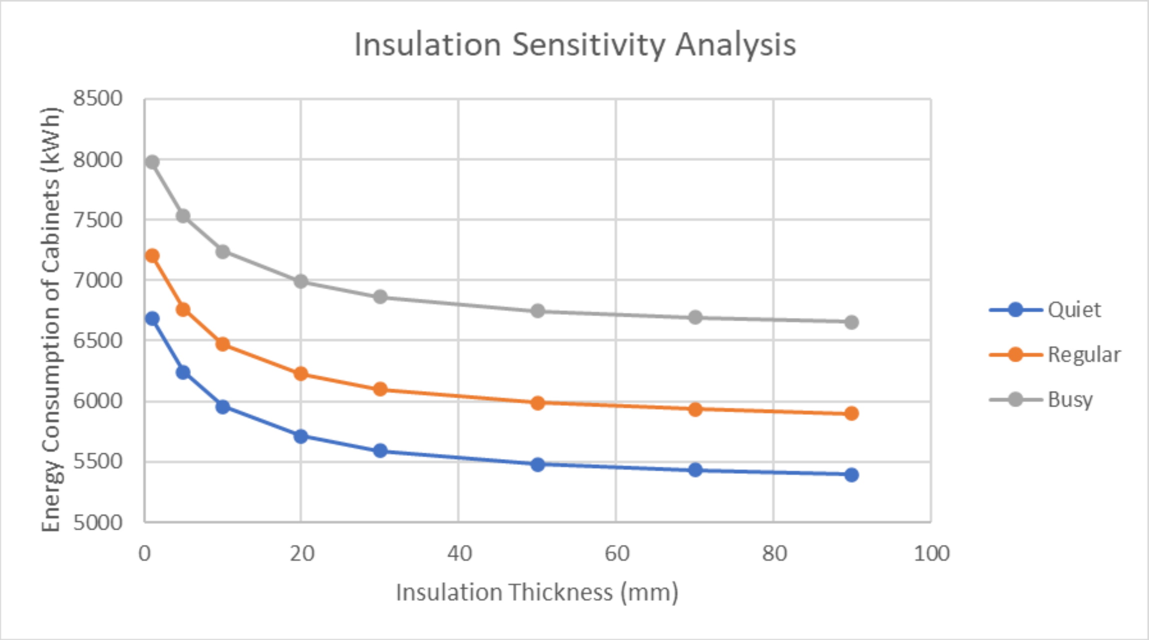


Figure 30: Sensitivity analysis for increasing cabinet insulation

4.2.3 Night Infiltration

In Figure 31 results are shown for the introduction of night infiltration to the test environment. Introducing infiltration has shown to be an effective way of reducing the cooling demand for the year. When night infiltration of 2.5ac/h was first introduced, the cabinets' consumption reduced by a maximum of 3.47% in the regular test environment. In the quieter store, where consumption was smallest to start with, only 1.58% was saved. Similar to the regular simulations, the busy store observed good savings of 3.09%. As the air changes were increased towards 5ac/h, savings began to slow down with maximum savings of 3.82% in the regular store. In the regular test environment savings remained the same for 10ac/h but the consequential rise in heating demand of 5.52% points towards 5ac/h being the optimum. Similar trends are seen in the other test environments where increasing infiltration beyond 5ac/h significantly impacts the heating demand of the model.

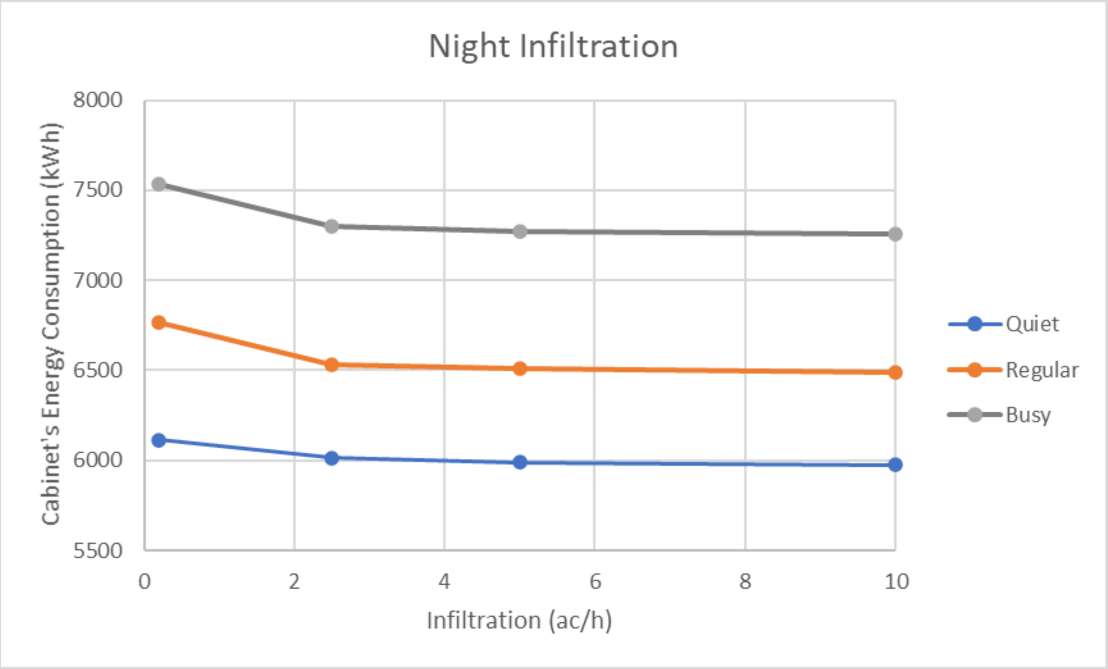


Figure 31: Night infiltration results in each environment

During the analysis periods substantial reductions were made in consumption per m^2 and cooling hours required by the cabinets. The quiet environment's consumption was reduced by 2.7kWh/m^2 and the hours for cooling were cut back by 382hrs. On average the amount of cooling hours was reduced by 379.33hrs ± 2.51hrs although in the regular and busy stores consumption per m^2 was lowered by 5.2 kWh/m^2 and 11.4 kWh/m^2 respectively.

