SIMULATION OF ENERGY USE IN UK SUPERMARKETS USING ENERGYPLUS

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ABSTRACT

This paper investigates the interaction between supermarket heating, ventilation and air conditioning and refrigeration systems through simulation in EnergyPlus. This interaction has been studied by modelling a generic UK supermarket. The impact on the sum of HVAC and refrigeration energy consumption due to changes in a range of operating conditions was studied. These include the effect of altering HVAC temperature set-points, supply air temperatures and refrigeration case operating temperatures on their overall energy use. Optimum values of the supply air temperature, to minimise CO_2 emissions, delivered by the HVAC system were found to vary with UK location, with typical values around 14^oC to 16^oC.

INTRODUCTION

Context

The UK government has a target to cut greenhouse gas (GHG) emissions by 80% below 1990 levels by 2050 (DECC, 2011). Food retail buildings are responsible for approximately 3% of total electricity consumption and 1% of total GHG emissions in the UK (Tassou et al., 2011; Wu et al., 2015a). Addressing the energy performance of supermarket buildings can contribute to achieving the GHG emissions reduction target.

Supermarkets typically have some of the highest annual energy intensities (annual energy use per unit floor area) amongst non-domestic buildings of around 1,000 kWh/m^2 (Mavromatidis et al., 2013). Typical values for other non-domestic buildings are about 100 – 300 kWh/m^2 for hotels and 100 – 200 kWh/m^2 for offices (Galvez-Martos et al., 2013). Combined with the large average floor areas, these high values of energy intensity give supermarkets the highest total energy use of non-domestic buildings (Mei et al., 2002).

Electricity for refrigeration and for heating, ventilation and air conditioning (HVAC) accounts for about 30% of the total energy demand in large supermarket buildings, and gas for about 20% (Spyrou et al., 2014).

HVAC and refrigeration in supermarkets

The HVAC system in a supermarket conditions the air in the store, heating it when the sales floor air temperature is below the heating set-point and cooling it when it is above the cooling set-point. Tesco supermarkets typically use a heating set-point of 18°C and a cooling set-point of 24°C, along with setback values of 17°C and 25°C at unoccupied times, usually at night (Reed, M., personal communication, November 25, 2014).

Internal heat gains occur due to the operation of lighting and electrical appliances and the presence of customers and store staff. Heat is lost through the fabric of the building and because of air changes for ventilation. Thus far, the situation resembles that in other non-domestic buildings. What distinguishes supermarkets is the additional presence of refrigeration cases, typically in large numbers in a defined area of the store, that display chilled and frozen food and remove heat and moisture from the sales floor air. The interaction between the HVAC and refrigeration systems is the subject of the present paper. The work forms the initial stage of a project that will go on to study the potential for energy saving by the application of a range of HVAC control strategies.

A typical variable air volume (VAV) HVAC system supplies conditioned air to the sales floor. It does this in two stages. First, the outside air is heated (if it is cold outside) or cooled (if it is warm) in an air handling unit or AHU (ASHRAE, 2008) as shown in Figure 1 to reach the fixed supply air temperature (SAT), often set by default to 14°C. Second, if the zone air temperature is below the heating set-point, the temperature of the incoming air is raised by heat supplied by the boilers to reheat coils. If the zone air temperature is above the cooling set-point, no further treatment is applied to the incoming air and it is supplied at the SAT.

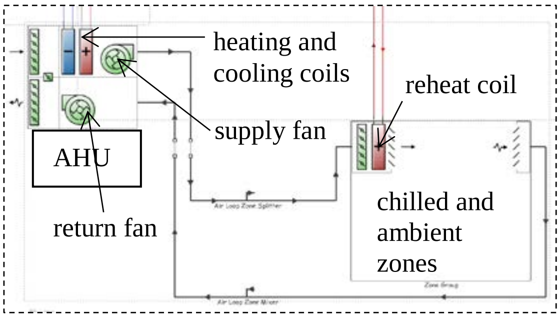

Figure 1 Template of HVAC VAV system air loop with terminal reheat coils in each zone

Typically, areas of a supermarket with different thermal requirements are supplied by their own AHU. In particular, areas containing large numbers of refrigeration cases are supplied by dedicated AHUs which are distinct from those supplying parts of the store where items that need no special treatment, such as clothes, are displayed.

