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Frozen food retail: Measuring and modelling energy use and space environmental systems in an operational supermarket

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ABSTRACT

Energy use intensity in supermarkets is high compared to retail buildings due to the refrigeration needed for the preservation of chilled and frozen products. The modelling of their energy use and environmental conditions is difficult due to the interdependence of their subsystems such as refrigeration, heating/cooling, ventilation, lighting and requirements of products, store operation schedule and transient occupancy patterns.

This paper reports the development of an EnergyPlus model calibrated with operational data for a frozen food supermarket in the UK. The developed model can predict hourly energy use with an average error of 2 kWh. The paper also presents monitored operational data indicating that energy use intensity is near the upper range of other supermarkets due to increased refrigeration load of 60% compared to 40% of typical supermarket and operation of fans because of required high ventilation rates. Environmental conditions were maintained within comfort requirements for staff and customers because closed frozen food cabinets are used. The developed model was used to investigate the interaction between the subsystems and building envelope to reduce energy use; a significant interdependence was found with the highest energy reduction (4%) when the HVAC is operating during trading hours only.

1. Introduction

The frozen food market and retail/consumption is reported to be on the increase during the last decade. The global market was valued at USD 241.72 billion in 2014 and is projected to USD 307.33 billion by 2020. This is due to increasing standard of living and lifestyle changes with less time to cook. Europe was the largest regional frozen food market in 2013 and accounted for 38.9% of total market revenue [1].

UK represents Europe's largest market for chilled prepare foods [2] with the frozen food market to perform well over the retail sector [3].

In addition, consumer lifestyle impacts on this growth with frozen ready meals being the leading product consumed accounting for over 35% of total market. One explanation for consumer preference is the reduced preservative levels in frozen meals compared with chilled while the economic recession impacts on careful shopping with shoppers opting more for frozen foods [4,5].

In parallel to this trend, market research on consumer behaviour [6] suggests that variety of merchandise and choice does not increase customers who are short of time and focused during shopping. This tendency has created a shift towards new relatively small convenience food shops instead of out-of-town hypermarkets with a variety of products. IGD [7] estimate that spending in convenience stores will rise over the next five years but they also warn that supermarkets might have overestimated their profit potential as convenience stores are more expensive to build and operate [8,9].

Supermarkets are high energy consumption complex buildings for which energy demand analysis and prediction is a difficult task because of interlinked heat exchanges between the building, HVAC and refrigeration systems coupled with varying requirements of stored products, hours of operation and transient occupancy patterns. Therefore, available literature on modelling their performance is extensive with the majority of existing works focussing on improving energy efficiency of refrigeration systems as the largest consumer of energy and essential for the preservation of products [10–16]. Among the three types of refrigeration systems in supermarkets that are used; stand-alone, condensing units and centralised, the latter is facing further development by the use of natural refrigerants (CO_2) [17]. Models coupling HVAC, refrigeration and building have been developed which can be divided into two categories:

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Nomenclature

ANN	Artificial neural network
BEM	Building energy management
BWM	Box whisker mean
RH	Relative humidity
CAGR	Compound annual growth rate
CVRMSE	Coefficient of variance of root mean square error
EPW	EnergyPlus weather file
GWP	Global warning potential
HDD	Heating degree days
HVAC	Heating, ventilation and air-conditioning
LT	Low temperature
LHR	Latent heat ratio
m	Mean
MBE	Mean bias error
MT	Medium temperature
ODP	Ozone depletion potential
ppm	Parts per million
sa	Sales area
VRF	Variable refrigerant flow
σ	Standard deviation

Symbols

N	Sample size
y_i	Measured data
$\hat{y}_i$	Simulated data
$\overline{Y_s}$	Sample mean of measured data

1. Coupled Refrigeration/HVAC/building. Three models have been developed under IEA Annex 31 collaborative project [18]: SuperSim [19] EnergyPlus and CyberMart [20]. In addition, other models have been developed within TRANSYS investigating the potential of night ventilation and active cooling for cold climates [21] and ESP-r to investigate retrofit measures [22]. A moisture balance equation was used by Bahman et al. [23] to simulate energy use which was shown to correlate with internal air relative humidity.
2. Data driven models include spreadsheet based, regression and ANN models. A supermarket model was developed within RETScreen [18], which was shown to correlate well with the other three more detailed models. An ANN model was developed by Datta et al. [24] to predict the electrical energy use in supermarkets. A diagnostic tool [25] was developed to evaluate and predict the energy consumption of the supermarket as a whole and of its individual energy systems separately. Regression analysis was used [26] to predict future energy consumption. However, these models are specific to the case-studies of data sources.

Within this context, this paper reports on the development of an energy model calibrated with operational data from a case-study frozen food medium size supermarket in the UK recently built (2013) with a sales area of 315 m^2. This can be classified as a large convenience store (usually up to 280 m^2) or a small supermarket (280–2500 m^2) and includes a high percentage of frozen food as opposed to chilled food and other groceries; almost 1/3 of the products are frozen food. The case-study supermarket additionally includes cold rooms which are usual in stores with high percentage of frozen food; this means that the refrigeration systems capacity is higher than typical supermarkets.

EnergyPlus is particularly suited for the present work focusing on dynamic energy and environmental analysis for which an integrated simulation tool is required to solve simultaneously building, system and plant considering a range of HVAC systems [18]. Its refrigeration system capability focus on sensible and latent energy exchanges between the refrigerated cases and the building HVAC systems and includes a model for walk-in coolers (coldrooms) exchanging energy with multiple conditioned zones [27]. Secondary loops, shared condensers and sub coolers are also included as well as a library of data for different refrigerants [28]. To-date although intermodal calibration exercises have been carried out [18] there is limited work on energy models calibrated using operational data from operational supermarkets. In a recent study in simulation of energy use in supermarket using EnergyPlus a generic model of a typical supermarket in UK has been developed in order to investigate interactions between HVAC and refrigeration system [29].

This paper first presents operational data from the case-study frozen food supermarket and continues with the development and the calibration of a detailed three-dimensional model using EnergyPlus. The model is validated against the operational energy use and the field measurements of internal environmental conditions in the sales area. It concludes with building energy performance evaluation providing insights for potential energy efficiency opportunities for the building envelope and HVAC systems. Although case-study specific, it will be shown that energy demand is driven by the operational requirements of the building rather than external weather and therefore arrived conclusions can be applied to any frozen food store (or part of store) in the UK or other locations for which the performance of the refrigeration system is known.

2. Case study building and monitoring results

2.1. Building description

The store is in south of London, UK in a typical small out-of-town retail centre. It is mainly food retailer (9 out of 10 products are food products) which is different than typical supermarkets. There is not a bakery or hot food ovens making it similar to convenience stores which usually bring in ready-made bakery products. It is single storey, 450 m^2 total gross area and 315 m^2 net sales area (Fig. 1). The trading hours are 8:00 to 20:00 for weekdays and Saturdays and 10:00–16:00 for Sundays. Geometry and operational data were extracted from the existing layout, mechanical plan drawings, and in-situ building surveys, interviews with the energy managers and transactions data.

The building has two concrete walls providing high levels of thermal mass; one (south-east) is attached to another supermarket of similar size and the other to the back of the store (staff access areas). The north-west and front sides are single glazed window construction. The main entrance is a sliding door with an air curtain and the partition between the sales area and the storage is of gyproc wallboard.

2.2. HVAC system

The HVAC system for the sales area is a Variable Refrigerant Flow (VRF) system which is the choice of many town centre convenience supermarkets because of its easiness in installation especially in retrofitted high street stores. Fig. 1 illustrates a schematic overview of the HVAC system for both heating and cooling. Two equally sized outdoor condensing units provide total heating output of 113 kW and cooling output 101 kW delivered to sales area only through 7 ceiling cassettes and 1 door heater. The design cooling duty requirements is estimated at 60 kW sensible. The HVAC system is operated 24 h with 20–21 °C set point temperature for both cooling and heating; the heat pump works either as a compressor or evaporator controlled by the BEM system. Extraction of the air from sales and

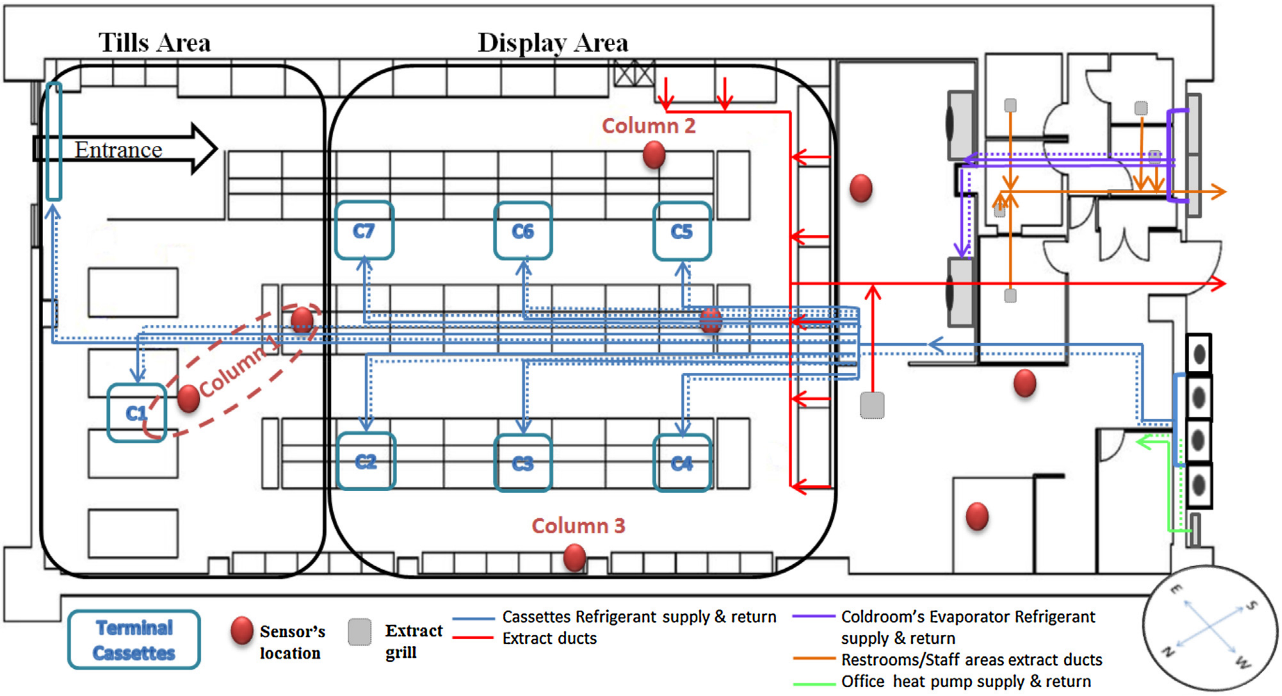

Fig. 1. Schematic presentation of the mechanical plan of the case study store.

