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Coupling night ventilative and active cooling to reduce energy use in supermarkets with high refrigeration loads

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ABSTRACT

Supermarkets are energy intensive buildings and present a unique space conditioning challenge because of the interaction between the HVAC system and the refrigerated display cabinets. HVAC system is the largest consumer of energy after refrigeration depending on system design, geographical location and controls. Night ventilation is used extensively as a low energy strategy to cool buildings in climates where night temperatures are suitable. This paper presents a study of cooling benefits of night ventilation for supermarkets with high cooling demand. Energy and environmental data from two stores with high percentage of frozen and chilled goods and with different HVAC systems are presented. Validated models in EnergyPlus are developed for the two stores and their systems. A parametric study of the coupled operation of night ventilation and active cooling for the climatic conditions of south east England is carried out and optimisation strategies are modelled. Results indicate that effective night ventilation can reduce the duration of active cooling during trading times and achieve 17% reduction in cooling annual energy use, 3.3% in total annual energy use while refrigeration energy use is not affected.

1. Introduction

Retail stores are among the most energy-intensive commercial buildings, consuming two or three times as much energy per unit floor area as office buildings. In the US, supermarkets represent 5% of the total commercial building primary energy use [1,2]. According to US Energy Information Administration [3], commercial sector energy use accounts for 18% of the total energy use and is responsible for 16% of the carbon dioxide emissions of the country. In the Asian countries forecasts show a sales growth in the retail sector; the fastest in the world presenting an average of 4.6% increase with sales of almost 7 trillion USD in 2014 [4]. In the UK energy consumption in food supermarkets is around 3.5% of the total UK energy consumption [5]. Currently, there are over 1 million supermarkets in Europe. Thus, just a small percentage reduction in energy use can result to substantial savings. Estimating 25% energy saving in Europe in supermarkets will result in 31 TWh of annual electricity savings which equates to carbon reductions of 16.2 million tons [6]. The global retail landscape is evolving and new trends such as internet purchasing and home deliveries along with changes in consumers' lifestyle have an impact on conventional food retail stores. This tendency has created a shift towards new relatively small convenience food shops instead of out-of-town hypermarkets. In the UK, IGD [7] estimate that spending in convenience stores will rise and that online and convenience stores.

Heating, Ventilation and Air-Conditioning (HVAC) systems contribute to a considerable amount of the total energy use of supermarkets. In the UK supermarkets, reported energy use by subsystems assign 35% refrigeration, 26.8% to HVAC and 18.6% to lighting [8,9]. The total energy use of a supermarket depends on business practices, store format, product food ratio, equipment use for in store preservation and display. This paper presents a study of the energy use and the potential for savings due to mechanical night ventilative cooling of the HVAC systems of frozen food supermarkets and consequently of supermarkets with high cooling requirements. The paper focuses on small size supermarkets energy use which is basically food dominant. They are usually small in sales floor area (less than 1000 m^2), and are classified as small supermarkets [10].

In supermarkets with high food goods refrigeration could be as high as 60% [11]. The smaller the store the highest the energy use due to the higher refrigeration equipment used because of the higher ratio of food and non-food products [12]. As the total sales area increases, the refrigeration energy use share in the total energy use reduces and the lighting becomes more significant. Convenience food stores are usually defined as food stores located in central urban areas, near stations and shopping malls with a

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Abbreviations

AC	Air conditioning
ach	air change per hour
AHU	Air Handling Unit
BEM	Building Energy Management
BWM	Box Whisker Mean
CAV	Constant Air Volume
CS1	Case study 1
CS2	Case study 2
CVRMSE	Coefficient of Variation of the Root Mean Squared Error
DX	Direct Expansion
HDD	Heating Degree Days
HVAC	Heating, Ventilation and Air Conditioning
LED	Lighting emitting diode
LT	Low Temperature
MBE	Mean Bias Error
MT	Medium Temperature
NC	Night Cooling
ppm	Parts per million
RH	Relative Humidity
TRY	Test Reference Year
Tsurface	Surface Temperature
VC	Ventilative Cooling
VRF	Variable Refrigerant Flow

Symbols

T_{out}	Outdoor Temperature
T_{in}	Inside Temperature
T_{offset}	Difference between inside temperature and outdoor temperature
$T_{surface}$	Surface Temperature

food sales area <400 m^2 [13]. Energy analysis of supermarkets has shown that smaller stores are more energy intensive [5] and therefore in the desire to capture customers supermarkets might have overestimated their profit potential as convenience stores are more expensive to build and operate [14,15].

Food retail markets are complex environments designed to have high visibility display of goods with sufficient thermal comfort to encourage longer stay for the customers. The refrigeration requirements of the display goods and indoor environmental conditions are sometimes in conflict because of the significant heat exchanges between them. Thus, optimised control strategies for HVAC systems are required in order to achieve acceptable environmental conditions for customers and good operation of the refrigeration system.

One control strategy is Ventilative Cooling (VC) during non-operational hours at night. VC has been receiving attention in recent years because of the energy saving potential for all types of buildings. However, most published work focuses on residential and relatively simple in operation commercial buildings such as offices and schools [16]. A simplified tool to evaluate the potential of ventilative cooling has been developed [17], focussing on similar types of buildings [18]. However, the potential of ventilative cooling is also high in more complex buildings such as shopping malls and supermarkets but very few studies to date reports application to such buildings [19,20,21].

First, an analysis of the measured energy use and indoor environmental conditions of the two case study stores representing two different HVAC systems and associated controls but the same displayed products and refrigeration system is presented. Differences and similarities are discussed. It continues with the validated baseline model by EnergyPlus which enables the coupling approach of HVAC with the refrigeration system. This model is used for parametric analysis of the night ventilative cooling control strategy applied to evaluate potential of VC in different HVAC applications in comparison with active cooling during night.

2. Selected HVAC systems and description of case study supermarkets

HVAC systems in supermarkets can be divided into two categories:

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

The coupled HVAC system is the most common and provides air through overhead distribution ductwork to different parts of the store. The coupled HVAC systems can provide uniform air distribution in large areas with similar cooling requirements such as the retail shops and with the potential to incorporate heat recovery can be a very efficient and trustworthy solution. The decoupled HVAC system is a non-duct air conditioner where heat is transferred to or from the space directly by circulating refrigerant to evaporators. They are more sophisticated multi-split systems with many evaporators and refrigerant management and control systems. As they do not provide ventilation, a separate ventilation system is necessary. These systems are lightweight and modular and do not require big and specific structure on the roof of the buildings so they are convenient for retrofit installations. Condensing units are placed outside and as ducts are not needed, apart from ventilation system, building costs and space are saved. Energy efficiency is also improved due to the elimination of duct losses. Moreover, compressors are variable speed enabling the control of the required load. Maintenance costs include mainly the changing of filters and cleaning of coils.

Two case study stores were selected according the above categorisation. CS1 is a refurbished two storey building located in central west London using an all air constant air volume HVAC which represents the coupled HVAC case. CS2 is a new purposed built store located in a suburban commercial area in southern London. The heating and cooling requirements are fulfilled by a variable refrigerant flow (VRF) system and thus this store represents the decoupled HVAC case as there is separate ductwork for extract mechanical ventilation. The refrigeration systems are stand-alone which result to high internal heat gains due to heat released to the sales area from the condensers. For that reason, the cooling demand is higher than heating and mitigation actions of cooling requirements are essential [24].

The two case study stores (Fig. 1) belong in the same supermarket chain with similar products and same refrigeration equipment. CS2 has been presented and analysed in detail in [11] and in this paper both case study stores are analysed and compared. CS1 is in a city location and surrounded by commercial buildings. It is a refurbished two storey heavy–weight [22] building with the sales area (469 m^2) on the ground floor while the second floor is used as a storage area. The coupled HVAC system for the sales area is roof mounted AHU with a DX cooling coil (88 kW) and an electric heating coil (24 kW). The set point temperatures have been set to 19.5 °C for heating and 20.5 °C for cooling during trading times while cooling for non-trading hours (night cooling, NC) is in operation with 16 °C setpoint temperature. It is a Constant Air Volume (CAV) system which provides sales area with 6 m^3/s in trading hours through 11 four way diffusers, 1 three-way and 3 two way blow fixed blade diffusers. There is also an electric door heater rated at 18 kW. Ventilation rates for the exhaust system during trading hours are set to 6 ach for sales and 1 ach for the stor-

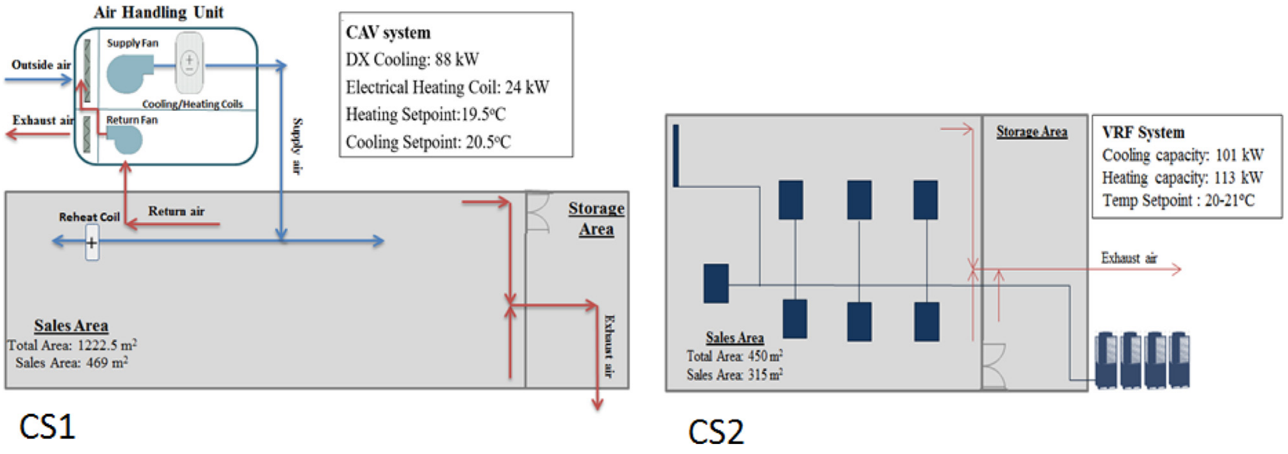


Fig. 1. Sales areas floor plan and HVAC systems description of CS1 and CS2.