Two types of refrigeration cases are used in supermarkets. Those displaying chilled food (chilled cases), typically operate between 1°C and 5°C, while those displaying frozen food (‘freezers’) operate between -22°C and -16°C. Both types are affected by the surrounding conditioned air, especially if the cases are open, as is the norm. The energy use of the refrigeration system, servicing the refrigerated cases in the store, depends on the type of the refrigeration cases and the interaction between the HVAC system and air inside the cases (Ge & Tassou 2000). The warm, moist air in the supermarket sales floor, treated by the HVAC system, enters inside the refrigeration cases mainly via infiltration and radiation (Ge & Tassou, 2011). This increases the sensible and latent cooling load and so the electricity use. Wu et al., (2015b) showed that an increase in the temperature of the supply air of the HVAC system increases the operational energy use of the refrigeration cases due to infiltration of warmer air into an open case. The split of electricity consumption attributable to different types of heat gain and other causes is shown in Figure 2 (Ge & Tassou 2011), demonstrating that infiltration has a major effect.

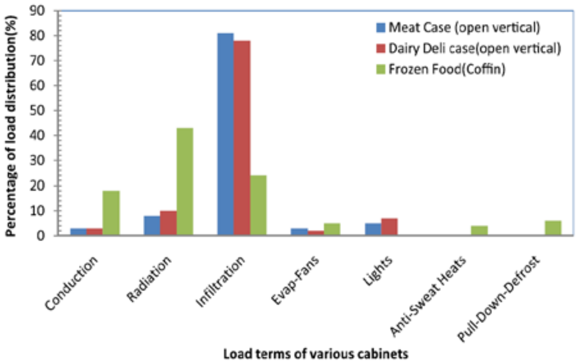

Figure 2 Refrigeration case energy use proportion for meat, dairy and frozen cases (Ge & Tassou 2011)

The operating temperature of a refrigeration case is the temperature at which the contained food products are stored. Safe maximum operating temperatures for chilled and frozen food ensure that products remain fresh for customer health. Lower temperatures may be used for higher product quality. Typical maximum safe operating temperatures are 5°C for chilled cases and -16°C for freezers.

In this study, the interaction between HVAC and refrigeration systems was studied by modelling a generic supermarket environment. The refrigeration case operating temperatures, zone heating and cooling temperature set-points and SATs were varied subject to the typical values referred to above. The process was carried out for weather in three different UK locations, London, Belfast and Aberdeen.

Research problem

The effect of operational settings of HVAC systems and refrigeration cases on the overall energy use in UK supermarkets is not well understood. This is due to an interaction between the thermal characteristics of the building, the HVAC system and the refrigeration cases in supermarkets (Ge and Tassou, 2000; Mathews et al., 2000). The refrigeration system energy use is influenced by the sales floor air temperature and humidity, which is in turn controlled by the HVAC system. The energy use of the HVAC system depends on the fabric of the building, temperature set-points and the temperature of the refrigeration cases.

There has been little work on simulating the energy use of supermarkets as distinct from other types of non-domestic building. Wu et al (2015b) stated that future work is required to take into account the effect of the HVAC system on the energy use of refrigeration cases in a supermarket scale building simulation.

The aim of this work is to investigate the interaction between HVAC and refrigeration systems in UK supermarkets by modelling the impact on HVAC and refrigeration system energy use by modifying the HVAC system temperature set-points, SATs and refrigeration case operating temperatures.

SIMULATION

DesignBuilder (DesignBuilder, 2015) was used as a Graphical User Interface (GUI) to develop the building model (geometry, construction, lighting and occupancy schedules etc.) and the detailed HVAC model and its controls. Current limitations mean DesignBuilder cannot model refrigeration systems. The building and HVAC models saved in DesignBuilder were exported directly into EnergyPlus (Figure 3). Following this EnergyPlus (DOE, 2015) was used to model HVAC and refrigeration system energy use.