Figure 32 plots the variation in temperatures between 01/07 – 07/07 when 2.5ac/h of night infiltration was simulated in the quiet environment. When the night infiltration automatically starts the temperature in the zone was reduced by around 4°C. For higher infiltration the reduction was in the range of 7°C- 10°C although all tested levels failed to reduce the temperature in the aisle to 10°C. Compared to the base model which required 3.5kW capacity for cooling in the summer, night infiltration has lowered this to 2kW.

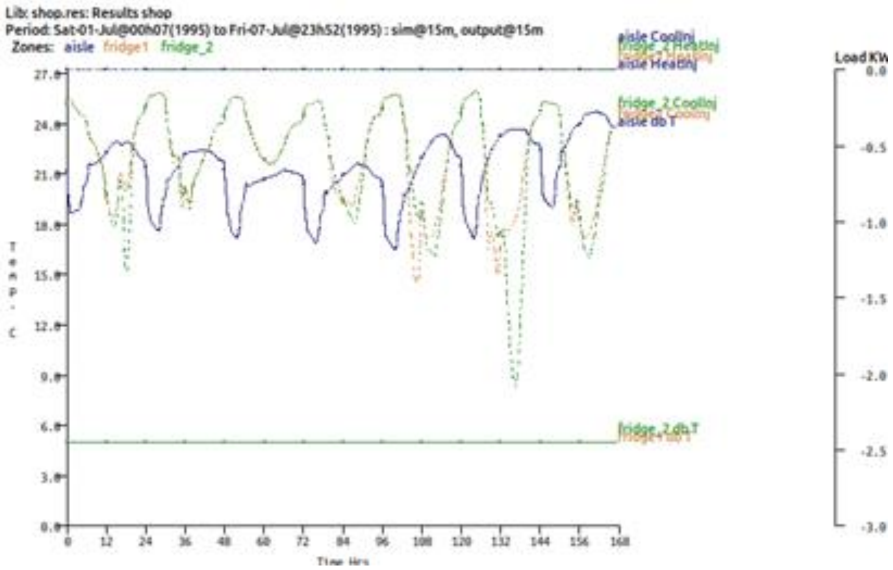


Figure 32: Zone temperatures and cooling capacity for 01/07-07/07 (2.5ac/h)

Consequently, when the temperature in the aisle is lowered the heating demand increases significantly. Between 4:00am and 6:00am the infiltration is stopped, and the zones temperature is left to naturally raise. When the temperature was reduced too much active heating had to step in and therefore was increased. The busy supermarket witnessed the largest increase in heating demand by 13.4% which exceeds the potential savings that could be made from night infiltration.

5ac/h across all test environments was shown to be the optimum for reducing the cabinets cooling capacity although major increase in heating demand makes it an unviable option. Therefore, the recommended amount of infiltration is 2.5ac/h which will deliver savings of 2.7% ± 1% and heating demand will only increase by 0.87% ± 0.05%.

5.0 Conclusion

In conclusion, this thesis has investigated a number of methods in which a supermarket can lower its electricity consumption. Two investigations were carried out that utilized case studies and computer modelling to assess how consumption is reduced by low carbon solutions.

The first investigation looked at three case study supermarkets in the UK where doors had recently been retrofitted to refrigerated display cabinets. Across all of the analyzed stores a significant reduction in energy was observed with some packs consuming over 60% less energy than before the doors were retrofitted. In the Edinburgh location, an average of 37.78% ± 17.8% was saved in the 12-week analysis after doors were installed. On average Hartlepool's energy consumption was reduced the least by 21.45% ± 9.59%, but due to the analysis taking place in a 4-week summer period, this was still considered to be a significant reduction in energy. The Middleton location performed very well after the installation and too experienced high average savings of 34.79% ± 16.3%.

The second investigation modelled a supermarket cross section to evaluate other improvements that can be made to display cabinets to reduce energy consumption. To fully assess the potential energy savings, three test environments were modelled to represent a quiet, regular, and busy supermarket. The first set of simulations proved that maximum savings were made when the door and side window glazing was improved to triple glazing. The cooling demand for the display cabinets was reduced by 9.47%, 7.73% and 9.66% in the quiet, regular, and busy environments. The cost of upgrading to triple glazing is significant and resulted in the payback period reaching almost 5 years. Low-E glass coatings were also explored, and it was proven that for a fraction of the cost, substantial savings of 4.85%, 6.58% and 5.91% in the quiet, regular, and busy simulations. The second set of simulations investigated the impact that insulation has on display cabinets. The results quickly demonstrated the requirement for insulation, as consumption reduced by an average of 10.11% ± 0.83% when insulation was increased from 1mm-10mm. Further modelling of up to 90mm demonstrated that the optimum amount of insulation is 30mm, as savings are restricted past this point. In the quiet store 30mm of insulation saved 5.7% ± 0.49% compared to the base model with 10mm. The final set of simulations proved that introducing night infiltration to the zone was able to reduce the cooling demand by a maximum of 3.82% in the busy environment. Unfortunately, the high infiltration of 10ac/h increased the heating demand by 5.52% making it an unsuitable amount of infiltration. 2.5ac/h was revealed as the optimum amount of night infiltration where cooling demand was reduced by an average of 2.7% ± 1% and the heating was only increased 0.87% ± 0.05%. During the night infiltration simulations, the active cooling hours required by the zones was lowered by an average of 379.3hrs ± 2.5hrs.

This thesis has therefore highlighted four areas where supermarkets can make cost conscious decisions to lower their energy demand and reduce their carbon consumption:

1. Adding doors to existing open display cabinets
2. Use glass with a Low-E coatings for the doors and side windows
3. Insulate the cabinet with 30mm of polyurethane insulation
4. Introduce night infiltration when the store is unoccupied.