staff area is by an extract fan which is in operation 24 h. Ventilation rates for the exhaust system during trading hours have been set to 6 ach for staff areas and sales area, 10 ach for restrooms and cloaks and 1 ach for the storage area. During night time the exhaust fan is set to lower speed 0.75 m^3/s. The staff and rest rooms are heated by 1.5 kW electric heaters and an outdoor condensing unit serves as an inverter heat pump for the office area.

2.3. Lighting system

The lighting luminaires are typically T8 (36 W) type fluorescent for the sales area. They consist of luminaires with 3 lamps; 23 luminaires in the tills area and 30 luminaires in the display area. LED strips (2 strings of 42 and 64 LED lamps (5.6 W) respectively) are installed in the north-east and back sides of the sales area which operate 24 h. The storage areas have 6 T8 (36W) type fluorescent lamps in total. There is 1 T8 (58 W) fluorescent lamp in each office room and restroom The same applies for the kitchen where there are 4 luminaires with 3 T8 (18 W) type fluorescent lamps.

2.4. Refrigeration system

The refrigerated displays consist of three different stand-alone refrigeration cabinets; (a) chilled food open front multi-deck cabinets, (b) lift up lid and (c) open top case frozen food cabinets with a total refrigeration load of 86 W/m^2 sales area. One freezer (29.4 m^2) and one chiller (5.8 m^2) coldrooms are located in the storage area; the freezer cold room has a high efficient split refrigerated system with one 8 kW condenser outdoor unit. The chiller cold room with condenser capacity of 2.3 kW is a mono-bloc system of a single unit containing the evaporator, compressor and condenser with the evaporator inside and the compressor/condenser outside the cold room.

2.5. On-site monitoring

The monitoring focused on the internal environmental conditions and the total energy use; energy data are available for two years (June 2013-opening of store-to May 2015) and space monitoring data for one year (April 2014–May 2015). Additionally half hourly energy data and sub metering of the operating systems from similar stores of the same supermarket chain have been acquired.

Table 1
Environmental conditions monitoring equipment.

Monitoring Equipment	Accuracy	Resolution
HOBO U12-012	±0.35 °C, ±2.5% RH, 1–3000 footcandles (lumens/ft^2)	0.03 °C, 0.03% RH
HOBO UX100-003	±0.21 °C, ±3.5% RH	0.024 °C, 0.07% RH
TELAIRE 7001 connected with HOBO U12-012	±50 ppm	±1 ppm
I-buttons DS1922L	±0.5 °C	0. 5 °C

The indoor environmental conditions monitoring was carried out by 21 HOBO loggers recording air temperature, relative humidity (RH), CO_2 and lighting levels (see Table 1) located at different points as well as at different heights (knee level, head level and ceiling level) within the store (10 in the sales area and 3 in the storage area and coldrooms) (Fig. 1). 4 of the HOBO loggers (U12-012) which have the ability to monitor temperature, RH and lighting levels were used to monitor the lighting intensity within the sales area in addition with the temperature and RH. All the columns included at least 1 HOBO logger for lighting levels monitoring apart from column 3 which had this kind of HOBO logger for both head and ceiling level as it was the one nearest to the north-west single glazing façade and more vulnerable to solar radiation. Finally 1 HOBO logger (U12-012) were used in the middle point of the back area in the sales area for temperature, RH and lighting levels as well as CO_2 levels measurements because it enables its connection with the Telaire 7001. 8 less expensive HOBO loggers (UX100-003) measuring temperature and RH only were used for the other levels of the columns. Some results are presented in this section while all acquired data of energy and air temperatures were used for the model calibration. I-buttons as well as 8 HOBO loggers (UX100-003)

Table 2
Comparison of energy use intensity with previous research projects.

Description	Energy Use Intensity (kWh/m^2/year)	Reference
315 m^2 frozen food store	1117.3	Case Study
Convenience stores	1320–1700	[30]
Supermarkets	850–1500	[30]
Convenience stores	1050–1330	[31]
Supermarkets	747–1082	[31]
Supermarket	795	[32]
Supermarket	810	[32]
300 m^2 mainly food store	840–1200	[33]

Convenience store: less than 280 m^2.
Supermarket: 280 m^2–1400 m^2.

were used to monitor the temperature of each cassette's output. These data were used to evaluate the heating and cooling setpoint temperature schedules as an input in the model development as well as the heating and cooling demand of the areas in the sales area in combination with the indoor air conditions.

Fig. 2 presents an overview of hourly measured energy data using box whisker mean (BWM) plots. Winter 2015 was colder than 2014 (average HDD for June 2013–May 2014 was 1760 and for June 2014–May 2015 was 1908); therefore energy use is higher during winter 2015. The store has a consistent energy demand throughout the year and especially during cold months were on average, in trading hours the hourly energy use floats at around 0.14 kWh/m^2 sales area (25th percentile) with peaks on warm months (July) at around 0.17 kWh/m^2 sales area before falling to the non-trading hours energy use of about 0.10 kWh/m^2 sales area (75th percentile). Higher cooling demand during warm months increases the trading time load at around 21%. The lowest energy use was observed on December (0.04 kWh/m^2 sales area) during Christmas closure.

Average annual energy consumption is 1117.3 kWh/m^2 sales area. Table 2 presents data available from previous research projects which show that the case study store is at the upper range of supermarkets stores and at the lower range of the convenience stores. However, the high refrigeration load leads to higher energy use in comparison with a typical supermarket and this will be discussed in Section 5.

Comparing energy use between summer and winter, there is a difference during trading times while the difference is not significant during the non-trading times. Apart from the increased cooling demand during trading times, temperature and humidity levels are key factors for the refrigeration cabinets' performance because is affected significantly by the temperature, humidity and air movement. Especially, open vertical cabinets are more vulnerable to humidity variations [34].

Figs. 3 and 4 present the results in BWM plots for air temperature for two months (July 2014 and December 2014), indicative for warm and cold periods respectively.

In July, air temperature ranged between 22 °C and 23.5 °C in tills area and between 19.5 °C and 22 °C in display area. Internal pattern seems to follow external maximum air temperatures and the continuous opening of the door and heat gains of the single glassed windows in the tills area affects significantly internal air temperature. For the same reason, air temperature range for December 2014 during trading times in tills area (17–19 °C) was lower than in the display area (19–22 °C).

During non-trading times, average air temperature in the tills area fluctuates between 21 °C and 22 °C, slightly higher than the setpoint temperature (20–21 °C). In the display area the average air temperature is 1 °C lower than in the tills area. The opposite was observed in December 2014; average air temperature in the tills area was 1 °C lower than the temperature in the display area. Internal air temperature variations follow external daily minimum temperature.

RH does not present significant difference between tills and display areas for both months; 40%–65% during warm months and unremarkably lower in cold periods.

Air temperature and RH are important parameters in supermarkets because of their impact impacts on the performance of the refrigeration display cabinets. In addition, the risk of condensation on the surface areas should be prevented as it impacts on the sales and customer satisfaction. During trading times of December 2014, there is not a significant risk for condensation but during the warm period (July 2014), dehumidification action could prevent condensation. The same applies to the non-trading hours.

Light intensity is also an important parameter in supermarkets; both in terms of energy use and illumination of displayed products. CIBSE Guide A (2015) recommends light intensity levels between 750 and 1000 lx for supermarkets and 500 lx for convenient stores [35]. A supermarket chain is specified near the upper range [36] while surveys indicate levels lower than the minimum range [37]. Measured lighting levels in the case study store ranged from 700 in the tills area to 1200–1800 lx near the windows and to 250 lx at the back of the sales area under shelving and partially obstructed by display products.

CO_2 concentration measurements ranged between 400 ppm during the night and 650 ppm during operational times indicating good ventilation provision [35,38].

3. EnergyPlus model

3.1. Methodology of model development

A model within Energy Plus was created using data and measurements from the operational store. Fig. 5 shows the method followed for the creation and calibration of the model following available literature [39–41]. Bertagnolio proposed two levels of thermal and energy model calibration; level 1 based on available design data to create the as-built model and level 2 that included as-built and operating information [42]. Two levels of calibration were used in this work.

At level 1 an initial whole building energy model with separated thermal zones is created based on available data (plans and drawings, observations, interviews and surveys, technical characteristics of system components etc.) (Fig. 6). Detailed envelope composition is defined in this step as well. Material properties datasheets and drawings were used to build the proposed design for the model in level 1.