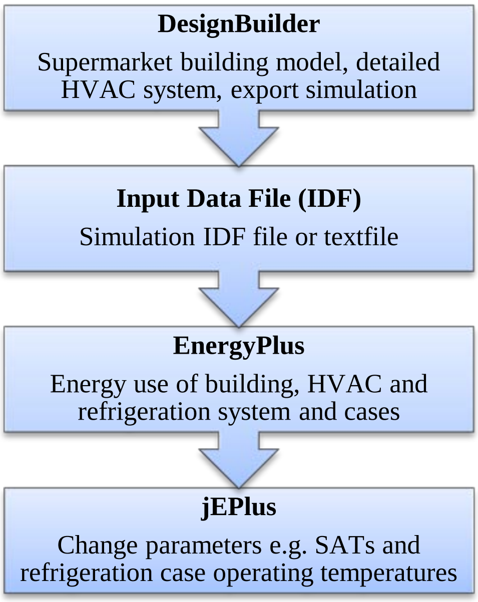

Figure 3 Stages of the simulation method, including building, HVAC and refrigeration system and refrigeration case models

Figure 3 is unidirectional: once the Input Data File (IDF) has been exported into EnergyPlus, it cannot be re-opened in DesignBuilder and similarly once the IDF file has been exported into jEPlus it cannot be re-opened in EnergyPlus to develop the model. jEPlus was used for parametric analysis. It defines a range of values, inserts them sequentially within the IDF file and then runs EnergyPlus simulations with the different values in place. It can change an IDF file to vary a certain parameter, e.g. a SAT, with the defined range of values.

A generic supermarket model was developed to explore the interaction between the HVAC system and refrigeration cases and variations in a range of operating conditions (Figure 4).

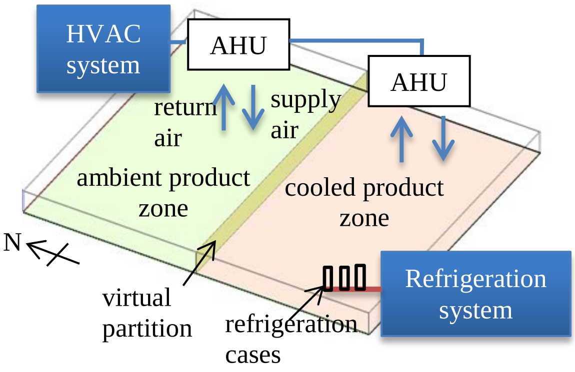

Figure 4 Generic supermarket model

No windows were included to minimise solar heat gains. The building model was 40m wide, 70m long and 3.5m high. Walls were 0.2m thick aerated concrete slab with metal framing, the roof was a concrete slab of thickness 0.3675m and the internal ground floor was 0.1m insulated concrete. Two adjacent zones of equal size were defined, one ‘ambient product zone’ (with product kept at room temperatures) and one ‘cooled product zone’ (with chilled and frozen product, where the chilled cases and freezers were located). The zones were separated by a ‘virtual partition’, a permeable boundary definable in DesignBuilder, that allows heat and mass transfer but allows different air temperatures and relative humidity on either side. The air flow rate that defines the heat and mass transfer was kept at the default value of 0.1 m^{3}s^{-1} per m^2 of partition for all simulations. In order to demonstrate the impact of the refrigeration equipment, exactly the same conditions, including schedules of occupancy, lighting and appliances were applied to the two zones. Occupants (customers and store staff) were present between 09:00 and 06:00 every day of the week including weekends. Lighting and electrical appliances were on continuously from 09:00 to 06:00. Lighting, electrical appliance and heating and cooling time schedules were taken from the retail sales DesignBuilder templates. Ventilation was provided mechanically by the HVAC system. There was no natural ventilation as is typical in supermarkets. An infiltration rate of 0.5 ac/h was assumed. Lighting energy levels of 750 lux and ventilation rates of 10 L/s/person for supermarkets were taken from CIBSE Guide A (CIBSE, 2015). An occupancy density of 8 people per 100 m^2 was taken from ASHRAE Standards 62.1 (ASHRAE 2013).