6.0 References

Adande Refrigeration (2013) *The case for glass doors on refrigerated display cabinets*. Available at: https://grocerytrader.co.uk/the-case-for-glass-doors-on-refrigerated-display-cabinets-is-closed/ (Accessed: 15 June 2021).

Bahman, A., Rosario, L. and Rahman, M. M. (2012) 'Analysis of energy savings in a supermarket refrigeration/HVAC system', *Applied Energy*, 98, pp. 11–21. doi: 10.1016/j.apenergy.2012.02.043.

BP (2020a) 'Renewable Energy', *Statistical Review of World Energy*, (69th edition). Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-renewable-energy.pdf.

BP (2020b) 'Statistical Review of World Energy globally consistent data on world energy markets . and authoritative publications in the field of energy The Statistical Review world of World Energy and data on world energy markets from is The Review has been providing', p. 66. Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf.

Cameron, J (2021) "Requesting energy consumption data" Interviewed by Richard Faulkner on 17/06/2021

Chaomuang, N. *et al.* (2019) 'Influence of operating conditions on the temperature performance of a closed refrigerated display cabinet', *International Journal of Refrigeration*, 103, pp. 32–41. doi: 10.1016/j.ijrefrig.2019.03.031.

CityFM (2017) *Our Secvices*. Available at: https://www.cityfm.com/about-city/our-services/ (Accessed: 23 July 2021).

Cui, J. and Wang, S. (2004) 'Application of CFD in evaluation and energy-efficient design of air curtains for horizontal refrigerated display cases', *International Journal of Thermal Sciences*, 43(10), pp. 993–1002. doi: 10.1016/j.ijthermalsci.2004.02.004.

Davis, R. (2021) 'Quietest time to shop at Aldi, Asda, Tesco, Sainsbury's and Morrisons supermarkets in lockdown', *Lancslive*, 6 January. Available at: https://www.lancs.live/whats-on/shopping/quietest-time-shop-aldi-asda-19570387.

Fangareggi, A. and Bertucelli, L. (2018) *Thermoset insulation systems*. 2nd edn, *Thermosets:*

Structure, Properties, and Applications: Second Edition. 2nd edn. Elsevier Ltd. doi: 10.1016/B978-0-08-101021-1.00012-5.

Garsten, E. (2018) 'Formula One Spreads Its Wings To The Supermarket', *Forbes*, 20 September. Available at: https://www.forbes.com/sites/edgarsten/2018/09/20/formula-one-spreads-its-wings-to-the-supermarket/?sh=5fc8368a7c7a.

Getu, H. M. and Bansal, P. K. (2007) 'Modeling and performance analyses of evaporators in frozen-food supermarket display cabinets at low temperatures', *International Journal of Refrigeration*, 30(7), pp. 1227–1243. doi: 10.1016/j.ijrefrig.2007.02.003.

Giovannetti, F. *et al.* (2014) 'High transmittance, low emissivity glass covers for flat plate collectors: Applications and performance', *Solar Energy*, 104, pp. 52–59. doi: 10.1016/j.solener.2013.10.006.

GOV.UK (1995) 'The Food Safety (Temperature Control) Regulations 1995'. Available at: https://www.legislation.gov.uk/uksi/1995/2200/made.

GOV.UK (2019) 'Energy Consumption in the UK (ECUK) 1970 to 2019', *Energy Policy*, 62(October), pp. 82–93. Available at: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk.

Gray, I. *et al.* (2008) 'Improvement of air distribution in refrigerated vertical open front remote supermarket display cases', *International Journal of Refrigeration*, 31(5), pp. 902–910. doi: 10.1016/j.ijrefrig.2007.09.005.

Hammond, E., Marques, C. and Ketteringham, L. (2016) 'Application of short air curtains in retail display refrigerators', *Refrigeration Science and Technology*, 2016-Janua, pp. 49–56. doi: 10.18462/iir.iccc.2016.0007.

Hill, F., Edwards, R. and Levermore, G. (2014) 'Influence of display cabinet cooling on performance of supermarket buildings', *Building Services Engineering Research and Technology*, 35(2), pp. 170–181. doi: 10.1177/0143624413478955.

Hill, F., Watkins, R. and Edwards, R. (2014) 'Developing figures for "gain" in relation to refrigerated cabinets in a supermarket building', *Building Services Engineering Research and Technology*, 35(5), pp. 465–474. doi: 10.1177/0143624413510165.

IOR (2019) 'Guide to Good Commercial Refrigeration Practice Part 2', *Brittish Refrigeration Association*, 1(2), pp. 7–9.

Julie Vasquez (2019) ‘Retail Foods United Kingdom’. Available at: https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Retail Foods_London_United Kingdom_7-11-2019.pdf.

Lindberg, U. *et al.* (2008) ‘Supermarkets, Indoor Climate and Energy Efficiency - Field Measurements Before and After Installation of Doors on Refrigerated Cases’, *Refrigeration And Air Conditioning*, (2005), pp. 2–7. Available at: http://docs.lib.purdue.edu/iracc/879.

Lindberg, U., Axell, M. and Fahlén, P. (2010) ‘Vertical display cabinets without and with doors–a comparison of measurements in a laboratory and in a supermarket’, *1st IIR International Conference on Sustainability and the Cold Chain*, (January).

Månsson, T. *et al.* (2019) ‘Analysis of door openings of refrigerated display cabinets in an operational supermarket’, *Journal of Building Engineering*, 26(July), p. 100899. doi: 10.1016/j.jobe.2019.100899.

Mylona, Z., Kolokotroni, M. and Tassou, S. A. (2018) ‘Coupling night ventilative and active cooling to reduce energy use in supermarkets with high refrigeration loads’, *Energy and Buildings*, 171, pp. 26–39. doi: 10.1016/j.enbuild.2018.04.021.