At Level 2 internal loads (including occupancy) are inputted (lighting, electrical, refrigeration and HVAC systems) In this way a realistic thermal model was created. The characteristics of internal loads have been updated on a zone by zone basis. The model contains the actual values derived from data collected from electrical and mechanical drawings, observations, technical datasheets, HVAC control strategy report and transactions data. One day of the year (Christmas day) have been scheduled differently due to the store closure.

Measured indoor air temperatures (see Section 2.5) were used for the creation of thermal zones temperature setpoint schedules.

The model was run and the accuracy was checked by comparing with measured energy and air temperature data on an hourly and monthly basis for one year (June 2014–May2015) by calculating the following criteria [40]:

$$MBE = \frac{\Sigma_{i=1}^{N}(y_i - \hat{y_1})}{\Sigma_{i=1}^{N} y_i} \quad (1)$$

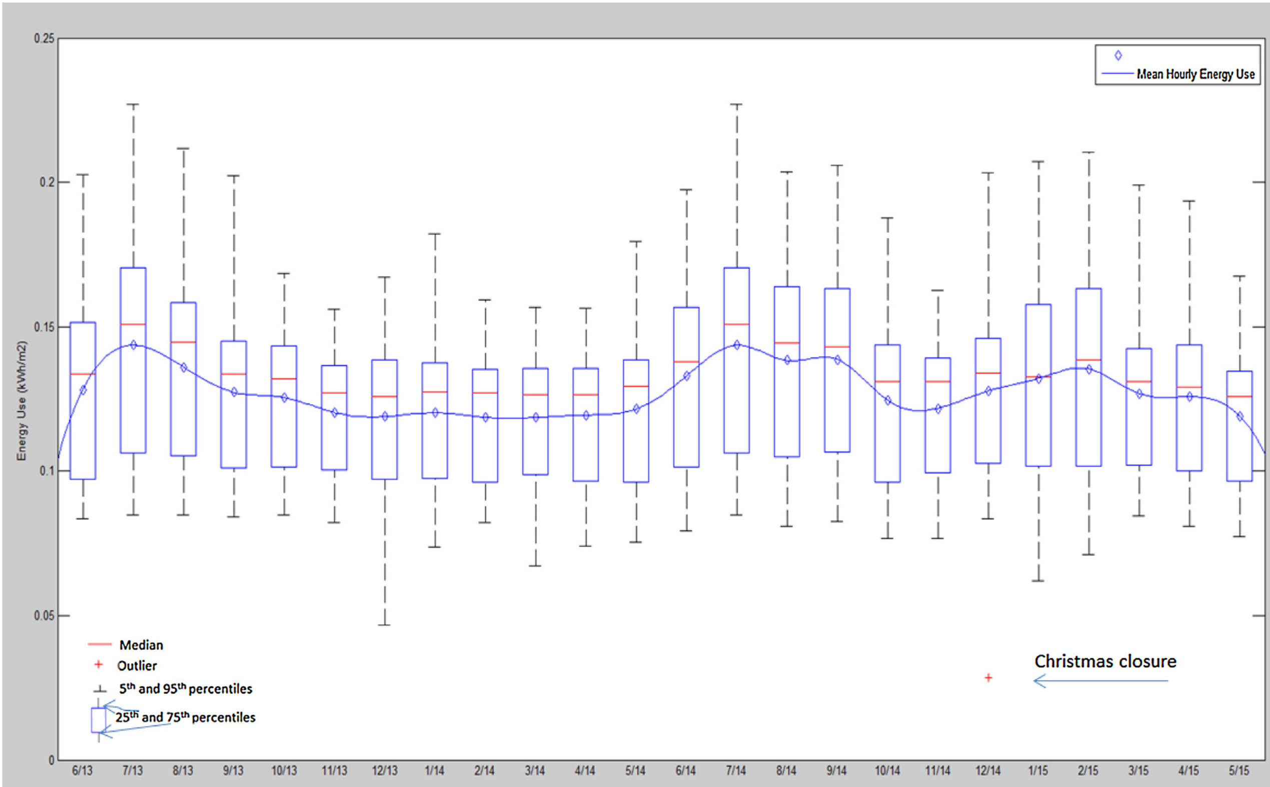

Fig. 2. BWM plot of measured energy use per sales area(June 2013-June May2015).

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{N}\left[\left(y_{i-}\hat{y}_1\right)^2/\mathrm{N}\right]}}{\bar{Y}_s} \quad (2)$$

$$\overline{Y_s} = \frac{\sum_{i=1}^{N} y_i}{N} \quad (3)$$

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

ASHRAE Guideline 14 recommends an MBE of less than 5% and a CVRMSE of less than 15% relative to monthly calibration data. If hourly calibration data are used, these requirements could be 10% and 30% respectively [40].

Following the first run, an inverse calibration methodology was followed to make small adjustments to the operating schedules and the internal loads of the model using as a guide energy data from the sub-systems from previous periods or from similar stores for lighting, refrigeration cabinets and HVAC. As Liam et al. [43] suggests, the HVAC system was adjusted lastly, after other input parameters and systems were calibrated because most of these inputs will influence the HVAC system performance.

The accuracy of the final adjusted model was evaluated by computing MBE and CVRMSE criteria on an hourly and monthly basis from June 2014 to May 2015.

Finally, the model was run for further 3 operational months (June-August 2015) for which data are available without any further adjustments on the model and MBE and CVRMSE criteria were calculated.

3.2. Description of model inputs

3.2.1. Construction

The dynamic thermal models require a 3-dimensional geometry and this was created in Google Sketchup. The building was separated into zones by similar functionality, boundary conditions and performance due to heat gains from occupants, lighting and equipment [44,45]. Hence, 9 thermal zones (Fig. 6) were created with the sales area divided into two separate zones, the tills area and display area by a "virtual" wall within the building modelling. The different colours indicate the separation of the thermal zones.

Construction details of the various elements (floors, rooms, external facades and internal partitions, windows, doors) was inputted; Table 3 presents their thermal properties [46].

3.2.2. Weather file

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

3.2.3. Operating schedules and model configurations

The majority of the schedule parameters such as lighting in the staff areas where occupancy sensors are installed and the electrical equipment (office PCs, kitchen equipment, and tills machines) are dependent on the people presence and behaviour. Thermostatic controls are also defined here (20–21 °C setpoint temperature).

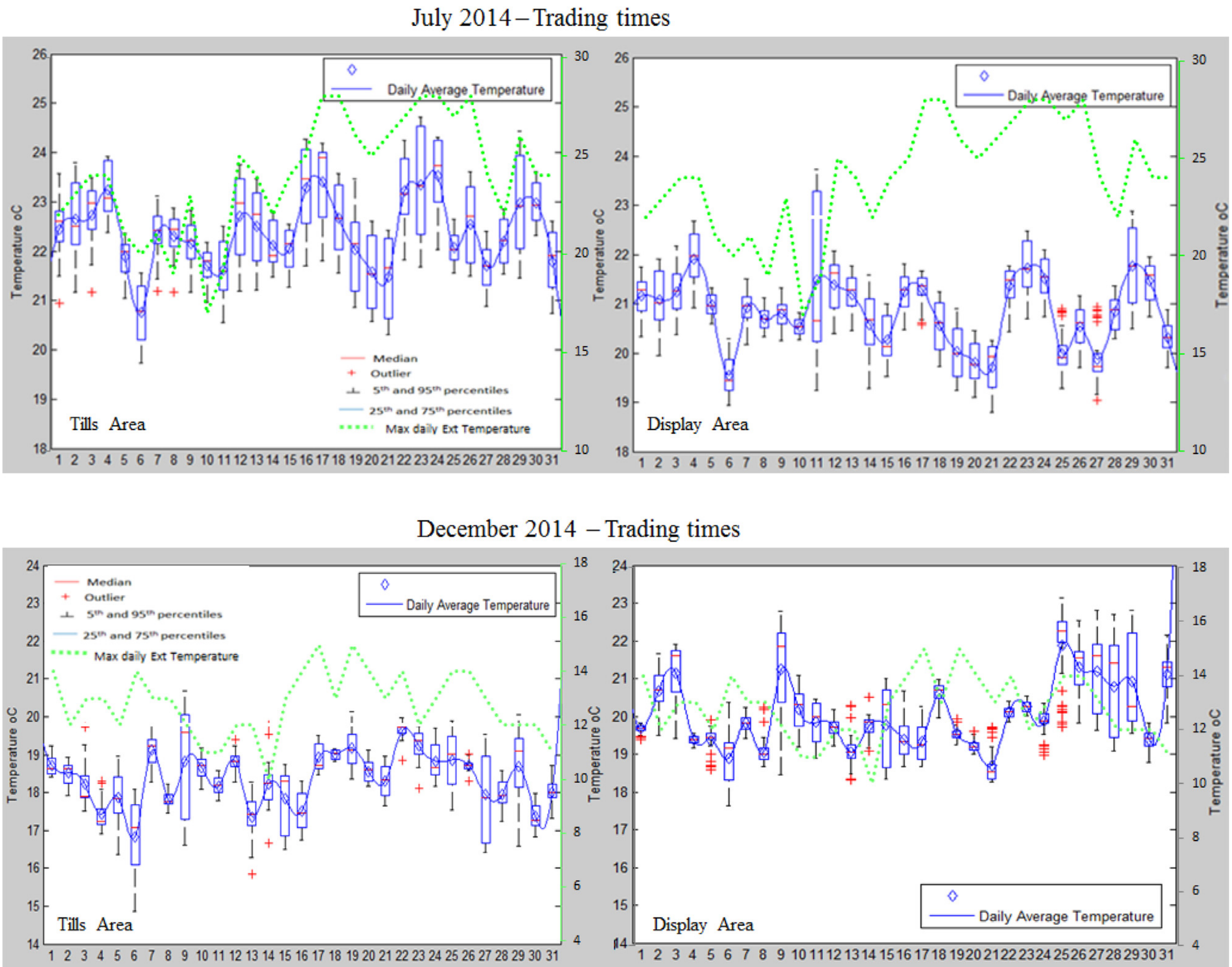

Fig. 3. BWM plot of measured air temperature in sales area (tills and display zones see Fig. 1) for June and December 2014 during operating times.