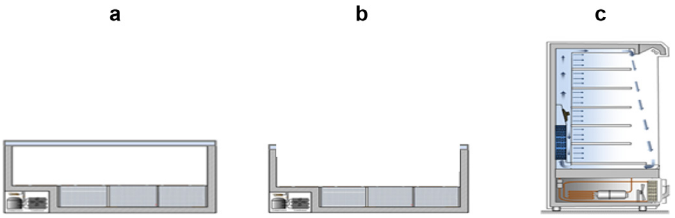


Fig. 2. a) LT lift-up lid frozen food cabinet, b) LT open top frozen food cabinet, c) MT open vertical cabinet.

age area. There are also supplementary extract ducts only above the open front multi deck cabinets whose warm air is either exhausted directly to the atmosphere or used to heat the storage area on the ground floor when heating is required. The lighting system is typical T8 type fluorescent for the sales area. They consist of luminaires with 3 lamps; 21 in the tills area and 63 in the display area. LED strips are installed in the north-east and back sides of the sales area which operate 24 h.

CS2, a medium-weight building [22], is in a typical small out-of-town retail centre. It is single storey newly built with 315 m^2 sales area. The decoupled HVAC system of the sales area is a VRF system for both heating and cooling. Two equally sized outdoor condensing units provide total heating output of 113 kW and cooling output 101 kW delivered to sales area only through 7 ceiling cassettes and 1 door heater. 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 staff area is by an extract fan operated 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 (3 ach). The lighting luminaires are typical T8 type fluorescent for the sales area. They consist of luminaires with 3 lamps; 23 in the tills area and 30 in the display area. LED strips are installed in the north-east and back sides of the sales area which operate 24 h .

For both case-studies, the refrigeration system consists of plugged-in cabinets and freezer and chiller coldrooms. The types of cabinets (Fig. 2) and the loads are presented in Table 1.

3. Monitoring results analysis

This section presents a comparison of the monitoring energy and indoor environmental conditions results of both case studies stores. Some preliminary results for CS2 have been already presented in [11] where the model development was presented. In this paper the data are comparatively presented focusing on the impact of different HVAC systems and controls on energy performance and resulting internal environmental conditions.

3.1. Energy use

Figs. 3 and 4 present an overview of hourly measured energy data using box whisker mean (BWM) plots. The mean hourly energy use of the months is presented based on hourly data. Fig. 3 shows 5 years data for CS1. Winter 2013 was colder than the other winters (approximately 535 higher HDD); therefore energy use is higher during this winter. The store has a consistent energy demand during cold months with average trading hours energy use at around 0.14 kWh/m^2 sa with peaks on warm months 0.18 kWh/m^2 sa before falling to the non-trading hours energy use (75th percentile). For CS2 (Fig. 2) winter 2015 was colder than 2014 (average HDD for June 2013–May 2014 was 1760 and for June 2014–May 2015 was 1908) and this resulted in higher energy use. CS2 presented an average 0.14 kWh/m^2 sa (25th percentile) during trading time with peaks on warm months at around 0.17 kWh/m^2 sa.

As the HVAC of the CS1 is not operating during night (in comparison with CS2 where HVAC is on 24 h) and only free night cooling is in operation, there is a difference between the non-trading time energy use between the two stores. CS2 energy use during non-trading times observed to be around 0.10 kWh/m^2 sa. On the other hand, energy use of CS1 during non-trading hours ranged from 0.09 to 0.12 kWh/m^2 sa.

Average annual energy use is 1103.3 kWh/m^2 sa for CS1 and 1117.3 kWh/m^2 sa for CS2 which are at the upper range of supermarkets and at the lower range of the convenience stores [11] because of the higher refrigeration load.

Fig. 5 presents the correlation of their daily energy use with the outdoor air temperature. It is observed that for both stores there is an outdoor temperature where the daily energy use is at its lowest level. This is around 9 °C for CS1 and between 8 °C and 12 °C for CS2. Above these temperatures the cooling requirements of the buildings increases and consequently the daily energy use; from 25% to 50% for CS1 and from 19% to 42% for CS2 The maximum daily energy use monitored for warm days is almost the same for both stores but slightly higher for CS1.

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

Table 1
Refrigeration equipment and loads of CS1 and CS2.

Case Study	Chilled food cabinets	Frozen food cabinets		Coldroom	
	Open front multi-deck cabinets	Lift up lid cabinets	Open top case frozen	Freezer	Chiller
CS1	10	70	3	60 m^2	12 m^2
Refrigeration Load	**20.3 kW**	**30.7 kW**		**30 kW**	**5.2 kW**
CS2	7	58	3	29 m^2	6 m^2
Refrigeration Load	**10.4 kW**	**26.3 kW**		**8 kW**	**2.3 kW**

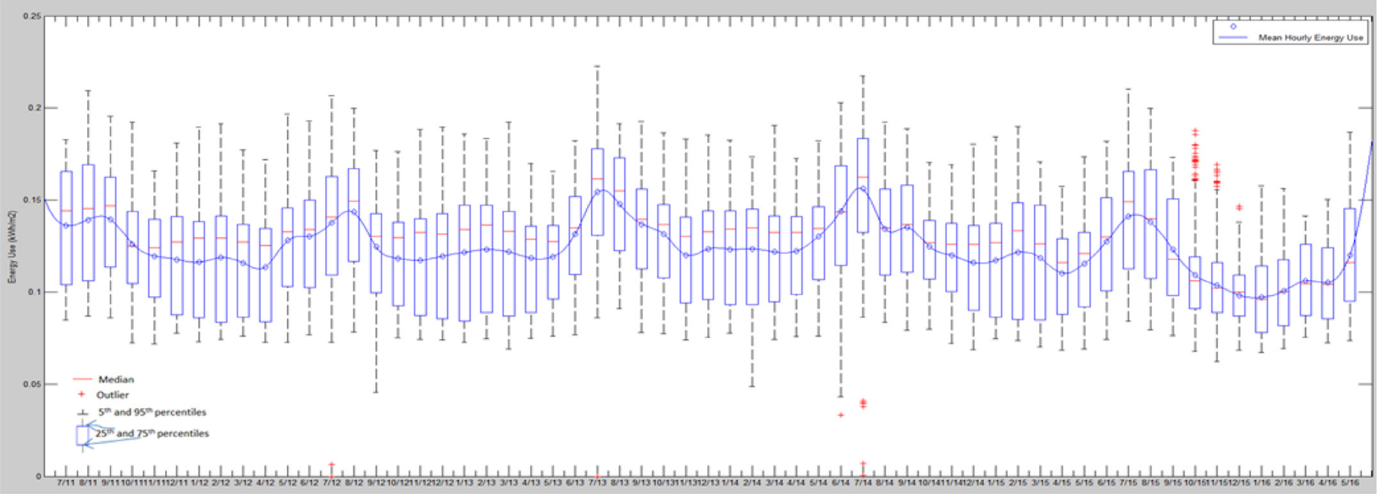


Fig. 3. BWM plot of hourly measured energy use per sales area (July 11–June 16).