RefreshRenovations (2021) *How much do glass windows cost?* Available at: https://www.refreshrenovations.co.uk/project-estimates/how-much-do-glass-windows-cost/ (Accessed: 23 August 2021).

Ritchie, H. (2020) *Energy Production and Consumption*, *Our World In Data*. Available at: https://ourworldindata.org/energy-production-consumption (Accessed: 24 May 2021).

Saengsikhiao, P. *et al.* (2020) ‘Improving Energy Efficiency in the Supermarket by Retrofitting Low E Glass Doors for Open Refrigerated’, *Journal of Advanced Research in Applied Sciences and Engineering Technology*, 20(1), pp. 11–17. doi: 10.37934/araset.20.1.1117.

Schaefer, C., Bräuer, G. and Szczyrbowski, J. (1997) ‘Low emissivity coatings on architectural glass’, *Surface and Coatings Technology*, 93(1), pp. 37–45. doi: 10.1016/S0257-8972(97)00034-0.

Statista (2021) *Average number of Morrisons customers per store per week in the United Kingdom from financial year 2009/2010 to 2020/2021*. Available at: https://www.statista.com/statistics/382353/morrisons-weekly-customer-numbers-united-kingdom-uk/ (Accessed: 5 August 2021).

Sun, J., Tsamos, K. M. and Tassou, S. A. (2017) 'CFD comparisons of open-type refrigerated display cabinets with/without air guiding strips', *Energy Procedia*, 123, pp. 54–61. doi: 10.1016/j.egypro.2017.07.284.

SwitchPlan (2021) *Electricity prices in the UK – 2021*. Available at: https://www.switch-plan.co.uk/compare-energy-prices/electricity/ (Accessed: 22 August 2021).

Tassou, S. A. *et al.* (2011) 'Energy consumption and conservation in food retailing', *Applied Thermal Engineering*, 31(2–3), pp. 147–156. doi: 10.1016/j.applthermaleng.2010.08.023.

Tassou, S. A. *et al.* (2014) 'Energy demand and reduction opportunities in the UK food chain', *Proceedings of Institution of Civil Engineers: Energy*, 167(3), pp. 162–170. doi: 10.1680/ener.14.00014.

TradesmenCosts (2021) *Triple Glazing Cost: 2021 Installation Price Comparison UK*. Available at: https://tradesmencosts.co.uk/triple-glazing/ (Accessed: 22 August 2021).

UNFCCC (2015) 'The Paris Agreement.', *United Nations Framework Convention on Climate Change*, pp. 24–45. doi: 10.4324/9789276082569-2.

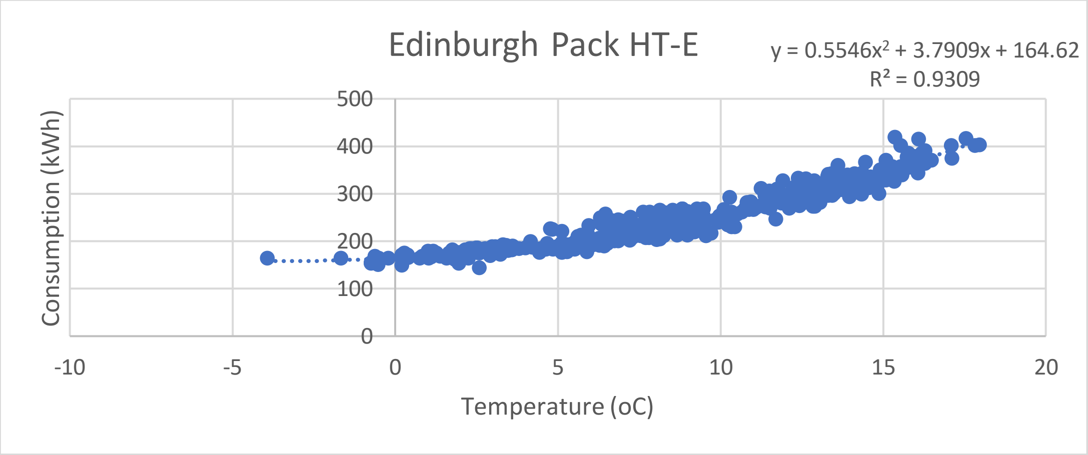
Wood, I. (2019) *NO CLOSURE IN THE DEBATE ON DOORS FOR REFRIGERATED DISPLAY CASES*. Available at: https://www.fcsi.org/industry/products/no-closure-debate-doors-refrigerated-display-cases/ (Accessed: 15 June 2021).

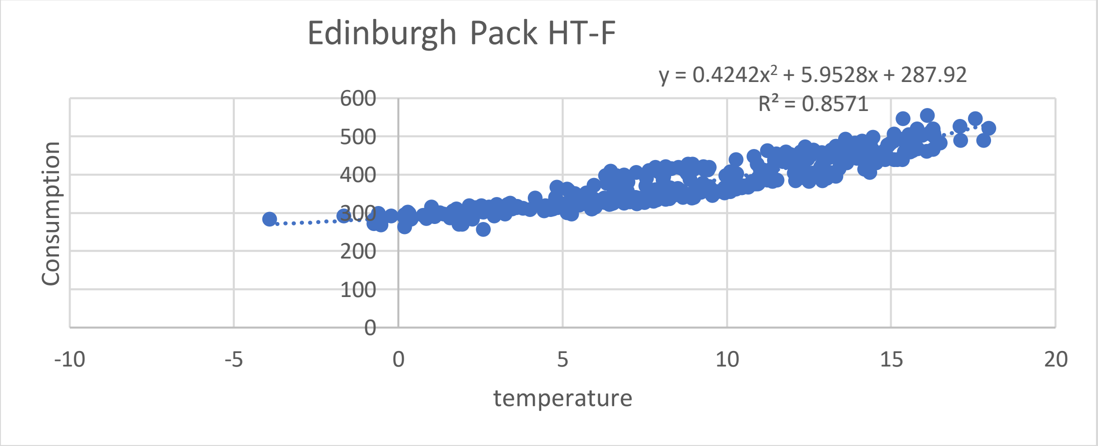
Wu, L. X., Zhao, J. N. and Wang, Z. J. (2006) 'Night ventilation and active cooling coupled operation for large supermarkets in cold climates', *Energy and Buildings*, 38(12), pp. 1409–1416. doi: 10.1016/j.enbuild.2006.02.011.