Table 3
Summary of parameters input for customers density, lighting load and electrical equipment.

Construction	U-value (W/m²K)
External Wall	0.35
Ground Floor	0.25
Roof	0.25
Windows (Single glazed)	5.7

Location/Thermal Zones	Customers' Density (m²/person)	Lighting Load (W/m²)	Electric Equipment (W/m²)
Tills Area	7.6	32.9	15.9 (Tills equipment)
Display Area	16	16	n/a
Office-Control Room	5.9	9.9	30.6 (PCs, printers and control equipment)
Office	4.2	13.8	17.85 (PCs)
Kitchen	3.9	36.7	274.2 (Fridge, microwave, kettles, dishwasher)
Restrooms	n/a	10.6	137.4 (Heaters)
Storage Area	31.6	1.9	n/a
Storage Area (B&W)	n/a	18.8	n/a

Opening times are 8:00–20:00 on weekdays and Saturdays and 10:00–16:00 on Sundays. Working shift starts one hour earlier than opening with 15 employees each day for 12 h and it is separated in 2 shifts per day. Customer flow numbers and density were observed in-situ for several days in July 2013 and were supplemented by transactions data for a week. Fig. 7 presents the occupancy density over a week. Hourly transactions data and customers counts lead to the hourly schedule of the customers' density in both sales and till area. Moreover, the in-situ spot observations enabled the mapping of the customers inside the sales area from which the customers' density in both tills and display area derived. According to these recordings the maximum amount of customers per timestep in the tills area set to 10 and 15 for tills area and display area respectively.

The lighting system operates from opening to closing time but the LED strips 24 h. Table 3 summarises the internal loads inputted to the model.

Air permeability is set at 15 m³/h m² @50 Pa (limiting value at the time of construction). This is increased by 80% in the tills area to

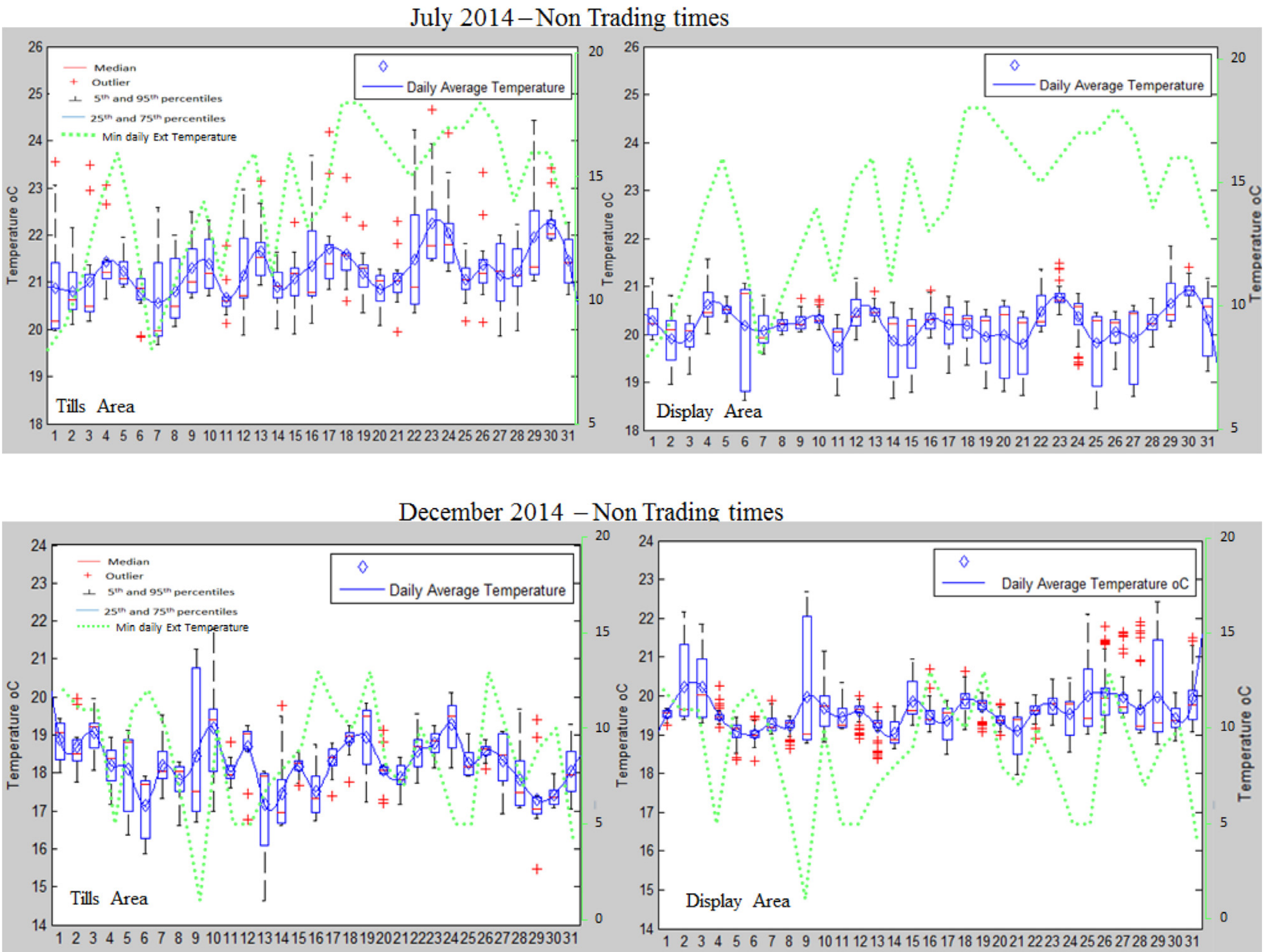

Fig. 4. BWM plot of measured air temperature in sales area (tills and display zones see Fig. 1) for June and December 2014 in non operating times.

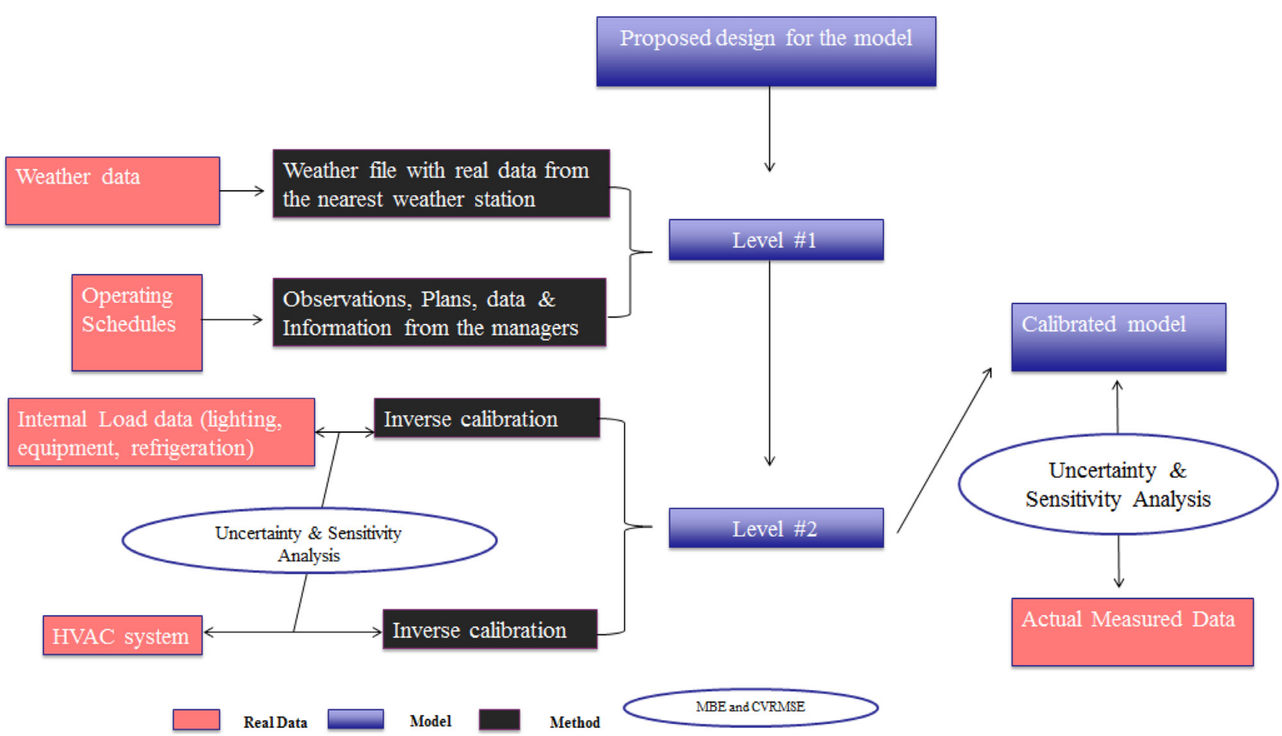

Fig. 5. Calibration methodology.