In this work a VAV HVAC system with no economiser or heat recovery of the recirculated air was modelled. The use of a VAV HVAC system provides a suitable way of varying the HVAC system operation because the SAT can be set to a range of fixed values. This is unlike the alternative constant air volume (CAV) system, where the SAT is dynamic to meet the thermal loads of a space (ASHRAE, 2004).

Generic freezer and chilled refrigeration case types were modelled from the EnergyPlus dataset in line with those in UK supermarkets including vertical open chilled cases and open and closed horizontal freezers. These cover the common food products available in UK supermarkets, typically meat, dairy, delicatessen and fish. Default settings were maintained, except for varying the operating temperatures to determine the energy performance of the refrigerated cases over time. The model determines the refrigerated case energy performance based on the surrounding air temperature and heat transfer from the supermarket store air.

The refrigerated cases modelled in EnergyPlus work in combination with “compressor racks” that contain the compressors and condensers. In line with standard practice, they were modelled as being outside the building, making their heat rejection environment the outside air. Two types were modelled, medium temperature for the chilled cases and low temperature for the freezers, with the default coefficients of performance (COPs) of 1.5 and 1.7 respectively. The default condenser fan power of 1.025 kW was used for both types.

External conditions will have an impact on building operational energy use. Therefore, energy use estimations were repeated for three UK locations: London, Belfast and Aberdeen. The International Weather for Energy Calculations (IWEC) weather files were from ASHRAE (2001) derived from up to 18 years of typical hourly weather data to match long term average trends. The focus was the interaction between refrigeration and HVAC systems on the sales floor. Other interactions, such as energy saving by recycling waste heat from the refrigeration to the HVAC system, were not modelled.

An assumption of the heat balance model used in EnergyPlus is that the air in separate thermal zones is simulated as a well-mixed body of air with a mean air temperature (Crawley et al., 2001). In reality, some vertical stratification of air will occur between the refrigeration cases and ambient air on the sales floor. Phan and Lin (2014) studied the effect of the temperature of supply air on energy use in EnergyPlus. They highlight that a multi-zone EnergyPlus simulation, with airflow between zones similar to the method in this paper, can show very similar air temperature results to those of Computational Fluid Dynamics (CFD) and suggests that the more detailed representation of reality offered by CFD is unnecessary.

Simulations were carried out to determine HVAC and refrigeration system energy use at a range of HVAC system temperature set-point temperatures, SATs and refrigeration case operating temperatures. The sales floor air temperatures were first determined for a summers day at fixed values of all operating temperatures of interest. Next, the separate impact on heating and cooling energy use of the presence of refrigeration equipment was determined. The SATs were fixed at 14°C and heating and cooling set-point temperatures were varied between 18°C and 21°C and 22°C and 25°C respectively, constrained by occpuant theraml comfort. Then HVAC SATs were fixed whilst refrigeration case operating temperatures were varied separately for freezers and chilled cases. Finally, refrigeration case operating temperatures were fixed at typical values whilst the SATs were varied from 12°C to 19°C.

RESULTS AND DISCUSSION

Energy use estimations included refrigeration system electricity use and HVAC system boiler gas and chiller, pump and fan electricity use. The first step was to understand how the HVAC and refrigeration systems operate and interact in the generic supermarket model (Figure 5, 6 and 7).