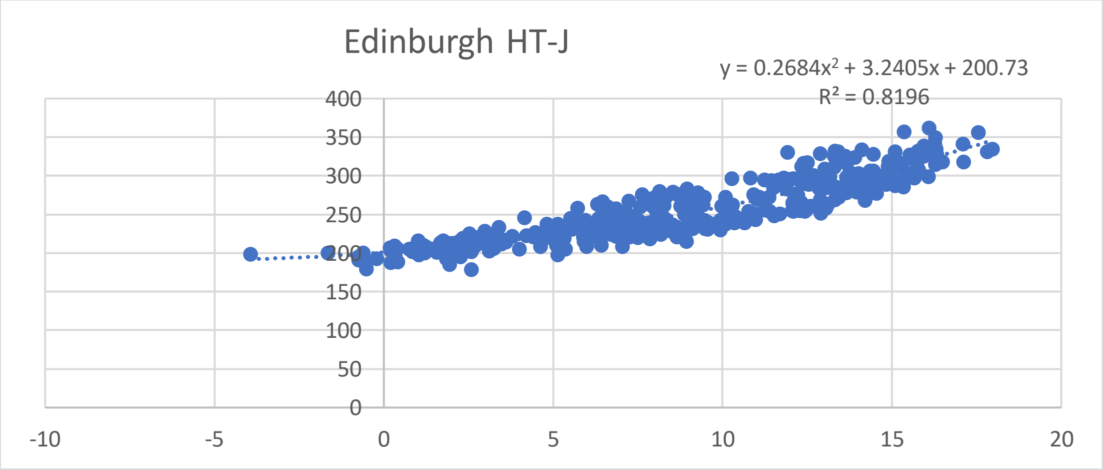
7.0 Appendices

Appendix 1 – Regression analyses for packs at each store

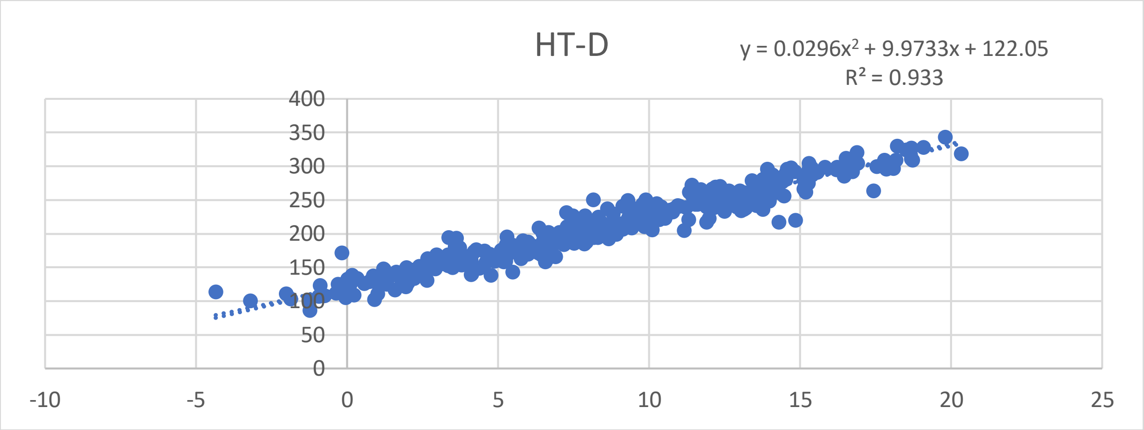
Edinburgh:

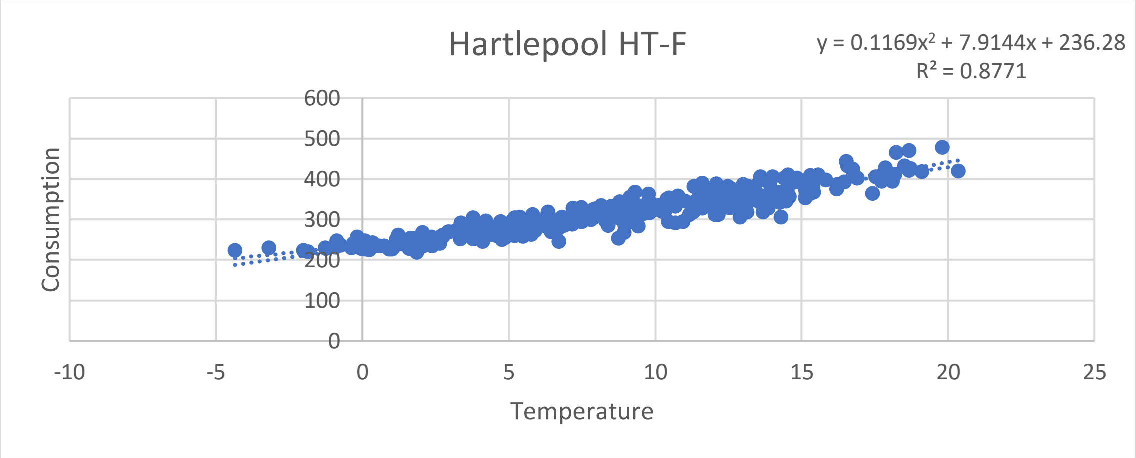


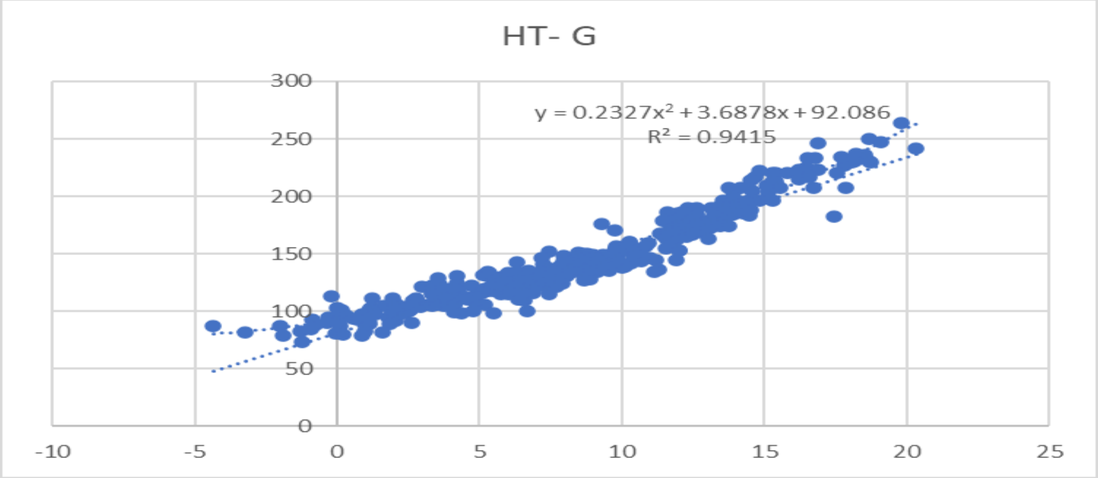


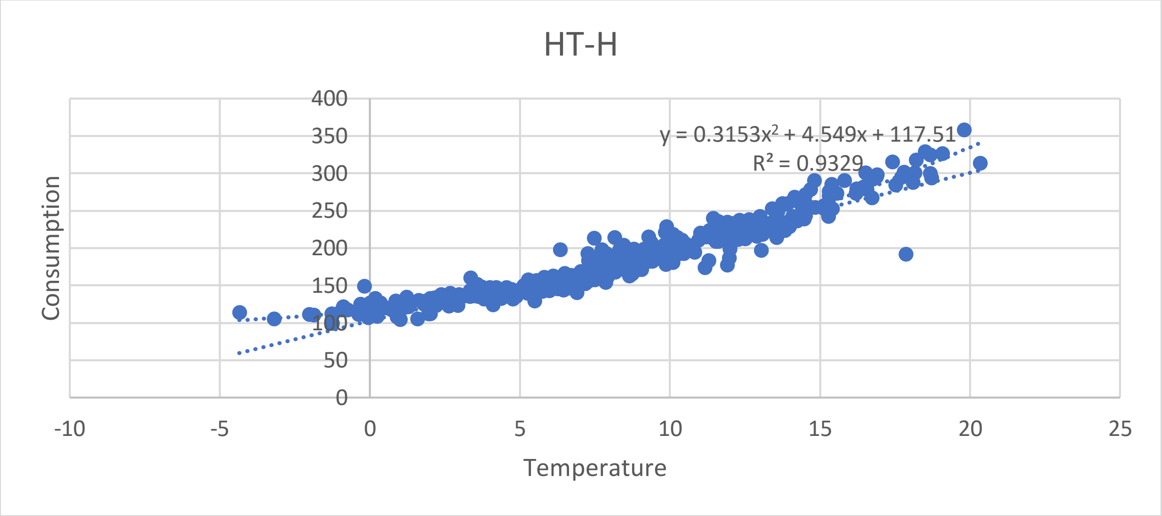


Hartlepool:

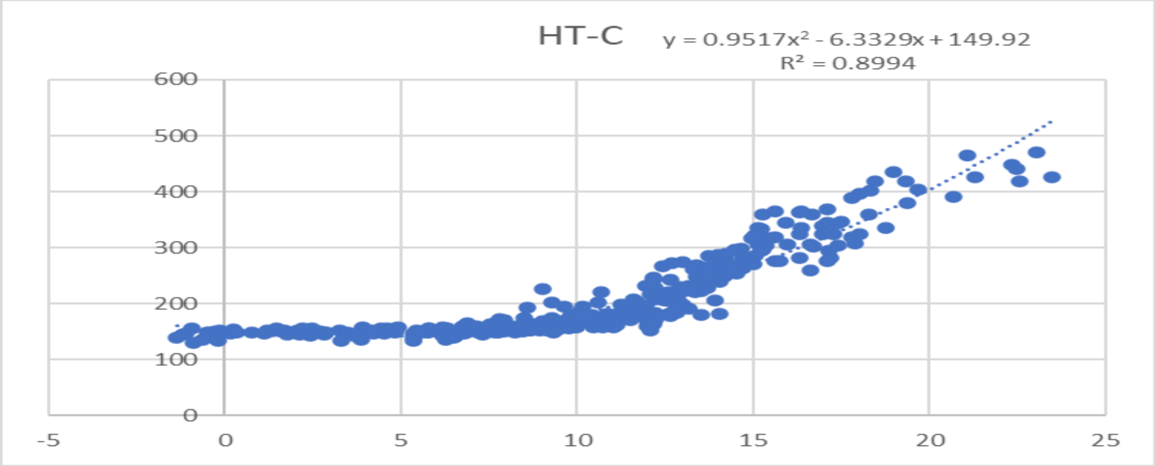

HT-D
y = 0.0296x² + 9.9733x + 122.05
R² = 0.933
400
350
300
250
200
150
100
50
0
-10
-5
0
5
10
15
20
25