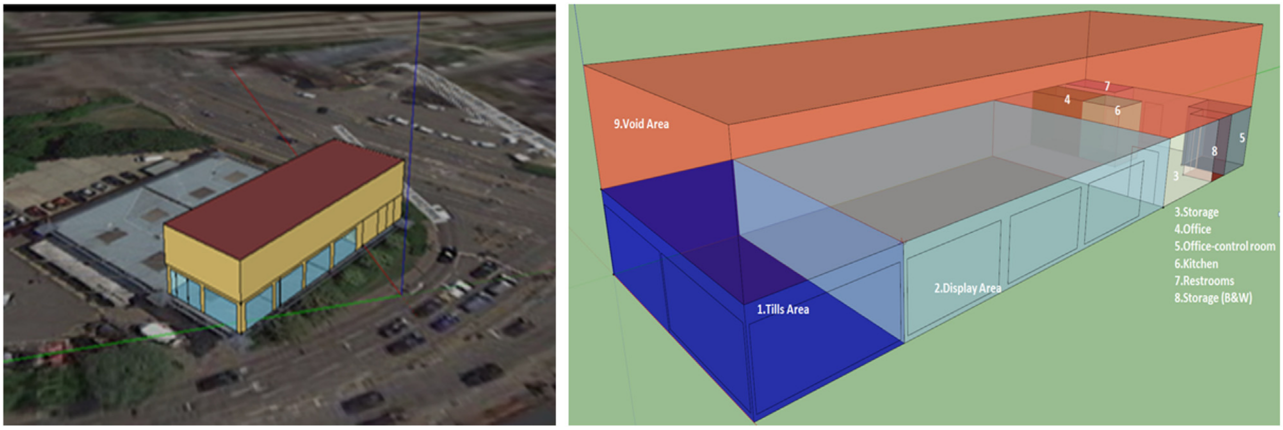

Fig. 6. Sketchup 3-dimensional building model.

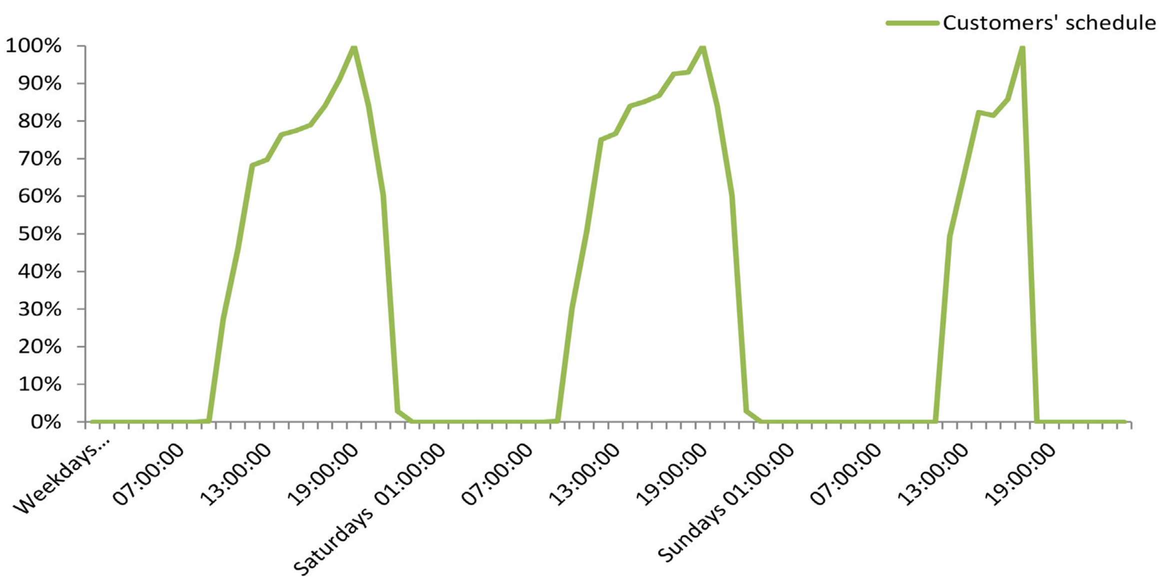

Fig. 7. Operating schedules for customers' density.

account for the opening of the main door; this was estimated from the customer flow observations.

The refrigeration display cabinets specifications are summarised in Table 4. According to EnergyPlus Engineering Documentation [47] the stand-alone refrigeration system is consisting of a compressor connected to refrigeration case or a walk-in cooldroom. The refrigeration system is modelled by the use of a compressor rack object where the compressor and the condenser are combined into a single unit with the performance determined by the heat rejection environment and the total case load. Refrigerated cases performance is based on the combined effects of evaporator load, fan operation, lighting, defrost type, and anti-sweat heater operation.

The refrigeration case models use performance information at rated conditions along with performance curves for latent and sensible heat exchange with the surrounding environment (termed as case credits) and defrost heat load to determine performance at off-rated conditions. Energy use for lights, fans and anti-sweat heaters, defrost heat load and the heat load due to the restocking of the products are modelled based on inputs for nominal power, schedules and control type. The model assumes that these load components are known for a refrigerated case at rated ambient air conditions and the specific case operating temperature. A combination of input curves and fixed correlations adjust for case performance at off-rated conditions. Several of the load components are provided by the manufacturer (total rated load, fan, lighting, anti-sweat heater and defrost load). The remaining load components are estimated. For estimating the latent air infiltration load, the model requires the latent heat ratio (LHR) for the refrigerated case at rated conditions. The rated LHR for refrigerated case typically ranges from 0.1 to 0.3 depending on the case configuration (i.e. glass door reach-in versus multi deck open case) and case operating temperature. The rated sensible case credits are calculated by subtracting the known loads at rated conditions (fans, lighting, anti-sweat heater, defrost and latent case credits) from the rated total cooling capacity of the case which is provided by the case manufacturer. For every simulation step, the rated sensible case credits are then adjusted to account for variations at off- rated ambient air temperatures. A case credit fraction schedule is also defined in order to identify cases that operate differently during specific times. For example, curtains that are installed on the open front multi deck cabinets during not trading hours which significantly reduces the case credits compared to occupied hours.

Compressor's electric consumption is calculated based on the evaporator load for the connected display cabinet and the coefficient of performance (COP) for the compressor. Freezer and chiller coldrooms are modelled separately. Freezer coldroom condenser rejects heat to outdoors while the chiller coldroom is a mono-block

Table 4
Summary of refrigeration system input parameters.

	Cold Rooms		Display Cabinets		
	Chiller	Freezer	Open front multi deck chilled food	Lift up lid frozen food	Open top case frozen food
Number	1	1	7	58	3
Capacity (kW)	2.3	8	1.46	0.2	1.75
Dimensions (L/D/H-m)	2.4/2.4/3	7/4.2/3	1.9/0.9/2	1.7/0.74/0.89	1.75/1/0.9
Operating temperature (°C)	0	−20.5	1 to 2	−20 to −22	−23
Defrost Type	Electric	Electric	Off Cycle	Off Cycle	Off Cycle
Refrigerant	R404a	R404a	R404a	R134a	R404a
Compressor COP	1.69	1.5	2.3	1.5	2.3
Condenser Type	Air Cooled	Air Cooled	Air Cooled	Air Cooled	Air Cooled

Table 5
Summary of the VRF system, cassettes and door heater input parameters.

VRF system		Air to Air Heat Pump
Condensing Unit		24 h/7d in operation at 21 °C
Total Heating Capacity (kW)		113
	COP	3.76
Total Cooling Capacity (kW)		101
	COP	3.15
Fan		Propeller fan x 4
	Air flow rate (m^3/s)	6
Refrigerant		R410a

Cassettes	Number	Cooling Capacity (kW)	Heating Capacity (kW)	Maximum flow rate (m^3/s)	Pressure (Pa)
Terminal cassettes	7	14	16	0.5	600
Door heater	1	n/a	15.7	0.6	600

system and the heat rejection is in the storage area. Coldrooms are modelled by using a compressor rack object connected to the walk-in coldrooms which combines the compressor and the condenser in a single unit. The boundary conditions' (walls and ceiling) thermal properties of the coldrooms are defined in order to enable the calculations of the sensible and latent heat exchange between the coldrooms and the storage area. Apart from that the energy use for lights, fans and anti-sweat heaters, defrost heat load and the heat load due to the restocking of the products are modelled based on inputs for nominal power, schedules and control type. On site surveys and manufacturers data were used in order to gather the refrigeration system inputs for the model development. The refrigeration defrost schedule and stocking schedule were created using data from similar frozen food stores of the same supermarket chain and default values from EnergyPlus supermarket schedules.

3.2.4. HVAC system

The outdoor unit of the VRF system includes two equally sized inverter scroll hermetic compressors with characteristics summarised in Table 5. The load is equally spread into the two units for lower starting currents and more precise indoor comfort with fast reaction to the load changes. Moreover, the system uses R410a as a refrigerant which according to the manufacturer provided higher COP of the system in comparison to other refrigerants [48]. The outdoor unit system is connected to indoor terminal units in the tills and display area. Zone terminal units operate to meet the zone sensible cooling or heating requirements as determined by the zone thermostat. The actual operation mode is determined on the master thermostat priority control type which has been set to load priority algorithm. In this way the total zone load where the master thermostat has allocated, defines the operation mode as either cooling or heating. Each simulation step, EnergyPlus performs a zone air heat balance to determine the zone load and then the VRF system operation mode is determined according to the specified master thermostat priority control.

Table 6
Comparison of the metered and simulated energy use.