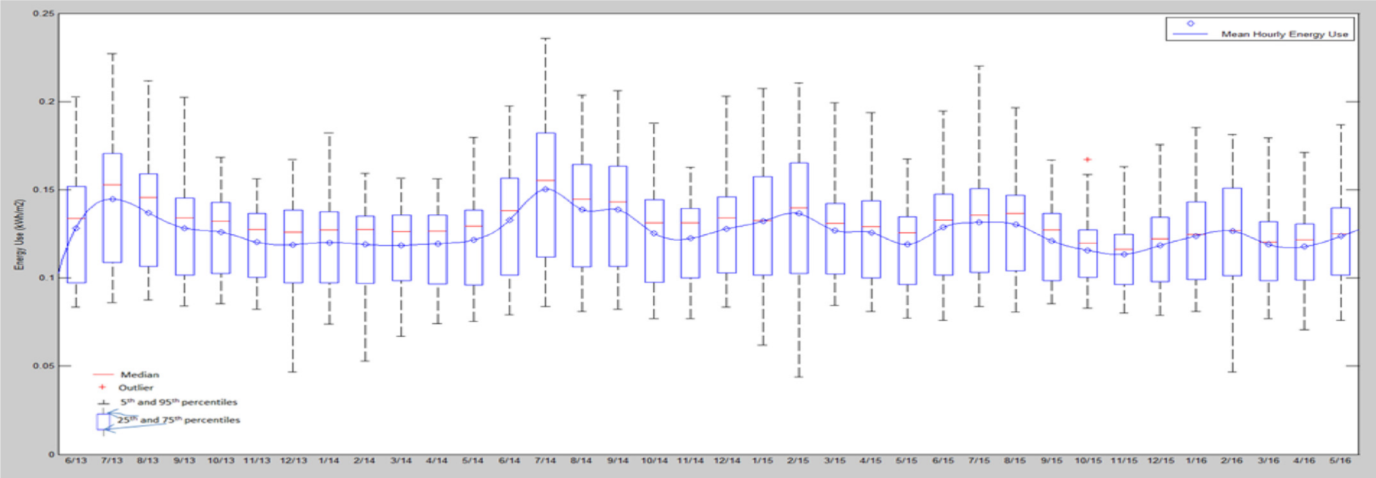


Fig. 4. BWM plot of hourly measured energy use per sales area (June 13–June 16).

CS2 resulted in higher heating requirements and thus higher daily energy use during cold days.

3.2. Indoor environmental conditions

Figs. 6 and 7 present the results in BWM plots for air temperatures for two months (July 2014 and December 2014), indicative for warm and cold periods respectively. In July and during trading hours, air temperature varied significantly between the days of the month and ranged between 22 °C to 24 °C for the tills area and 21 °C to 23 °C for the display area. July 2014 was the warmest month of this summer and during the days of the highest outside temperature the temperature inside the store (both tills and display area) reached 28 °C. For CS2, air temperature ranged between 22 °C and 23.5 °C in the tills area and between 19.5 °C and 22 °C in display area.

Internal patterns of temperature follow external maximum air temperatures and the continuous opening of the door and heat gains of the single glassed windows in both case study stores affect significantly internal air temperature. This is the reason why the air temperature in the display area differs from the air temperature measured in the tills area. This is observed more remarkably in the CS2 where the temperature in the display area found to balance around the setpoint temperature (21 °C) while the tills area presented temperature 1–2 °C higher or lower for warm months and cold months respectively. CS1 seemed to present insignificant fluctuations from the setpoint temperature (19.5 °C) for December while a bigger difference was observed for the July (1.5–2.5 °C above the setpoint).

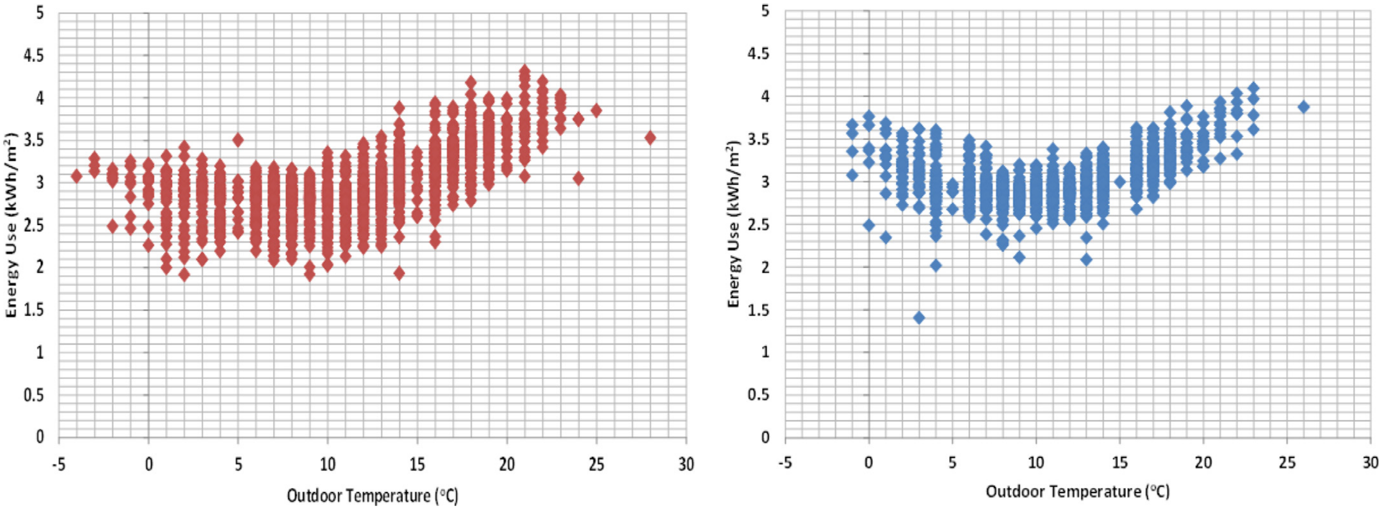


Fig. 5. Daily energy use per sales area according to different outdoor temperatures (left: CS1, right: CS2).

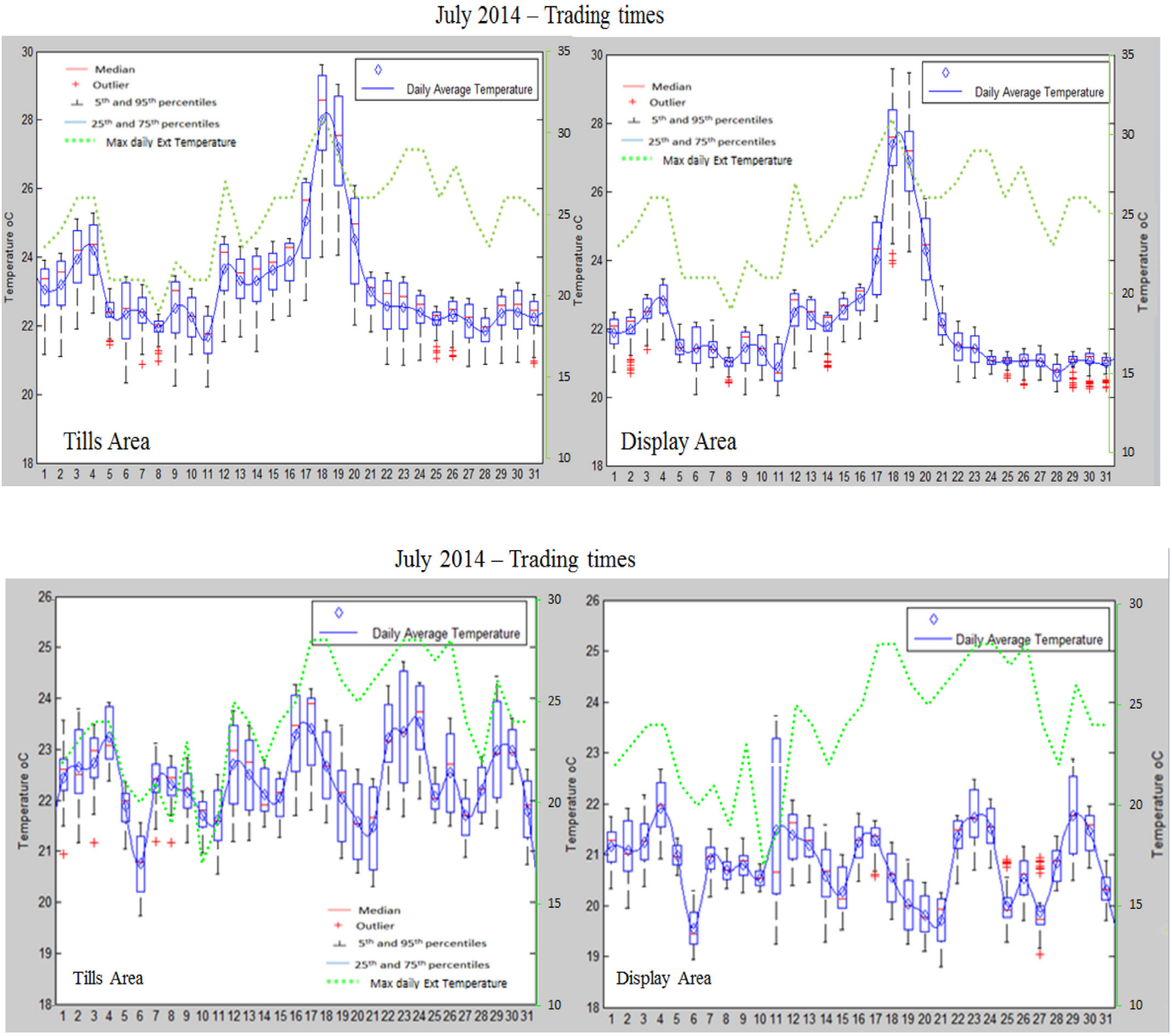


Fig. 6. BWM plots of measured air temperature in sales area (tills and display) for June 2014 during trading times (up: CS1, down: CS2).

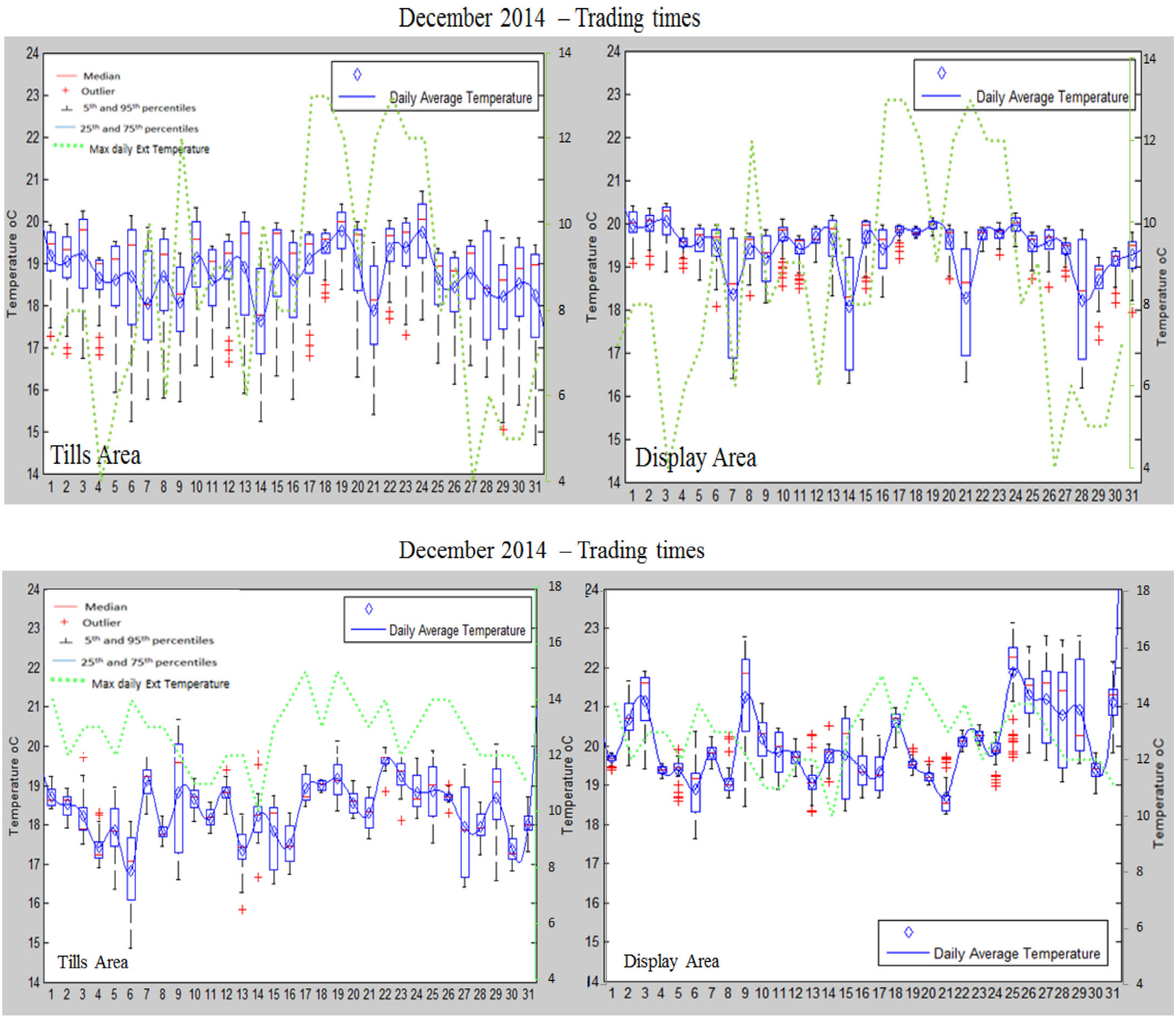


Fig. 7. BWM plots of measured air temperature in sales area (tills and display) for December 2014 during trading times (up: CS1, down: CS2).

According to measured data, a difference of 1–2 °C between tills and display area is observed. This is because the tills area is affected by the air infiltration of the continuous opening of the main entrance. Impacts on comfort during the extreme outside weather conditions were not analysed further as customers' visits in store does not exceed more than an hour. Recommendations [23] mention that there is no discomfort and health risk below 25 °C for summer period and above 19 °C. These values were not measured more than 2 h in order to create discomfort [24]. Moreover, electric door heater curtains are placed above the doors for maintaining acceptable environment in sales areas and helping to reduce energy losses from the conditioned area.

However, the temperature difference between tills and display area is taken into consideration in the model development where the sales area is separated into two thermal zones, tills and display area based on the observation of the recorded temperatures in different areas inside the sales area. For this reason different infiltration rates were used for the tills area and were approximately 80% higher than display area during trading times.

During non-trading times (Figs. 8 and 9), different control strategy is used for the two case study stores as described in Section 2. For CS1 where the ventilation is coupled with the heating and cooling system and the free cooling is in operation, the air temperature of the tills area ranged between 20 °C and 22 °C but reached up to 24 °C during the warmest days of the month. The same applies for the display area. During December the effect of the free night cooling is significant due to outside conditions permitting and the air temperature of both tills and display area varied between 16 °C (which is the minimum setpoint temperature that free night cooling is active) to 18 °C.

For CS2, where the ventilation is decoupled from heating and cooling system and the HVAC is in operation 24 h, during non-trading times of July, 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 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.

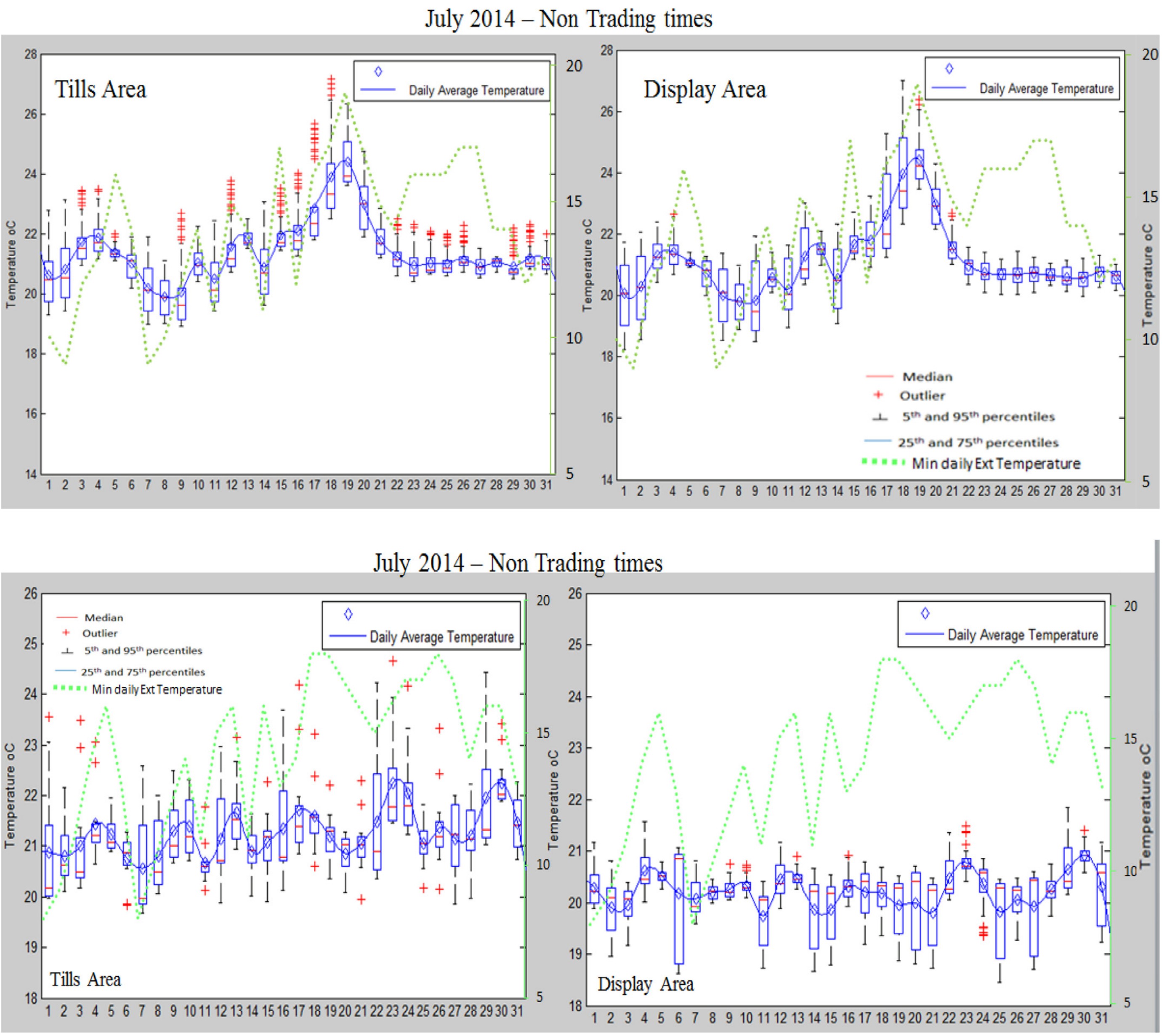


Fig. 8. BWM plots of measured air temperature in sales area (tills and display) for July 2014 during non-trading times (up: CS1, down: CS2).

In both cases, internal air temperature variations follow external daily minimum temperature pattern.

Relative Humidity (RH) does not present significant differences between tills and display areas; 40–75% for CS1 and 40–65% for CS2 for warm months and unremarkably lower in cold periods. Carbon dioxide concentration measurements ranged between 400 ppm during non-trading times and 650 ppm during trading times for both case study stores indication good ventilation provision [23,25].

4. EnergyPlus baseline model

4.1. Model development and verification

The model development of the baseline models and the verification methodology has been presented in [11] where the CS2 model development is presented in detail. The same methodology and procedure was followed for CS1.

Following two levels of calibration; level 1 based on available design data to create the as-built model and level 2 that included the as-built and operating information, the final thermal model for CS1 with 14 thermal zones was validated against measured data for both energy use and temperature conditions for a year. The building's annual energy use from June 2014 to May 2015 is 1103.6 kWh/m^2 sales area. The final calibrated model prediction is 1098.5 kWh/m^2 sales area (a deviation of −0.5%). Regarding CS2, the thermal model that was developed has 9 thermal zones and the final calibrated model prediction is 1104.3 kWh/m^2 sales area while the measured energy use from June 2014 to May 2015 was 1143.4 kWh/m^2 (a deviation of 3.4%). Figs. 10 and 11 enable a quick visual inspection of measured and simulated energy use for two indicative weeks. Fig. 10 refers to CS1 while Fig. 11 to CS2.

ASHRAE Guideline 14-2002 defines the evaluation criteria to calibrate a simulation model. Monthly and hourly data, as well as spot and short term measurements can be used for calibration. Mean Bias Error (MBE) and Coefficient of Variation of the Root

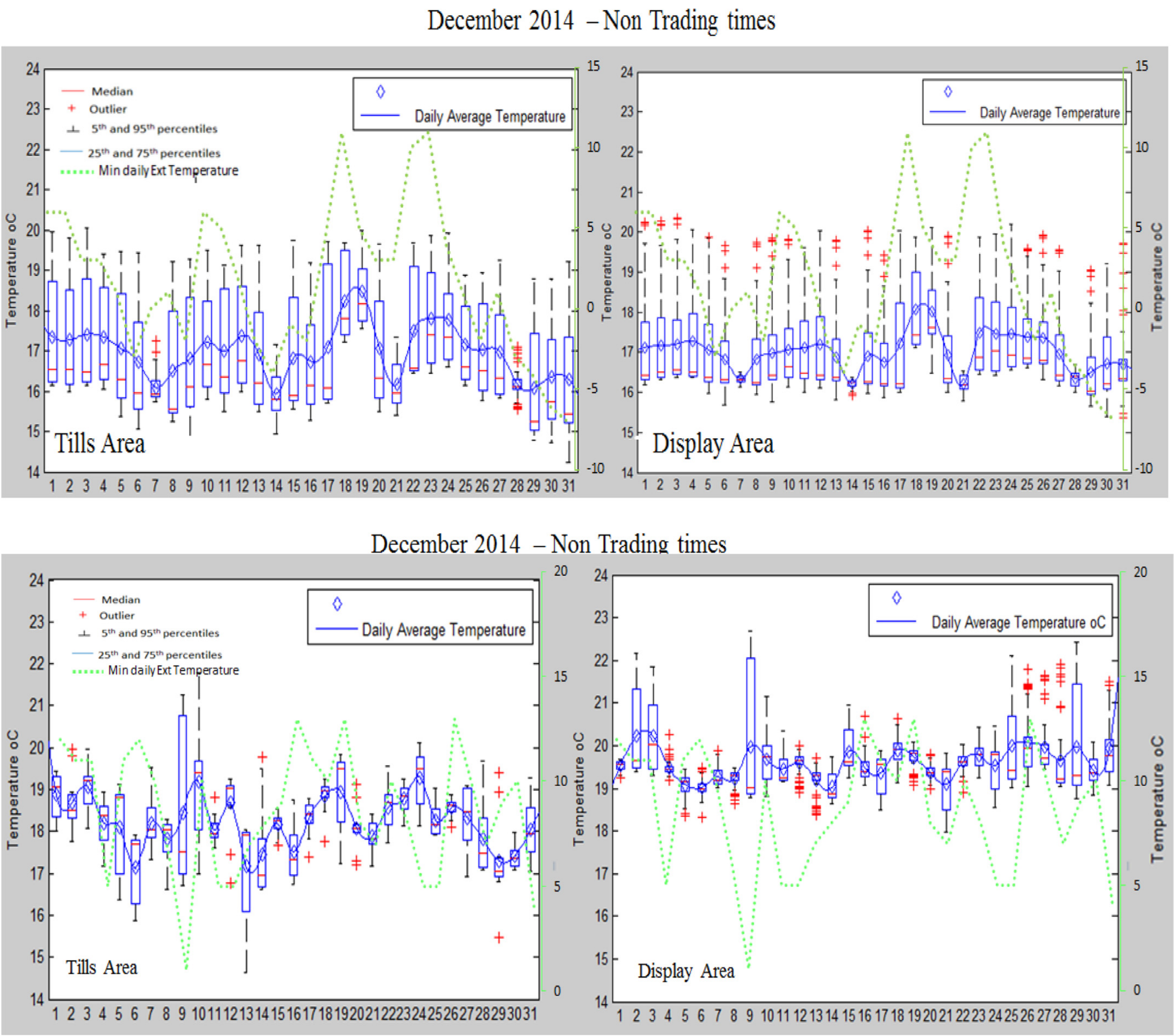


Fig. 9. BWM plots of measured air temperature in sales area (tills and display) for July 2014 during non-trading times (up: CS1, down: CS2).

Mean Squared Error (CVRMSE) are used to evaluate the model uncertainties [26].

According the results (Fig. 12), both case study stores EnergyPlus models presented MBE and CVRMSE values within acceptable limits for both energy use and indoor air temperature. Further analysis regarding the model validation is given in [11]. After that a calibrated EnergyPlus model with verified energy systems (CAV & VRF HVAC system and refrigeration system) is used for the parametric analysis for optimisation of NC control strategy applied in both coupled and decoupled HVAC systems. 403

4.2. Description of NC operation and control strategy

Most supermarkets use active cooling system to meet big cooling requirements during trading times while sales area temperature rise after active cooling stops. When NC is in operation, the heat stored at night will be released to the air during the next day to delay the increase of the room temperature.

A previous study for night ventilation implementation to a supermarket has concluded that longer night cooling activation results to fewer hours of AC system operation and higher energy savings [21]. However, studies for offices and other non-domestic building have indicated that three control aspects should be taken into consideration [27]; duration, system initiation and system continuation in order to maximise energy savings. In this case study, the following rules were implemented:

i) initiation: $T_{out} < T_{in}$,
ii) continuation: $T_{out} < T_{in}$ and $T_{out}-T_{in} < T_{offset}$
iii) termination: continuation rule and $T_{in} = T_{min}$

The continuation rule ensures that the outside air brought in is effective in cooling the building. When the temperature difference between inside and outside air (T_{offset}) is low, the incoming air will have little effect on cooling while the ventilation fan energy use will increase the total energy use. However, if the outside air temperature is significantly lower than the inside air tempera-

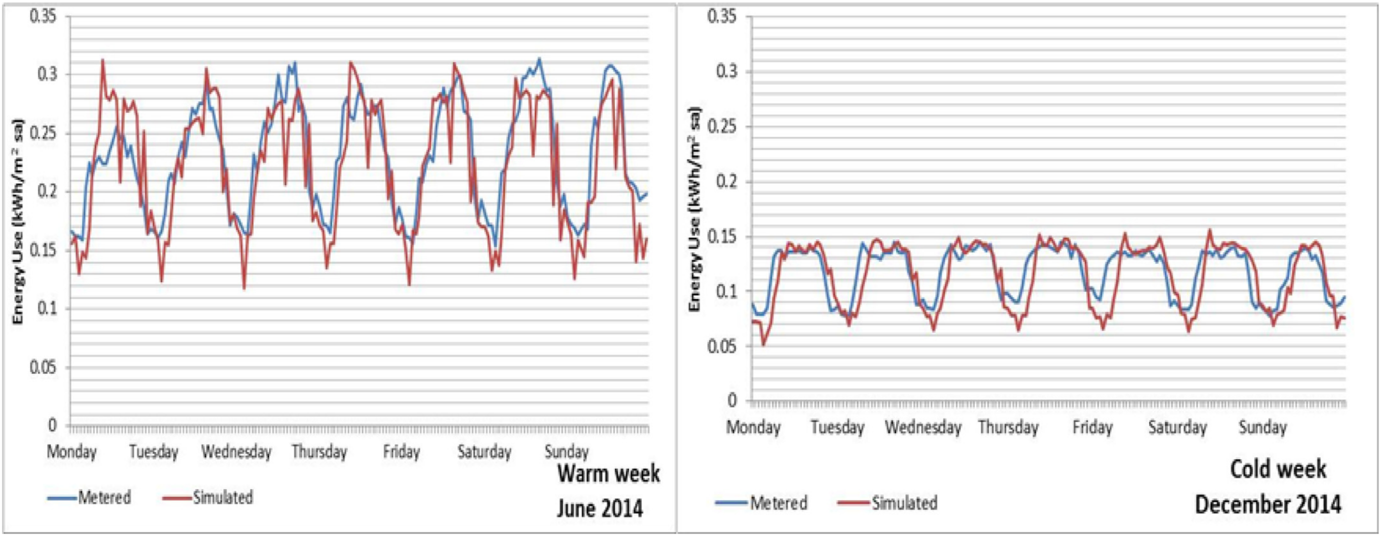


Fig. 10. Comparison between metered and simulated hourly energy use for an indicative warm and cold week, CS1.

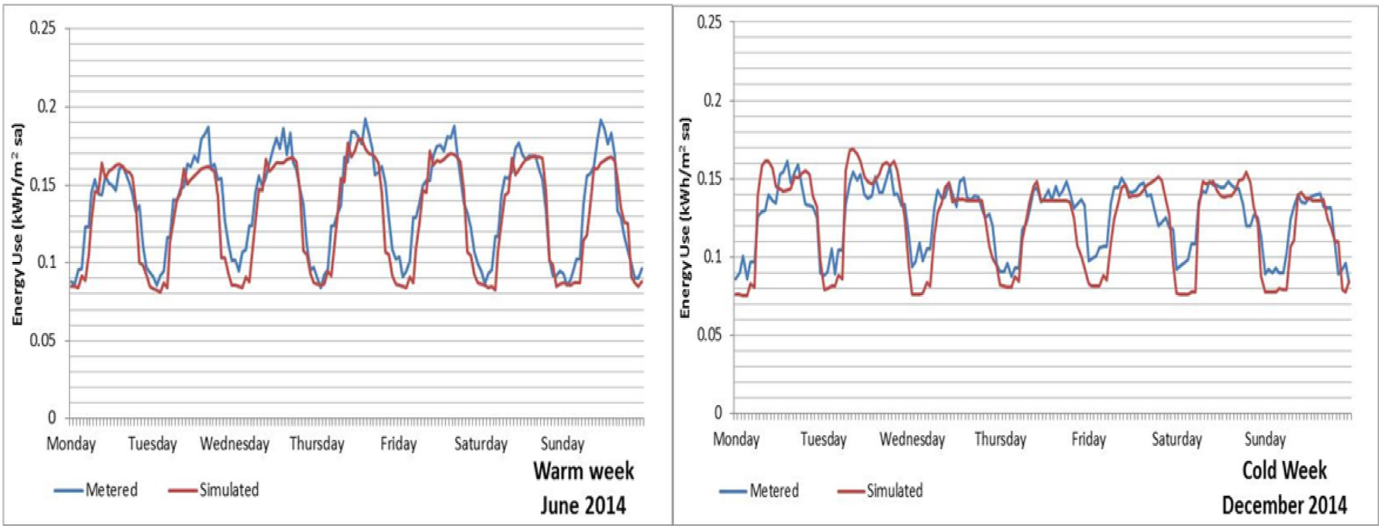


Fig. 11. Comparison between metered and simulated hourly energy use for an indicative warm and cold week, CS2.

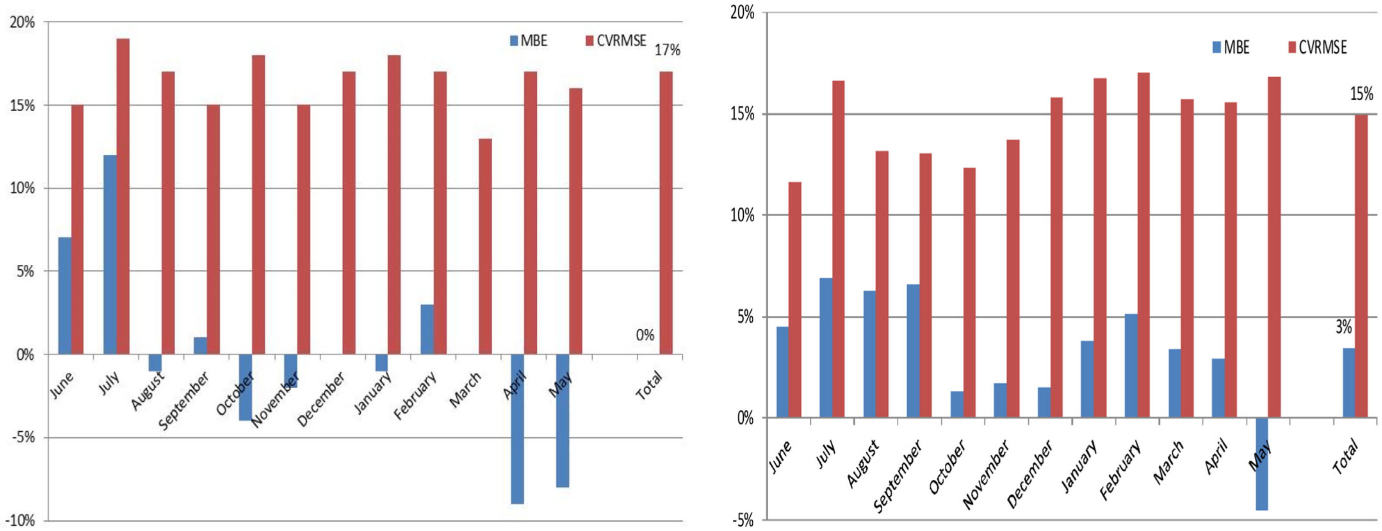
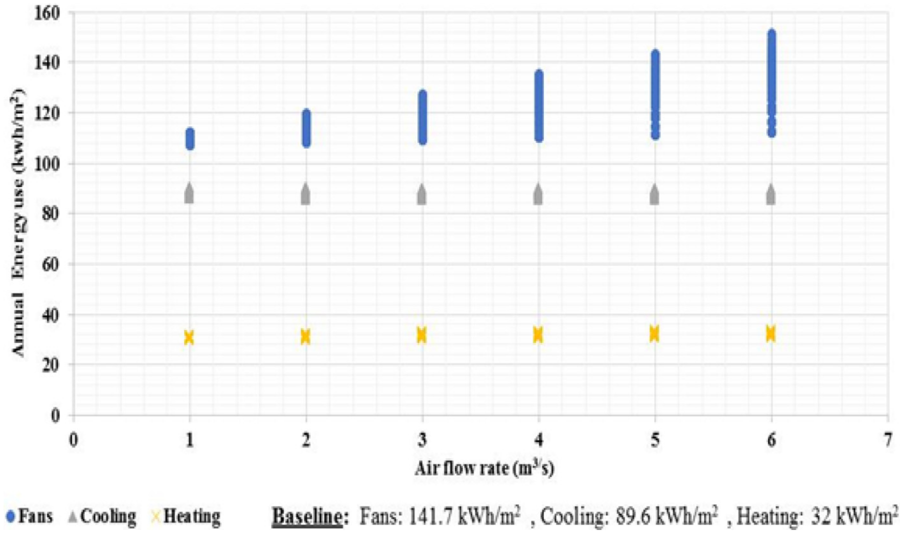


Fig. 12. MBE and CVRMSE analysis of the energy use based on hourly data.



Baseline: Fans: 141.7 kWh/m², Cooling: 89.6 kWh/m², Heating: 32 kWh/m²

Fig. 13. Heating, cooling and fans energy use for different air flow rates.

ture, T_{min} will be achieved fast and the duration of night ventilation is decreased [28].

Moreover, although NC could increase the total energy savings of the stores, attention should be paid in the air conditions (temperature and RH) brought in store as it may affect the cold surfaces of the cabinets from condensation or it may be harmful to the operation of the refrigeration system or its controls. The stores' LT cabinets are glass lift up lid cabinets which during NC operation remain closed so the evaporator coils are not affected by the ambient air (if hot or humid) and thus crucial problems are not created in the evaporator coils operation. However, action might be taken to prevent condensation on the surface of the glass. Fogging and risk of condensation on the external side of the glass or the multi deck cabinets' curtains might occur in humid climatic conditions while reducing the ambient temperature. For that reason, experimental results from laboratory test in the CSEF centre facilities took place in order to evaluate the $T_{surface}$ of the glass lid of the LT cabinets (which occupy the vast majority of the sales area). This temperature gives insights of the RH levels that must be maintained in the sales area in order to prevent condensation on the glass lid. According to monitoring results, the surface temperature of the cabinet's glass lid is not affected significantly from the temperature inside the frozen food cabinet but from ambient conditions and does not fall to low enough temperatures where the high relative humidity could create condensation problems. Taken into account that at 10 °C ambient conditions the surface temperature of the glass lid is around 7 °C, RH should not exceed 85% [24].

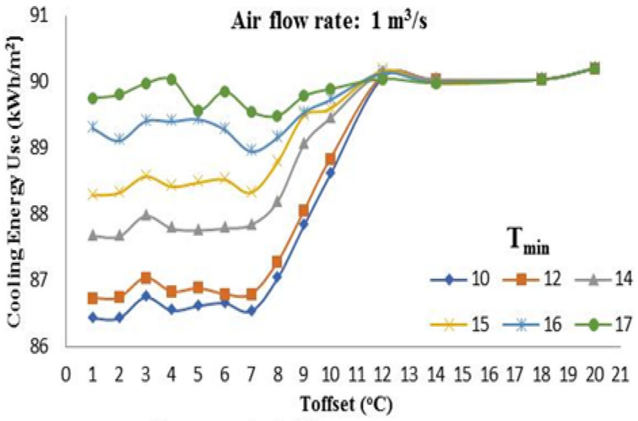
The parametric analysis was carried out with the Test Reference Year (TRY) weather file from CIBSE.

5. Results and discussion

5.1. Coupled HVAC system

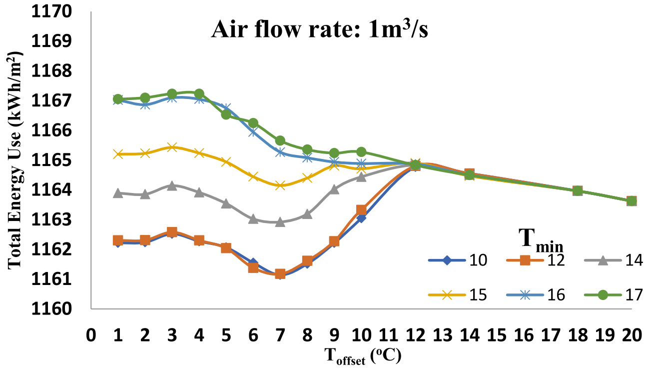
NC is already in operation in store with coupled HVAC system during non-trading times. The system is designed to provide free night cooling with 6 m^3/s when the return air and outside air temperature have 1 °C difference and until the inside temperature reaches 16 °C.

The parametric analysis was performed for different airflow rates according to fan speed (1–6 m^3/s), T_{offset} (1–20 °C) and T_{min} (10–17 °C). Minimum temperature inside the store was chosen not to fall below 10 °C in order to avoid condensation on the glass cabinets. Setting the T_{min} to the lowest levels (10 °C) glass surface temperature monitoring was taken into account to avoid risk of condensation on the glass lid as explained in Section 4.2.



Baseline: Cooling: 89.6 kWh/m²

Fig. 14. Cooling energy use for different T_{offset} and T_{min}.



Baseline: Total Energy Use: 1196.5 kWh/m²

Fig. 15. Total energy use for different T_{offset} and T_{min}.

Fig. 13 presents fan, heating and cooling energy use for different air flow rates, T_{offset} and T_{min}; the combinations are integrated and are presented as a range of energy use in the graph. Fig. 14 presents the cooling energy use for different T_{offset} and T_{min}. The air flow rate during night cooling plays an important role as

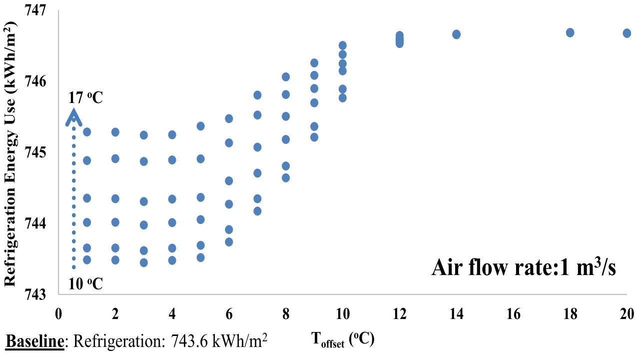


Fig. 16. Refrigeration energy use for different T_{offset} and T_{min}.

the higher airflow increases the fans' energy use. However, low air flow rates could have similar effect on cooling demand with a reduction of heating requirements during the following day. In Fig. 13, the fans' annual energy use range is indicated as a result of the different T_{offset}. Higher air flow rate has wider range because the reduction of the internal temperature to T_{min} is achieved fast and the duration of the NC is decreased.

For lower air flow rates there is a point where the maximum total energy use reduction occurred; energy use starts increasing until reaching the point where NC is not effective (total energy use equals the total energy use when NC is off) (Fig. 15). This is due to the increase of the cooling energy which afterwards leads to an increase of the total energy use (Fig. 14). This point is observed to range between 5 and 7 °C. Refrigeration system energy use decreases with lower T_{min} but after 5–7 °C T_{offset} starts increasing again until the refrigeration energy use observed when NC is not in operation (Fig. 16). The optimum combinations of parameters leads to up to 3% of the total energy use from the baseline model – this equates to energy use reduction of 35.3 kWh/m²/year in the store which is mainly due to the 10% reduction of the HVAC energy use.

Finally, Fig. 17 summarises the significance of the optimised control strategy of the HVAC system for NC operation with the optimum T_{offset} in order to achieve the biggest energy total energy reductions. It presents gathered results for lower air flow rates and setpoint temperatures to indicate their significance in the total results. Lower air flow rates reduce the fans energy use and enable the bigger duration of the NC and thus the total energy use reduction. Moreover, lower T_{min} inside the store reduces slightly the cooling demand of the store in comparison with the baseline model (dark blue) without affecting negatively the refrigeration system operation.

5.2. Decoupled heating/cooling from ventilation

For store with decoupled heating/cooling from ventilation, two different ways of providing night cooling were studied; exhaust and intake night ventilation. The same parameters as before were used for the parametric analysis; different airflow rates according to fans speed (1–10 ach), T_{offset} (1–20 °C) and T_{min} (10–17 °C).

The HVAC control strategy of the store changed to facilitate night ventilation as follows: operation between 6:00 to 23:00 for weekdays and Saturdays and 9:00 to18:00 for Sundays rather than 24 h of the baseline model. This change alone would save 41 kWh/m² sales area per year without any effect on the refrigeration system operation and consumption but with significant decrease in the HVAC due to reduction in fans energy use and cooling requirements.

Without any change to the equipment of HVAC system, optimised control strategy for exhaust NC resulted that the lower air flow rates lead to bigger total energy use reduction due to reduced fans energy consumption (Fig. 18). Higher air flow rates presented to have strongest correlation with the T_{offset} as mentioned for case store with coupled HVAC system; while T_{offset} increases, a sharper reduction is occurred and this is because the cold air that is brought inside has bigger effect on the inside air temperature and T_{min} is achieved quickly and thus the duration of the NC is decreased.

It is also observed that for low air flow rates there is a specific T_{offset} where the total energy use starts slightly increasing ($T_{offset} > 5$ °C). After that point, where the optimum total energy use reduction occurs, the cooling energy demand increases and with higher T_{offset} the cooling energy use increases more significantly as the NC is not more effective (Fig. 19). For higher air flow rates this T_{offset} increases up to 7 °C. The optimum combinations of the parameters lead to 3.6% reduction in the total energy use which equals to 40.8 kWh/m² per year. In other words, by replacing the active cooling with NC during non trading times, a reduction up to 17% is achieved in cooling demand and the same 17.5% in fans annual energy use.

Refrigeration energy use was found to follow the same pattern with what was analysed previously in Section 5.1; after a specific T_{offset} refrigeration energy use increases to the levels that NC is no more effective.

For intake NC the results agreed with what has been discussed for exhaust NC control strategy. The air flow rate is a key parameter for the NC and the lower air flow rates lead to lower total

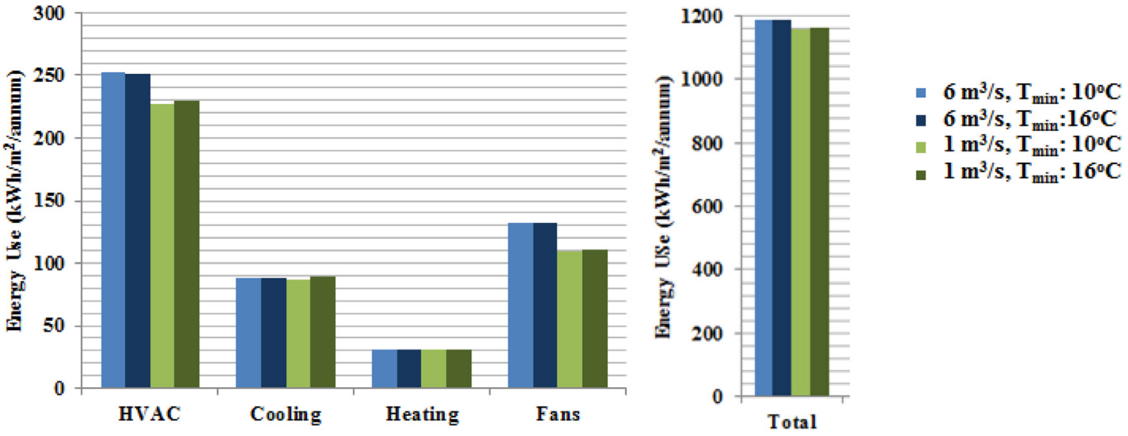


Fig. 17. Total annual energy use and sub-systems energy use for different air flow rates and T_{min}, coupled HVAC.

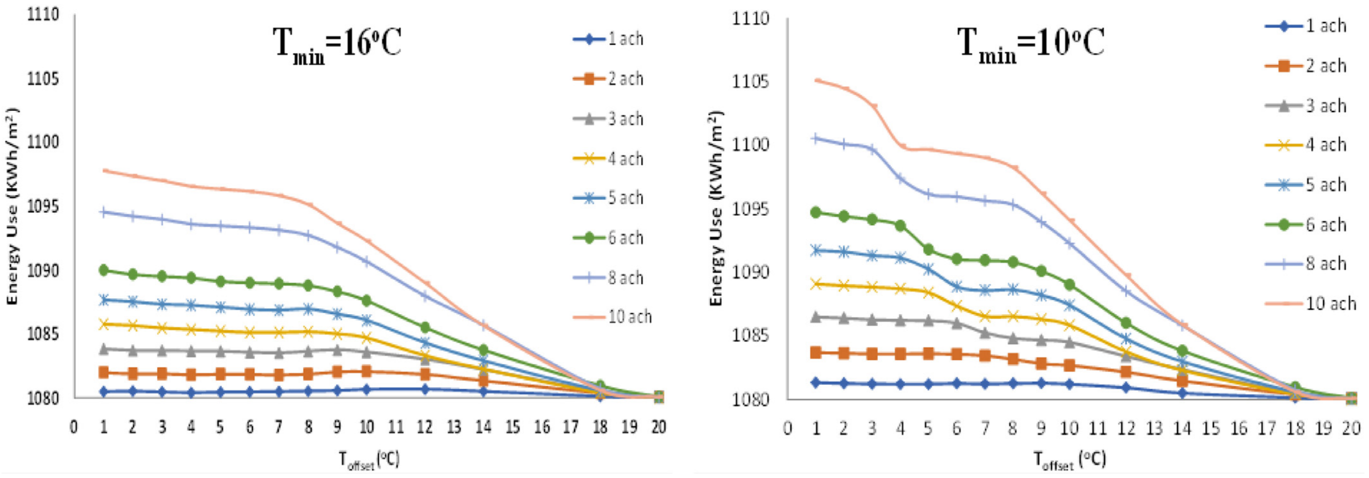


Fig. 18. Total energy use with different air flow rates for different T_{offset} and specific T_{min}.

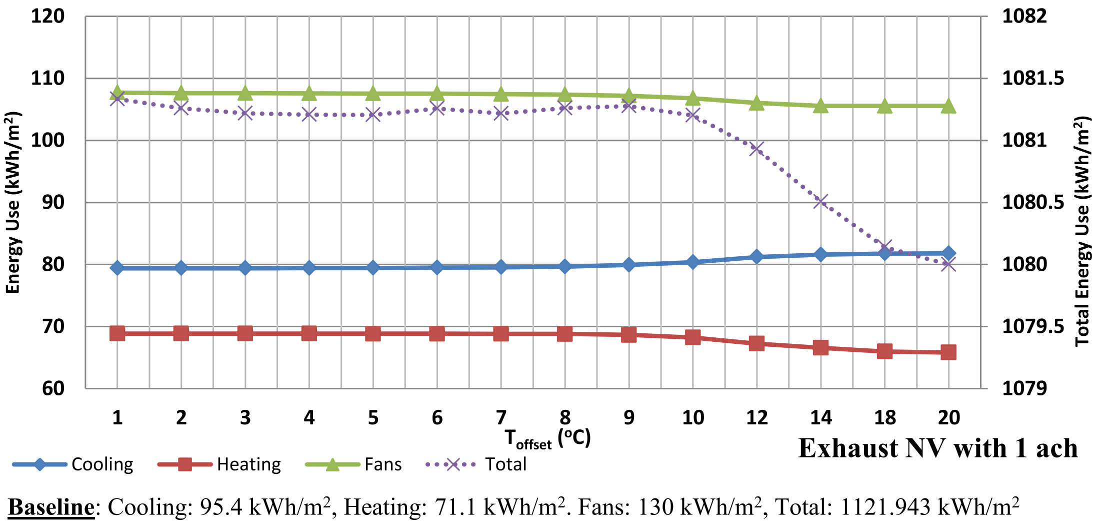


Fig. 19. Cooling, heating and fans energy use for different T_{offset} for $T_{min} = 10$ °C and with 1 ach air flow rate.

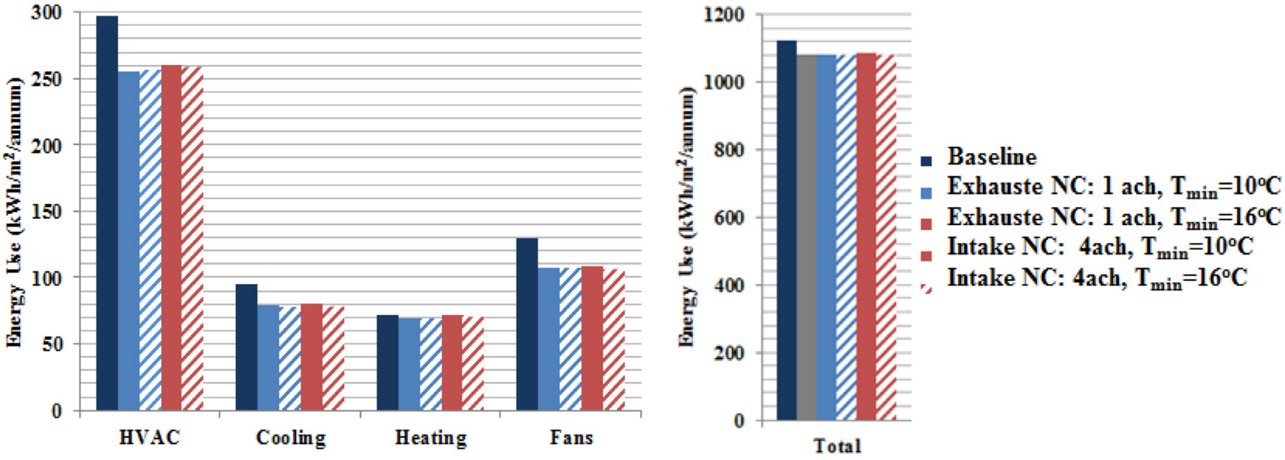


Fig. 20. Total annual energy use and sub-systems energy use for different air flow rates and T_{min}, CS2.

energy use due to fans energy use decrease but with the same effect of night cooling due to the fact that the night cooling duration is bigger. However, as is proposed for stores with coupled HVAC systems, for lower air flow rates there is point that the cooling requirements start increasing and NC is no more effective ($T_{offset} > 7$ °C). With higher T_{offset} than 2 °C, although the cooling energy demand increases, the fans energy use drops more significantly and leads to lower total energy use. The highest total reduction observed for lower air flow rates. As the T_{min} increases, the duration of the NC is decreasing and unremarkable reduction is observed on the total energy use. A reduction of around 3.2% on the total energy use (35 kWh/m^2/annum) is calculated for this case of decoupled HVAC system with intake night ventilation.

Fig. 20 summarises the significance of the optimised control strategy of the HVAC system for NC operation for decoupled HVAC system in operation. It includes results from both exhaust and intake NC. Lower air flow rates are presented as they are lead to the highest reductions in all systems due to reduction in fans energy use. Lower T_{min} inside the store results in same reduction as higher T_{min} because different T_{min} is not as strongly correlated with the cooling demand. This can be explained by the fact that the case with coupled HVAC system is a heavy-weight building and is able to store the amount of cooling energy better than the case store with decoupled HVAC system which is a medium-weight building.

6. Conclusions

Two frozen food supermarkets were monitored (energy use and environmental conditions) and an EnergyPlus model was developed and validated against measurements. Night ventilative cooling, taking into account interaction with HVAC and refrigeration systems, was explored as a strategy to reduce energy use. A passive cooling through night ventilation coupled with active cooling is proposed as a solution for supermarkets with high cooling requirements such as frozen food supermarkets with plugged in refrigeration equipment. Cold climates such as London enable this strategy to cool indoor environment during non-trading times. The potential of night ventilative cooling for supermarkets with high cooling requirements was investigated for implementation coupling with most common active cooling strategies (coupled and decoupled HVAC systems).

It was proven that NC in combination with high building mass has a potential to reduce the working hours and thus the cooling energy use of the next day active cooling. Parametric analysis for the optimisation of NC control strategy resulted to the followings:

- Night ventilative cooling has good potential for the specific case studies as they include high refrigeration loads which are delivered with plugged-in cabinets. Cooling demand is significant higher than heating.
- Control strategy for night ventilative cooling plays an important role as proved in CS1 where night ventilative cooling is already in operation but with better controls bigger reductions are achieved.
- CS2 is cooled during the night to maintain the setpoint 24 h. Implementing free exhaust or intake night ventilative cooling leads to a reduction in the total energy use.
- Simulations indicate that longer period of night ventilative cooling operation leads to higher energy savings enabled by lower air flow rates which have a small impact on fans energy use but cool effectively as longer period is needed to reach T_{min}.
- Inside-outside temperature is an important night ventilative cooling parameter. Parametric analysis indicated that optimum savings occurred if the air inside the stores has 5–7 °C difference with the outside air. The higher the air flow rate, the higher this difference should be for better changes.
- With night ventilative cooling, cooling demand during the day is decreased in both stores.
- Refrigeration system energy use has an unremarkable reduction; with T_{offset} higher than 5–7 °C, refrigeration energy use starts increasing until it reaches energy use without NC.
- Although night ventilative cooling has good potential for total energy savings of the supermarkets, condensation problems might arise on the glass surface of the frozen food cabinets and care should be taken in the selection of the control parameters.

By only optimising the parameters affecting the night ventilative cooling will result in annual total cost savings of around £3000–£5000/annum/store compared to baseline models. Assuming a medium sized supermarket chain with 1000 stores in UK where night ventilative cooling has great potential due to the weather conditions with low enough night outdoor temperatures, approximately £3–£4.7 million per year could be saved by optimising the control strategy of the night ventilative cooling.

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