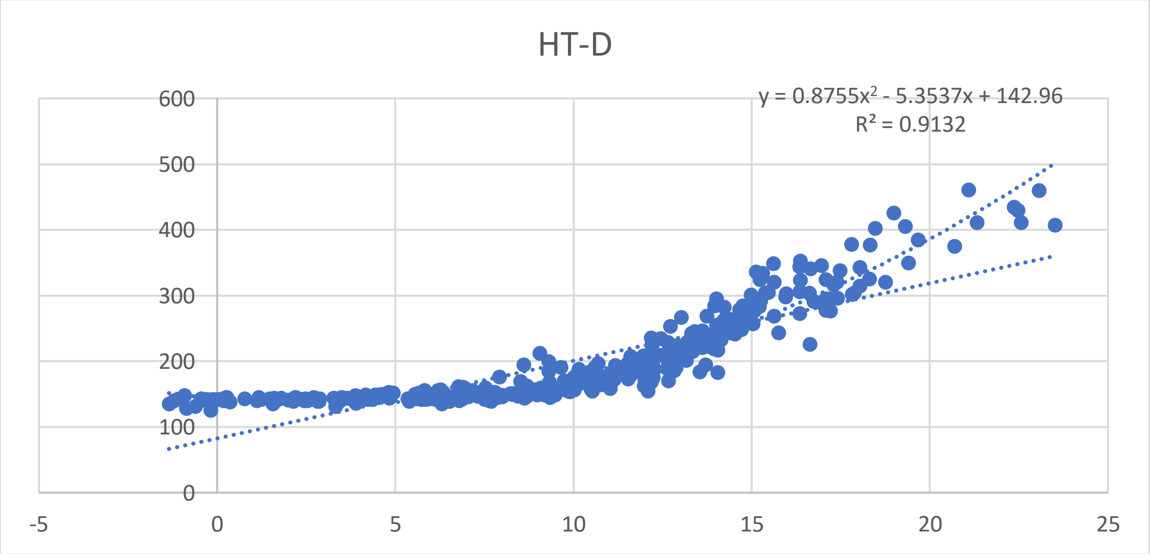

Hartlepool HT-F
y = 0.1169x² + 7.9144x + 236.28
R² = 0.8771
Consumption
600
500
400
300
200
100
0
-10
-5
0
5
10
15
20
25
Temperature

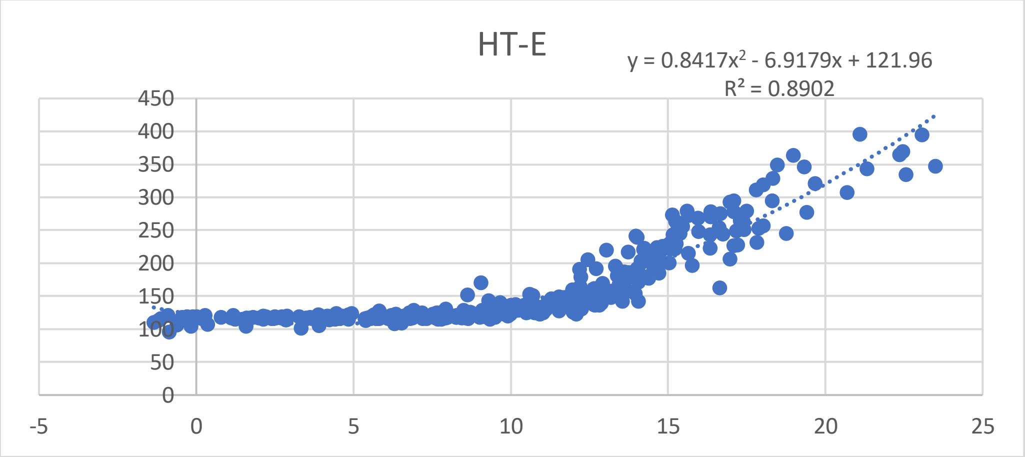

HT- G
y = 0.2327x² + 3.6878x + 92.086
R² = 0.9415
300
250
200
150
100
50
0
-10
-5
0
5
10
15
20
25


HT-H
y = 0.3153x² + 4.549x + 117.51
R² = 0.9329
Consumption
400
350
300
250
200
150
100
50
0
-10
-5
0
5
10
15
20
25
Temperature

Middleton:

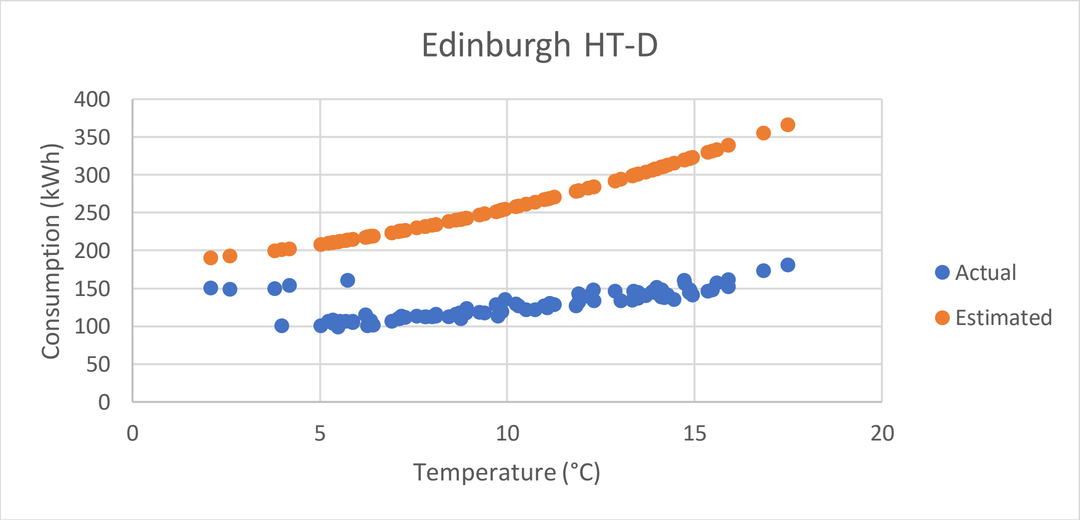

HT-C
y = 0.9517x² - 6.3329x + 149.92
R² = 0.8994
600
500
400
300
200
100
0
-5
0
5
10
15
20
25