		Metered	Simulated
Hourly	Minimum (kWh)	19.5	23.6
	Maximum (kWh)	71.5	69.9
	Average (kWh)	41.1	39.7
	Annual (kWh/m^2 sa)	1143.4	1104.2
	Standard deviation (σ)	9.2	10.4

4. Simulation results analysis

4.1. Energy use

The building's annual energy use from June 2014 to May 2015 is 1143.4 kWh/m^2 sales area. The final calibrated model prediction is 1104.2 kWh/m^2 sales area (a deviation of 3.4%). Fig. 8 enables a quick visual inspection of measured and simulated energy use for two indicative weeks while Fig. 9 presents their statistical variations. Data are discussed for the whole store (rather than normalised by sales area) because the focus is on the comparison of the measured data with simulation results (Table 6). Monthly simulation results have shown a MBE of 0% and CVRMSE of 4% for the year 2013–2014 and −2% and 6% respectively for the year 2014–2015. MBE negative values indicate that results from the building model are higher than results from measurements and vice-versa for positive values. According to the guidelines from ASHRAE the MBE and CVRMSE values are within acceptable limits for comparison with both monthly and hourly energy use data.

Residuals are estimates of metered error obtained by subtracting the simulated data from the model. The histogram of hourly residuals provides quantified conclusions of the magnitude and spread of errors of the annual hourly energy use. The residuals follow a normal distribution with mean value 1.85 kWh. The standard deviation of residuals is 5.93 kWh. Expressed in relative terms, 95% of the errors have magnitude falling within −10 kWh and 14 kWh of hourly energy use. Only 0.3% of the errors are larger than −15.9 kWh or 19.6 kWh which is approximately the half of the night time load

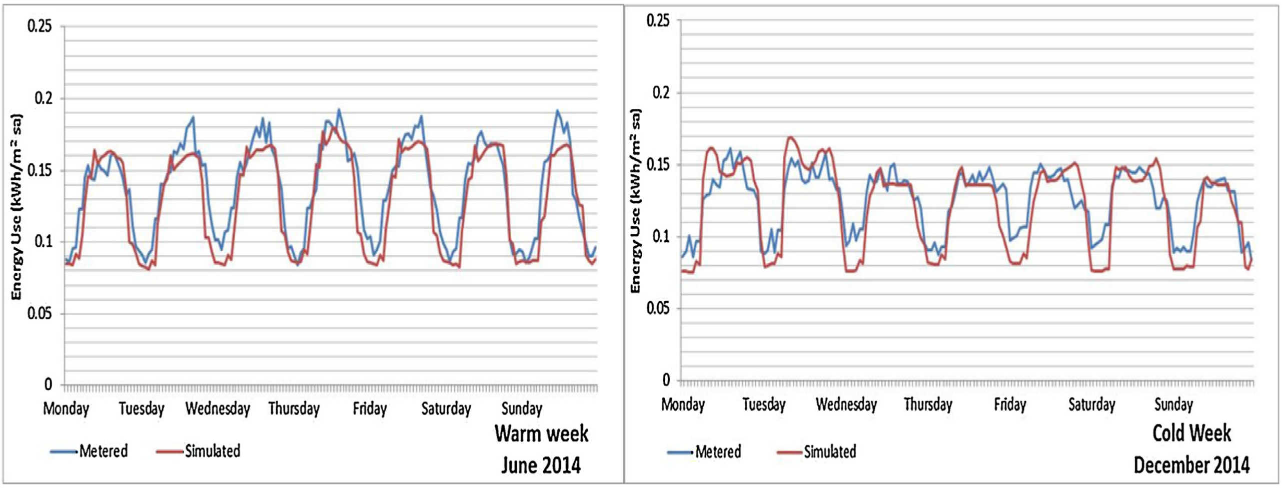

Fig. 8. Comparison between metered and simulated hourly energy for an indicative warm and cold week.

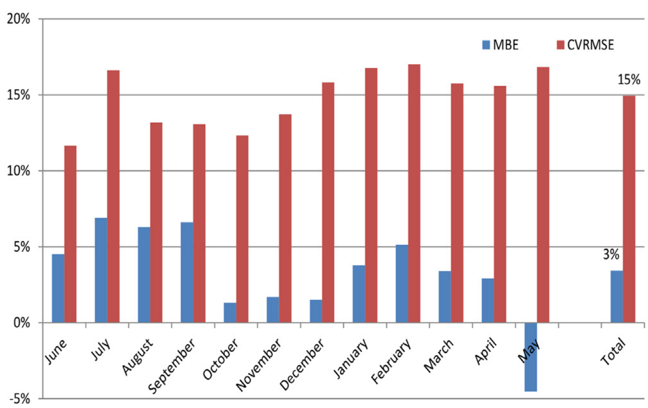

Fig. 9. MBE and CVRMSE analysis of the energy use based on hourly data.

of energy use of the store. Fig. 10 shows a constant spread of errors that are equally distributed on both sides with a slight under prediction of energy use values (m = 1.85 kWh). The under prediction of the energy use is basically observed in the lower energy use values while as the energy use increases during the day the model tends to over predict the energy use. The model maintains a constant level of accuracy across the full range of predicted energy use values with an average error of 2 kWh. The minimum error (29.9 kWh higher than the metered energy use) that occurred is on the 24th of July 2014 for 3 h only during the evening. The 24th of July 2014 was the day that the highest temperature observed (27 °C) during these three hours. Moreover, even the maximum error (21.1 kWh lower than the metered energy use) occurred during summer days. This is also evident from Fig. 9 and MBE values that are higher than the cold months of the year.

Fig. 11 shows the monthly energy use from both metered and simulated data based on hourly measurements for 12 months (June 2014–May 2015). May was the only month that the simulated data are higher than the metered; something that is also evident again from the MBE values, where May is the only month with minus MBE value and the simulated results were higher than the metered ones. This is due to a sharp increase in external temperature in the middle of May 2015 which leads to higher energy use during trading times.

Finally, the calibrated model was run for the next available operating data for three months (June 2015–August 2015) in order to check its accuracy. The MBE and CVRMSE values were found to be within acceptable limits according to guidelines and the percentage error between metered and simulated monthly energy use does not exceed 10% (Fig. 11).

4.2. Indoor air temperature

Fig. 12 shows a visual comparison for both metered and simulated air temperatures in the tills and display area. The measured mean temperatures in the tills area have fluctuations (19–22 °C) during the year with the lowest during December and the highest in July. Although the set point temperature is 21 °C continuously, the tills area does not maintain the temperature within the desirable set point. In comparison with the measured data, air temperatures of simulations are significantly more stable during the year and maintained slightly lower than 21 °C. Similarly to the measured data, during the cold months (December and January) lower values than set point temperature are predicted in tills area. These

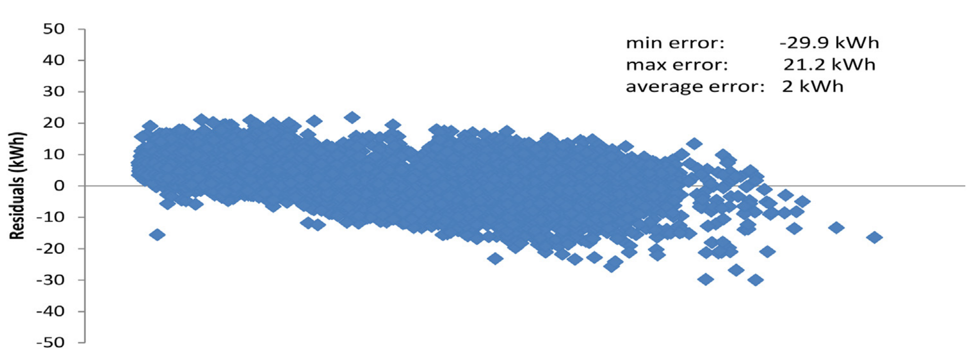

Fig. 10. Scatterplot of energy use residuals in correlation with the simulated energy use results.

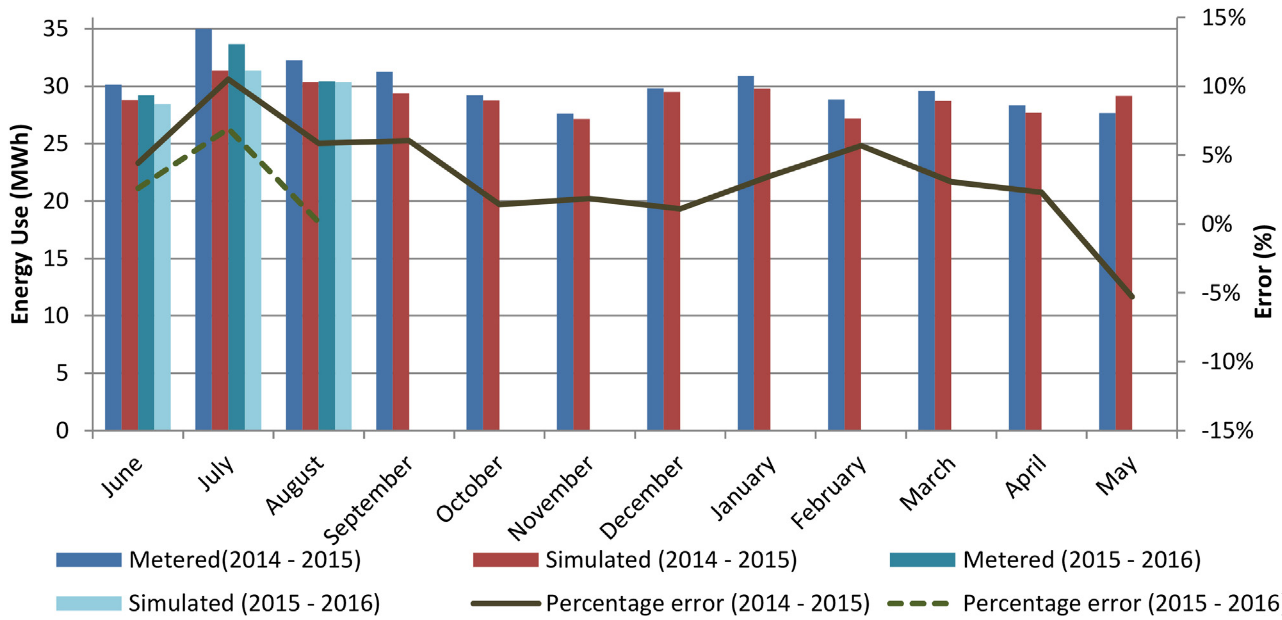

Fig. 11. Monthly energy use comparison for metered and simulated data and percentage error.

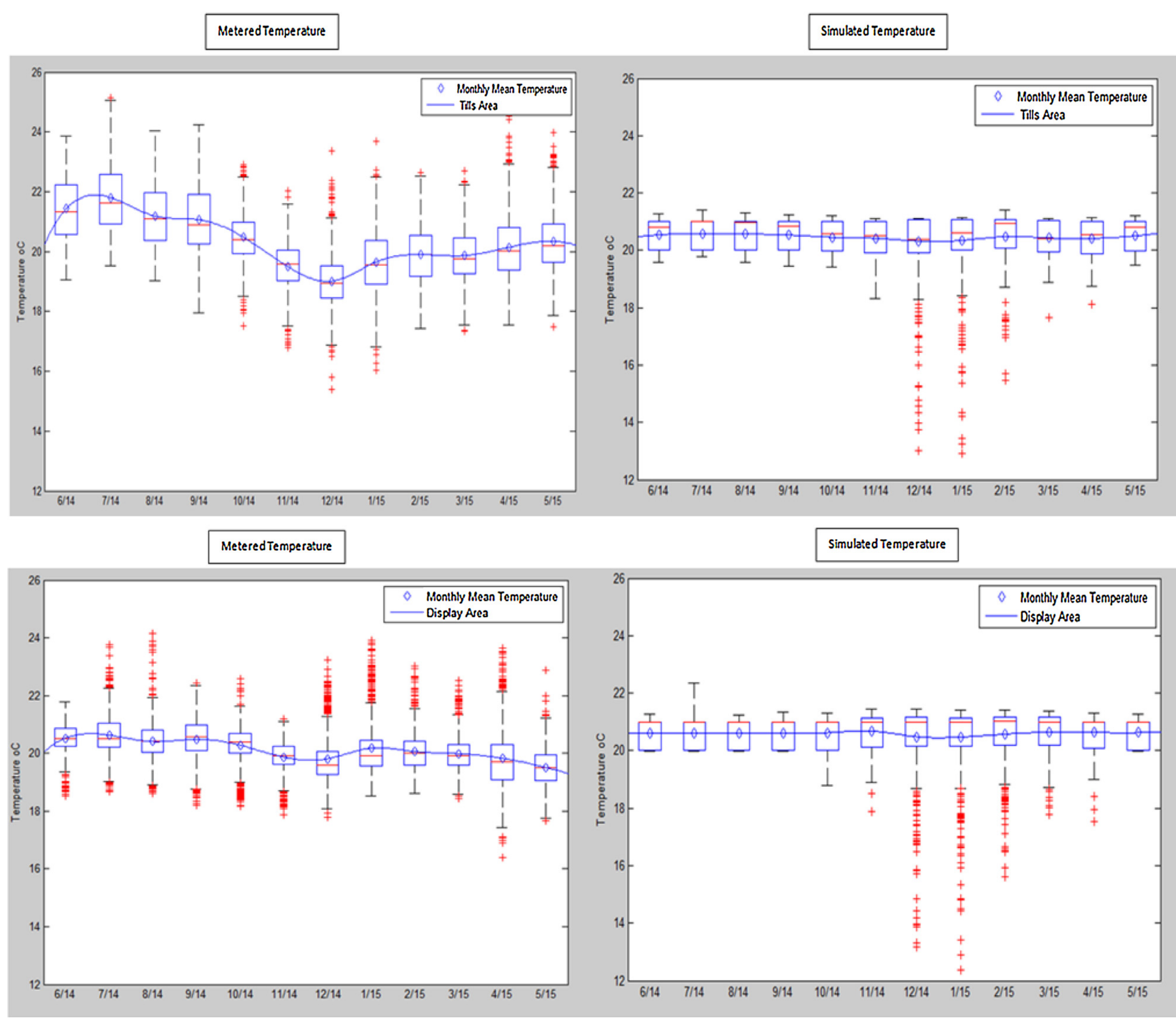

Fig. 12. BWM plots of metered and simulated air temperature for the Tills and Display area (hourly-based).

results indicate that a more accurate model for the air infiltration through the entrance door needs to be developed if more accurate air temperature prediction in the tills area is required.

In display area, a more stable mean temperature (20–21 °C) during the year was measured (Fig. 12). Simulation shows that the temperature is maintained during the year to the set point and only in the cold months a remarkable drop was observed in some hourly values and a slight increase (around 2 °C) during July which was the warmest month of the simulated year. As it was observed in the prediction of the energy use values, extreme external weather conditions increases the error.

Fig. 13 displays the MBE and CVRMSE error checks of temperature results based on hourly data. December was the month with the highest accumulated error in both zones but the annual values that are within the acceptable guidelines, indicating that the model has the ability to predict bulk air temperature of the two thermal zones accurately.

The residuals for both thermal zones follow normal distribution according to their histograms. In the tills area the mean value of the residuals is almost 0 (−0.14 °C) and an equal distribution of the errors occurs in both sides of the peak. Regarding the display area, the mean value of the residuals is −0.52 °C. In this case the model tends to slightly over predict the temperature in the display area which means that indoor air environmental conditions tends to better maintained to the set point temperature.

Fig. 14 shows the spread of errors with increasing simulated temperatures. The scatterplot for the tills area demonstrates that the EnergyPlus model maintains a constant level of accuracy across the full range of predicted temperatures for the tills area. The highest error occurred during the winter period which means that the external weather conditions introduce a larger element of error in the predictions of the temperatures of the thermal zones which in combination with the customers occupancy levels uncertainty lead to the difference between metered and simulated data. The scatterplot for the display area thermal zone indicates significant negative errors which are also an evidence of the ability to slight over predict the temperature of this thermal zone. However, as it was observed for the tills area, the highest errors occurred in the warmest and coldest month of the simulated year (December and July).

5. Discussion

The calibrated model gives the opportunity to further analyse the complex thermal and energy performance of a frozen food supermarket. Fig. 15 presents hourly energy use over two typical days of the supermarket's subsystems while Fig. 16 presents the relative annual energy use by subsystems.

It can be seen that the refrigeration system is responsible for most (60%) of the energy use followed by the HVAC (26%) system, lighting (8%) and electrical equipment (6%). For the HVAC system, 8% is due to cooling, 6% to heating and 11% to the ventilation (fans). These results differ from typical supermarket sub-system breakdown because refrigeration energy is higher by about 10–20% which leads to higher energy use than typical supermarkets (Table 2). Reported energy use by sub systems [32,49] assign 35% to refrigeration, 26.8% to HVAC and 18.6 to lighting.

Previous work reported in [50] has shown that improved refrigeration cabinets, low carbon design of the supermarket fabric and control of the ventilation system might lead to substantial energy reduction. Previous studies usually examine each subsystem in isolation. The developed model with coupled building/HVAC/refrigeration systems gives the opportunity to examine interventions to each system and its impact on the other subsystems. Recently, simulation results [29] for a generic UK supermarket using EnergyPlus investigated the effect of HVAC setpoints, supply air temperatures and refrigeration operating temperatures on the total energy use. Simulations showed that an increase of refrigeration cabinets operating temperature results to energy consumption reduction for HVAC and refrigeration.

Some preliminary results are presented in Table 7 for six interventions mainly in building characteristics and indoor air control strategies and their impact on subsystems. Improved refrigeration cabinets (with doors on frozen food) are not examined as these are already in use in the case-study. HVAC components characteristics and low energy strategies (i.e night ventilation) will be examined in future work.

Simulation results in Table 7 show that highest energy reduction is achieved when the HVAC system is operating during trading hours only, mainly due to the reduction of HVAC energy use and its subsystems. However, it impacts on the refrigeration performance due to the increased indoor air temperatures (∼25 °C) during warm periods and after the trading hours due to the orientation of the building and the glazed construction of the north-west side exposed to late day solar heat gains in the summer. Reducing setpoint temperature to 16 °C during the night has a positive impact on the refrigeration system but HVAC energy demand increases leading to a very small overall energy saving. In addition, impact of reduced temperatures on condensation on refrigeration cabinets needs to be examined in more details. The upgrade of the lighting system to LED reduces the total energy use by 2.5% due to the 30.2% decrease in the lighting demand.

The changes in the construction (scenarios 1, 2 and 3) has insignificant impact in the total energy use but lead to energy reduction for the HVAC system; heating and cooling demand are reduced due to higher insulation of the north-west side but double glazed windows lead to an increase in cooling demand due to the solar gains and reduced heat transfer through the windows. Finally, by changing the insulation of the external roof and installing it in

Table 7
Percentage changes from the baseline in the total energy use and the sub-systems.

Scenarios	Total	Refrigeration	HVAC	Lighting	HVAC		
					Heating	Cooling	Fans
#1	0.7%	0.1%	3.1%	0.0%	6.7%	3.6%	−0.1%
#2	0.3%	0.0%	1.5%	0.0%	9.9%	−3.0%	−0.1%
#3	2.5%	0.0%	0.1%	30.2%	−3.1%	2.5%	0.0%
#4	4.0%	−1.2%	22.7%	0.0%	10.5%	20.1%	24.6%
#5	−0.5%	0.1%	−2.7%	0.0%	−24.2%	9.5%	0.5%
#6	0.1%	1.4%	−3.8%	0.0%	11.9%	−18.4%	−0.2%

Scenario 1: North – west single glazed side replaced with an external wall (U-value = 0.35 W/m^2).
Scenario 2: Double glazed windows in Sales Area.
Scenario 3: LED lighting system upgrade in Sales Area (35% less W/m^2).
Scenario 4: HVAC system in operation only during trading hours.
Scenario 5: Insulation above the acoustic tiles between sales area and Void Area (U-value = 0.25 W/m^2) instead of the external roof insulation of the Void Area.
Scenario 6: Heating and Cooling setpoint temperature during non-trading hours: 16 °C.

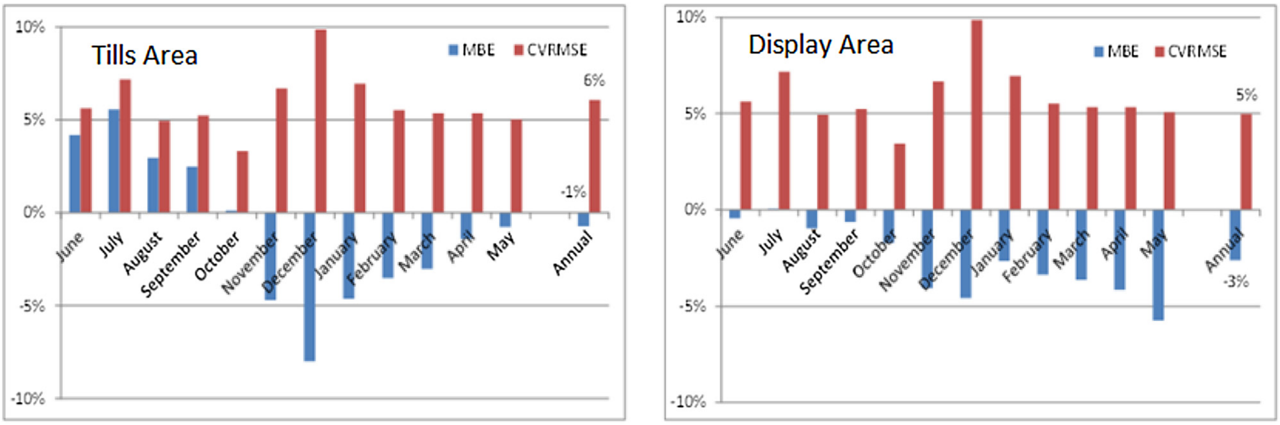

Fig. 13. MBE and CVRMSE analysis of the Tills area and Display area air temperature based on hourly data.

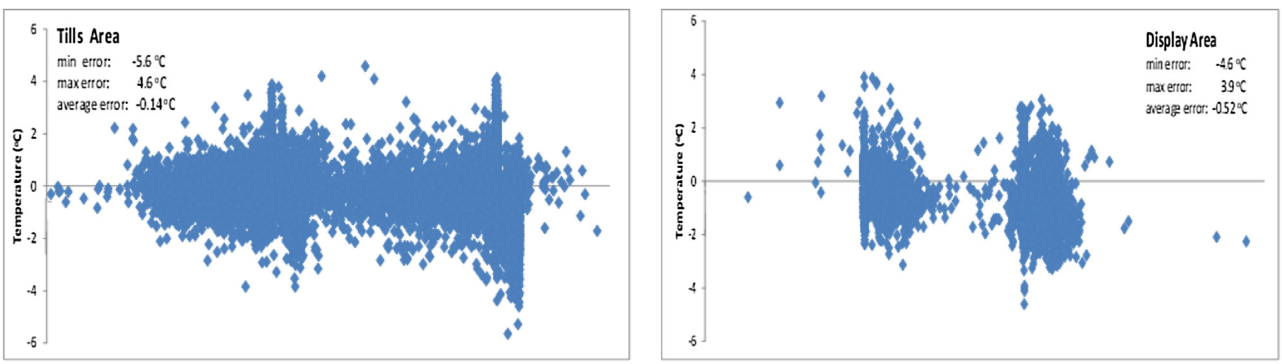

Fig. 14. Scatterplot of air temperature residuals in correlation with the simulated temperature results for the Tills area andDisplay area.

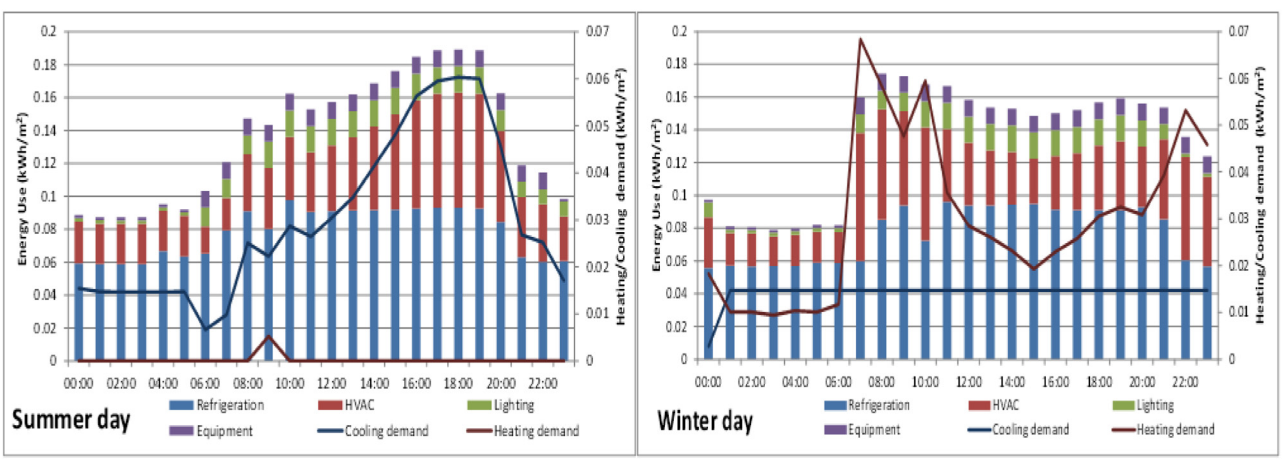

Fig. 15. Hourly energy use profile breakdown for indicative winter and summer day.

the interior ceiling reduces cooling demand and increases heating demand because of changes in the void air temperature which acts as an additional insulation layer.

6. Conclusions and future work

This paper presented work on developing an integrated building/HVAC/refrigeration supermarket model within EnergyPlus and validated this with data from an operational frozen food small supermarket in the UK. Taking into account the number of uncertainties and their unpredictable nature, building energy performance predictions can at best rest within a small allowable error margin. Results presented in section 4 indicate that the development EnergyPlus model can accurately predict both the total energy use and air temperature within the air conditioned thermal zones of the frozen food supermarket store. The EnergyPlus model containing local weather data, achieved hourly MBE and CVRMSE values of 5% and 15% respectively for energy use prediction. 95% of predicted energy use errors fall in the range of −10 kWh to 14 kWh with an average of 2 kWh. Moreover, the building model has the ability to demonstrate air temperature prediction accuracies with average error of −0.14 °C in the tills area and an average of −0.52 °C for the display area. The building model slightly over predicts the air temperature of both thermal zones and keeps the mean temperature

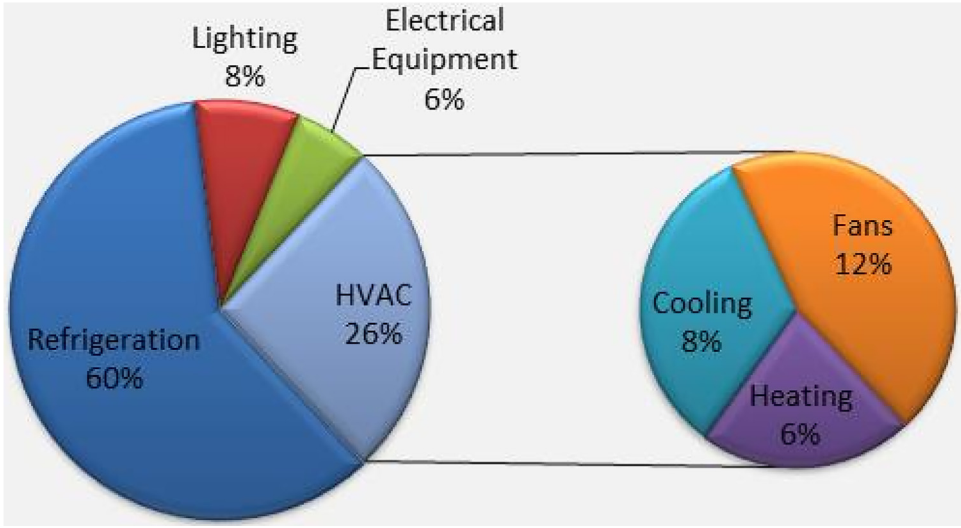

Fig. 16. Percentage contribution of sub-systems energy use in the case study frozen food supermarket.

within the sales area more stable during the year in comparison with the metered data.

Overall the developed EnergyPlus model provided an accurate evaluation of building energy and environmental performance whereby annual simulated energy demand was under predicted by 4.5% and air temperature in the sales area was also under predicted by approximately 0.5 °C.

The developed model is used to show some preliminary results on its capability to simulate the interaction of subsystems and provide predictions on intervention strategies for the building envelope, HVAC system and its control/operation and lighting system. Further work will examine in more detail the interaction of subsystems in terms of energy performance, the provision of desirable internal environmental conditions for staff/customers comfort and food products and impact on refrigeration system performance. These simulations will be supplemented with continuing detailed monitoring of these interactions in the case-study store and supplementary measurements in another case-study with different HVAC system.

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