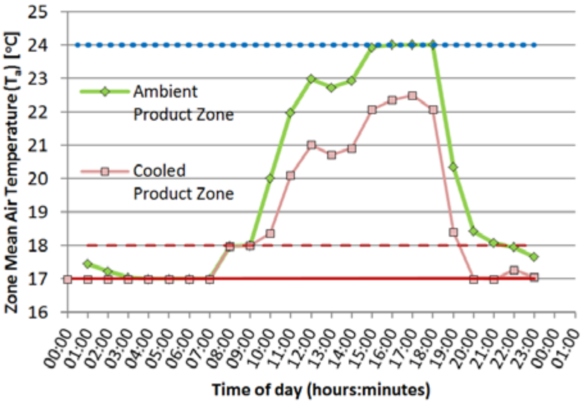

Figure 5 Hourly zone mean air temperatures for summer (8th July)

Figure 5 shows that the sales floor air was maintained at the setback temperature of 17°C until 07:00 when the heating set-points of 18°C operate for both zones. During the day, the zone mean air temperatures (T_a) increased due to internal gains from electrical appliances, occupants and lighting between 09:00 and 18:00. T_a increased in the ambient zone until it reached the cooling set-point of 24°C when space cooling began. The temperature difference between the ambient and cooled product zones was sometimes up to 2°C, in line with initial measurements in a real supermarket carried out as part of this work. Occupancy schedules account for the peaks in Ta at 11am and 4pm, clearly seen for both zones.

The effect on HVAC energy use by comparing the values of gas for space heating and electricity for space cooling was determined with and without the refrigeration cases present.

Figure 6 shows that the presence of refrigeration cases in the cooled product zone did not change cooling energy use significantly. The impact on heating energy use was different, however. Figure 7 shows that the presence of refrigerators has a significant effect on gas use by the HVAC system.

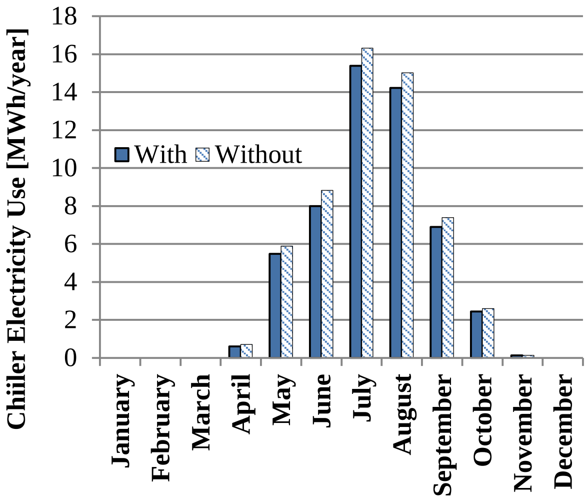

Figure 6 Monthly electricity use for space cooling with and without refrigeration equipment in the cooled product zone

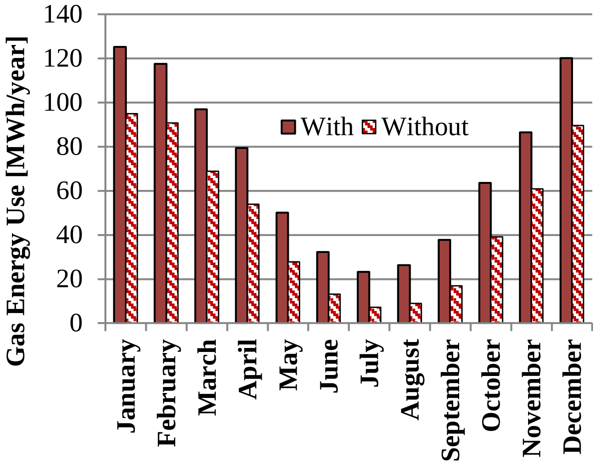

Figure 7 Monthly gas energy use for space heating with and without refrigeration equipment in the cooled product zone

The effect of varying heating and cooling temperature set-points on the overall energy use of the refrigeration system and HVAC system was explored as shown in Figure 8.

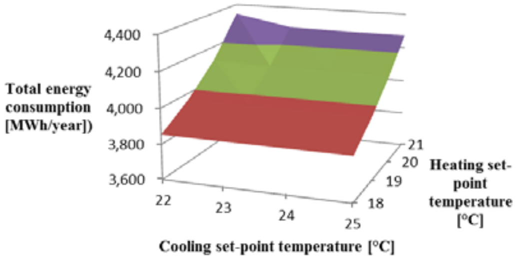

Figure 8 Variation of total energy use with heating and cooling set-point temperatures

Unsurprisingly, higher heating temperature set-points were associated with higher space heating energy use. However, space cooling energy use was relatively insensitive to higher cooling temperature set-points. This is because the heat gains in the daytime did not usually increase T_a above the cooling set-point of 24°C except for a few weeks in summer.

Figure 9 and 10 show a roughly linear relationship between freezer and chilled case operating temperatures and refrigeration and HVAC system energy use. The effect of refrigeration cases removing heat and moisture from the sales floor air decreases with higher operating temperatures, resulting in lower gas energy use required to maintain space-heating set-points. Additionally, higher refrigeration case operating temperatures lead to lower energy use by the refrigeration system. A 2% energy saving in the HVAC system and a 4% energy saving in the refrigeration system electricity use was estimated from increasing freezer operating temperatures from -22°C to -16°C (Figure 9). A 3% energy saving in the HVAC system and a 1% energy saving in the refrigeration system electricity use was estimated from increasing chilled case operating temperatures from 1°C to 5°C (Figure 10) (whilst holding freezer operating temperatures constant at any typical value).

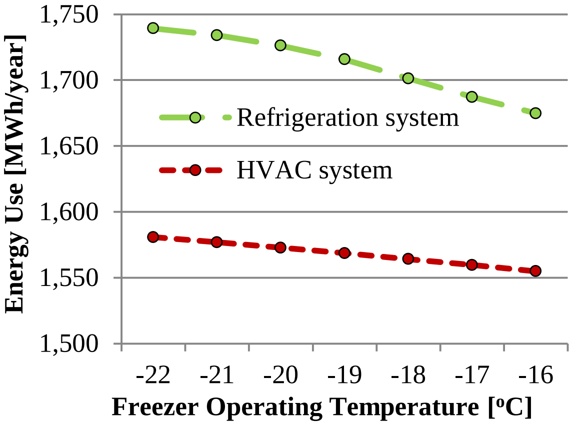

Figure 9 Annual refrigeration and HVAC system energy use with varying freezer operating temperatures

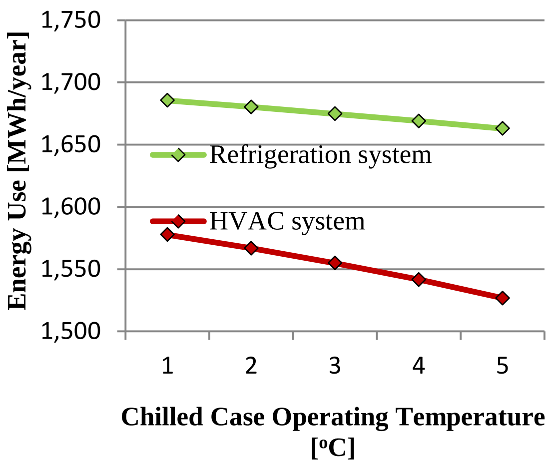

Figure 10 Refrigeration and HVAC system energy use at different chilled case operating temperatures

Figure 11 shows that an increase in SAT decreases (and almost eliminates the need for) space cooling energy. Space heating energy use decreases initially between 12 °C and 14 °C mainly due to a decrease in the significant gas energy use requirements of the terminal unit reheat coils. However, a higher SAT above 14°C requires higher AHU heating coil energy use and this starts to increase HVAC system energy use. Additionally, at a higher SAT value the difference in temperature between zone T_a and SAT becomes lower and as a result higher HVAC system air flow rates are required to meet cooling loads and this was found to slightly increase fan electricity use. Higher SATs increase refrigeration case and total refrigeration system energy use. As the air temperature increases from higher SATs this increases the refrigeration case sensible and latent heat energy and therefore the electricity use of the refrigeration cases.

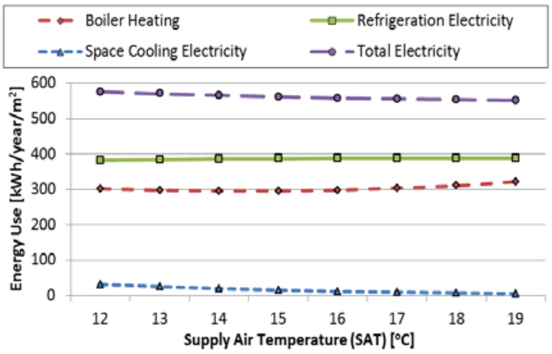

Figure 11 HVAC and refrigeration system energy use with various SATs for London

Wu et al., (2015b) found similar results, though that work was limited to cooling energy. They showed an increase in refrigeration case electricity use and a decrease in HVAC chiller electricity use when increasing the SAT from 16°C to 19°C.

Comparing the results from this work with supermarket benchmarks (CIBSE, 2008), total electricity use is higher than the annual electricity typical benchmark of 400 kWh/m^2 (Figure 10). Additionally, gas energy use is significantly higher than the annual fossil-thermal typical energy use benchmark of 105 kWh/m^2. A reason for this difference could include a set-back temperature of 17°C, which will require significant gas energy use for space heating at night-time.

The variation of the overall energy use by refrigeration and HVAC systems with SAT is shown in Figure 12 for the three UK locations studied. Clear minima around 14-16°C are visible.

The same results are plotted again in Figure 13 but this time in terms of CO_2 emissions rather than energy, to highlight the importance of electricity having a higher CO_2 emissions conversion factor than natural gas. It was found that overall HVAC and refrigeration system CO_2 emissions are lowest at a SAT of 16°C for London and 15°C for Aberdeen, with Belfast in-between. The lower optimum SAT for Aberdeen is mainly due to the higher space heating energy use requirements for Aberdeen than London with increasing SAT.

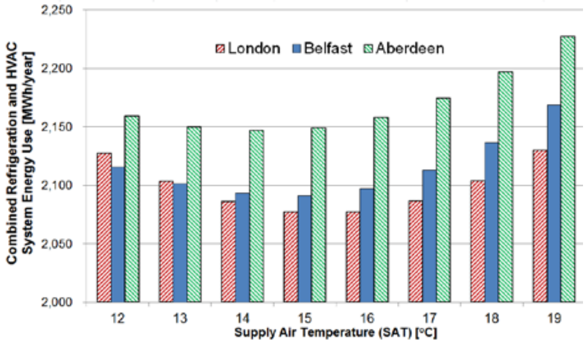

Figure 12 Change in the sum of energy use from HVAC and refrigeration systems with increasing SAT

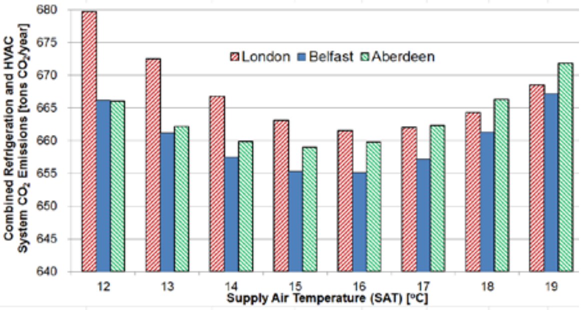

Figure 13 Change in total CO_2 emissions from HVAC and refrigeration systems with increasing SAT

CONCLUSION

The interactions between refrigeration and HVAC systems have been modelled for a generic UK supermarket. The research has contributed toward filling a research gap in the knowledge of supermarket energy use. In particular, it has highlighted the importance of different operating conditions of HVAC systems and refrigeration cases.

- Both HVAC and refrigeration system energy use was minimized by operating refrigerators at their safe maximum temperatures. Lower refrigerator operating temperatures led to greater energy use by both systems.
- The presence of refrigerators affected heating energy use more than cooling energy use.
- The optimum supply air temperature varies with local climate.
- The value of the optimum depends upon whether energy use or CO_2 emissions are to be minimized. For CO_2 emissions, the optimum value was about 16°C in London and 15°C in Aberdeen.

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