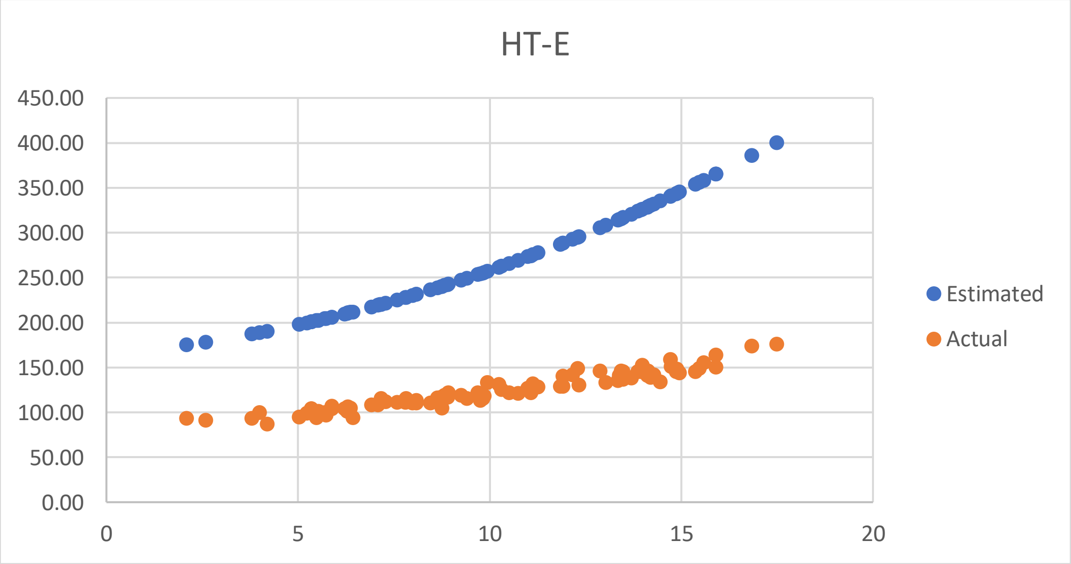

HT-D
y = 0.8755x² - 5.3537x + 142.96
R² = 0.9132
600
500
400
300
200
100
0
-5
0
5
10
15
20
25



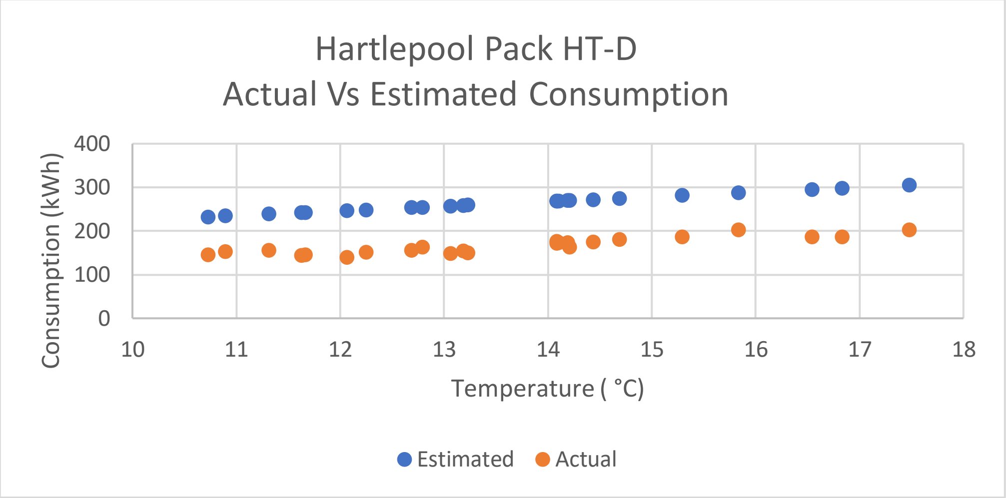
Appendix 2– Regression analyses after installation

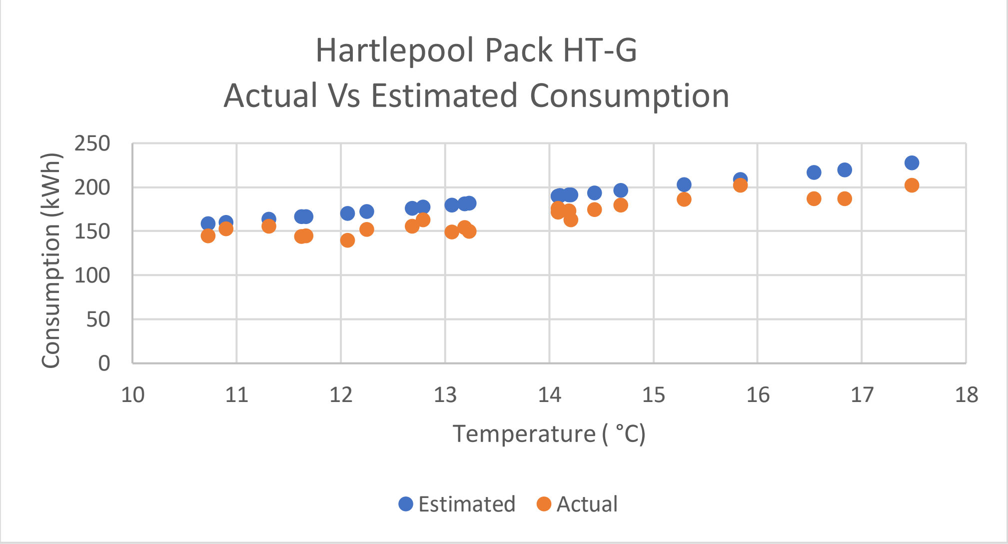
Edinburgh:





Hartlepool:





Middleton: