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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

Night ventilation is used extensively as a low energy strategy to cool buildings in climates where night temperatures are suitable. It can be used for spaces utilising natural or mechanical ventilation systems as well as active refrigerant cooling. Most published work focuses on domestic and relatively simple in operation commercial buildings such as offices. This paper presents a study of the cooling benefits of night ventilation for frozen food supermarkets with high cooling demand. Supermarkets present a unique space conditioning challenge because of the interaction between the HVAC system and the refrigerated display cabinets. HVAC systems are the largest consumer of energy after refrigeration in supermarkets depending on system design, geographical location and controls. The most common HVAC system used in supermarkets is the constant air volume (CAV) system integrating heating, cooling and ventilation in one system although different types of systems to decouple cooling and ventilation such as a combination of variable refrigerant flow (VRF) for heating and cooling and mechanical balanced or extract ventilation have been tried out to improve thermal comfort and reduce energy use.

This paper presents two case-studies (CS) which differ from typical supermarkets as they belong in a frozen food supermarket chain. CS1 is served by a typical CAV system for heating, cooling and ventilation (coupled HVAC), while CS2 provides conditioned air through a VRF system and ducted extract ventilation (decoupled HVAC). First, an analysis of their measured energy use and indoor environmental conditions is presented to highlight similarities and differences of the two systems. Then, a coupling approach for dynamic simulation of the air-conditioning with the refrigeration system by EnergyPlus is presented and the resulting models are validated against the monitored data from the two case-study supermarkets. Using the validated models, 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. The parametric analysis indicates that the air flow rate of night ventilation and climatic conditions are significantly correlated with the impact of night ventilation on the total energy consumption of the supermarket. Simulations have revealed that night ventilation results to lower cooling energy use for both HVAC systems. Night ventilation is in use in CS1 but optimised control strategy with lower air flow rate reduced the total annual energy use of the store by 3% due to reduction in fan energy use and active cooling, although refrigeration energy use was remain stable. In CS2 active cooling during the night is replaced with night ventilative cooling which leads to a reduction of energy use by 3.3%. Such a percentage reduction equates to 35 kWh/m^2/annum. The paper discusses the differences of the two systems (all air or decoupling of ventilation from heating/cooling) in terms of HVAC energy use, total energy use, impact on the refrigeration system and the importance of controls for the night ventilative cooling.

KEYWORDS

Supermarket, Energy Use, HVAC, Night Ventilation, EnergyPlus, Frozen food, Environmental and Energy monitoring

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 fact energy consumption in food supermarkets is around 3.5% of the total UK energy consumption (Tassou et al., 2011). Currently, there are over 1 million supermarkets in Europe (CREATIV, 2014). 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 (CREATIV, 2014).

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

Night Cooling (NC) has been receiving attention in recent years because of the energy saving potential mainly in buildings with reasonably high thermal mass. Most published work focuses on domestic buildings and offices. This paper is a study for the energy use and the potential for savings due to mechanical night ventilative cooling of the HVAC systems of frozen food supermarkets. Few studies to date have considered ventilative cooling strategies for supermarkets (Li-Xia Wu et al., 2006).

Many supermarkets use all air constant volume systems as the HVAC system. This system provides ventilation, heating and cooling by conditioning air in the central plant and providing it through overhead distribution ductwork to different parts of the stores, termed coupled HVAC. However, there are many supermarkets which use ceiling mounted cassette type air recirculating units for cooling and/or heating. In other words, the heating and cooling systems are decoupled from the ventilation which is provided through separate (usually exhaust only) ductwork, termed decoupled HVAC.

The 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 with ceiling mounted cassettes in the sales area and represents the decoupled HVAC case as there is separate ductwork for extract mechanical ventilation. The refrigeration systems are stand-alone which cause remarkably 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 (Mylona et al., 2017).

Firstly, an analysis of the measured energy use and indoor environmental conditions of the stores is presented and the differences that observed are discussed. It continues to present the baseline models developed by EnergyPlus which enables the coupling approach of HVAC with the refrigeration system. The models are used for parametric analysis of the NC control strategy applied to stores as NC could reduce the high cooling requirements.

2 CASE STUDY STORES CONFIGURATION

The two case study stores that were selected belong in the same supermarket chain with similar products and refrigeration system but different HVAC systems. CS1 is in a city location and surrounded by commercial buildings. It is a refurbished two storey heavy – weight (BS EN ISO 13790:2008) 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 (88kW) and an electric heating coil (24KW).

The set point temperatures have been set to 19.5°C for heating and 20.5 °C for cooling. It is a Constant Air Volume (CAV) system which provides sales area with 6 m^3/s in trading hours through 11 four way diffusers, 1 three-way and 3 two way blow fixed blade diffusers. There is also an electric door heater rated at 18kW. Ventilation rates for the exhaust system during trading hours are set to 6 ach for sales and 1 ach for the storage 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 24hrs.
CS2, a medium-weight building, 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 24h 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 24h hours. Ventilation rates for the exhaust system during trading hours have been set to 6 ach for staff areas and sales area, 10 ach for restrooms and cloaks and 1 ach for the storage area. During night time the exhaust fan is set to lower speed (3ach). 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 24hrs.
The refrigeration system consists of plugged-in cabinets and freezer and chiller coldrooms. The types of cabinets and the loads are presented in Table1.

Table 1: Refrigeration equipment and loads of CS1 & CS2

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

3 MONITORING RESULTS ANALYSIS

3.1 Energy Use

Figure 1 and 2 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. Figure 1 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 (Figure 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 24h) 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 at the upper range of supermarkets and at the lower range of the convenience stores (Mylona et al., 2017) because of the higher refrigeration load.

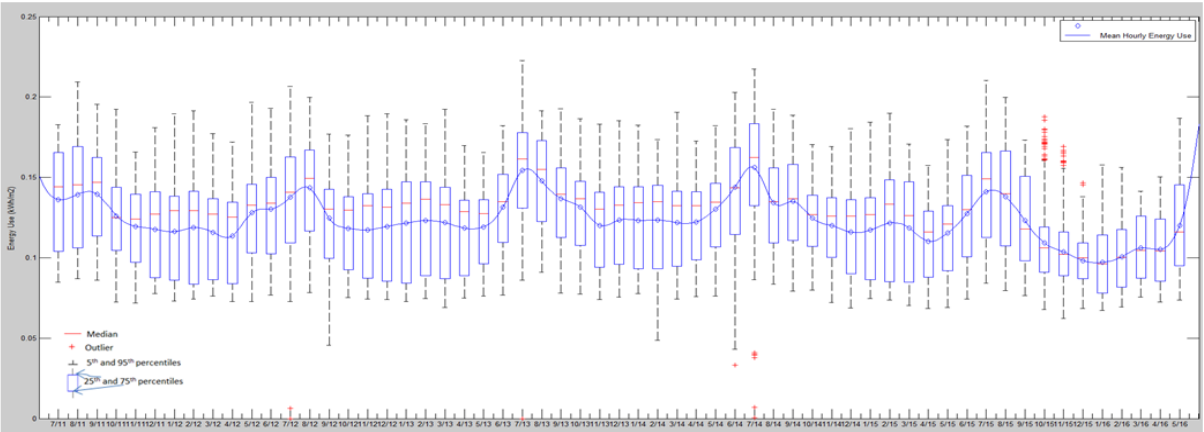


Figure 1: BWM plot of hourly measured energy use per sales area (July 11- June 16)

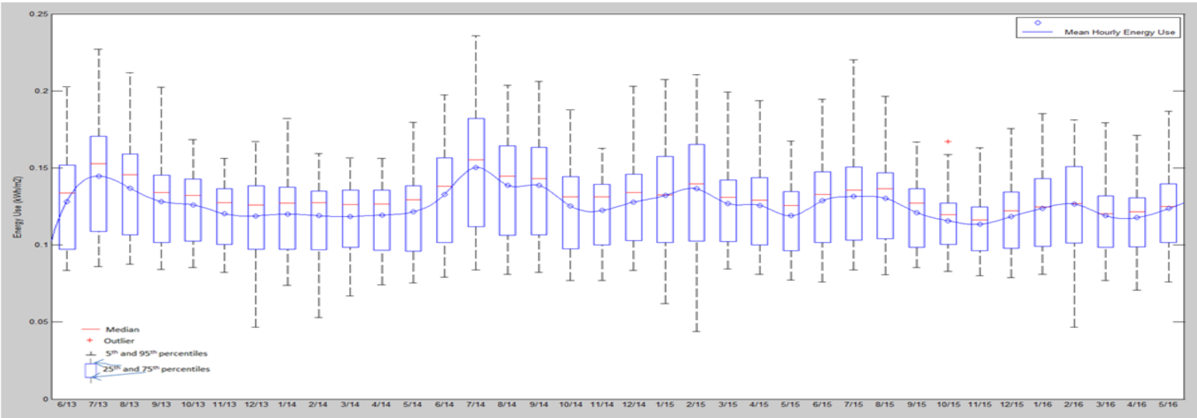


Figure 2: BWM plot of hourly measured energy use per sales area (June 13- June 16)

Figure 3 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 to 12°C for CS2. Above these temperatures the cooling requirements of the buildings increases and consequently the daily energy use; from 25%-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 24h HVAC system, presented lower daily energy use during cold days. The 24h HVAC system in CS2 resulted in higher heating requirements and thus higher daily energy use during cold days.

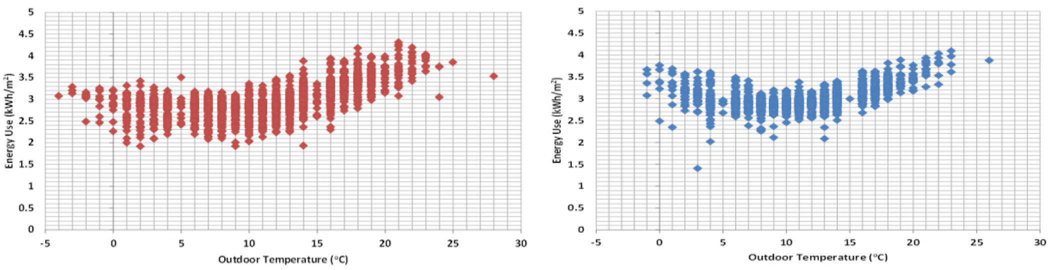


Figure 3: Daily Energy Use per sales area according to different outdoor temperatures (left: CS1, right: CS2)

3.2 Indoor environmental conditions

Figures 4 and 5 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^{o}C to 24^{o}C for the tills area and 21^{o}C to 23^{o}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^{o}C. For CS2, air temperature ranged between 22^{o}C and 23.5^{o}C in the tills area and between 19.5^{o}C and 22^{o}C in display area.

Internal patterns of temperature seems to 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^{o}C) while the tills area presented temperature 1^{o}C to 2^{o}C higher or lower for warm months and cold months respectively. CS1 seemed to present insignificant fluctuations from the setpoint temperature (19.5^{o}C) for December while a bigger difference was observed for the July (1.5^{o}C to 2.5^{o}C above the setpoint).

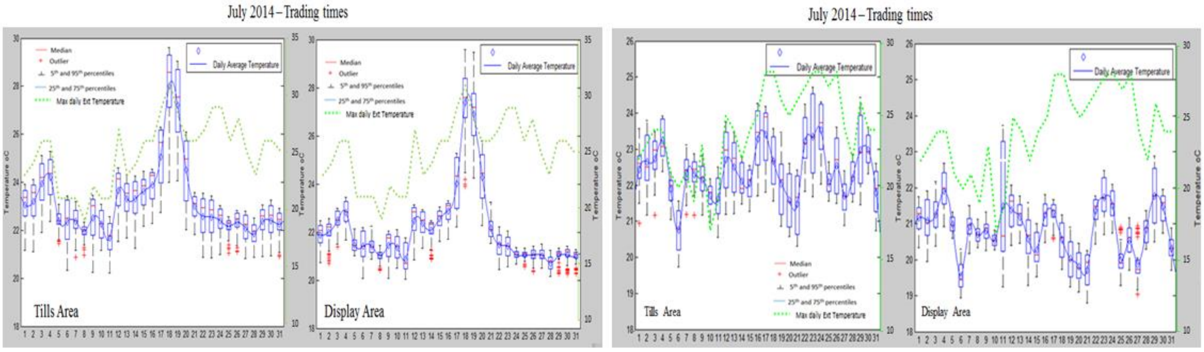


Figure 4: BWM plots of measured air temperature in sales area (tills and display) for June 2014 during trading times (left: CS1, right: CS2)

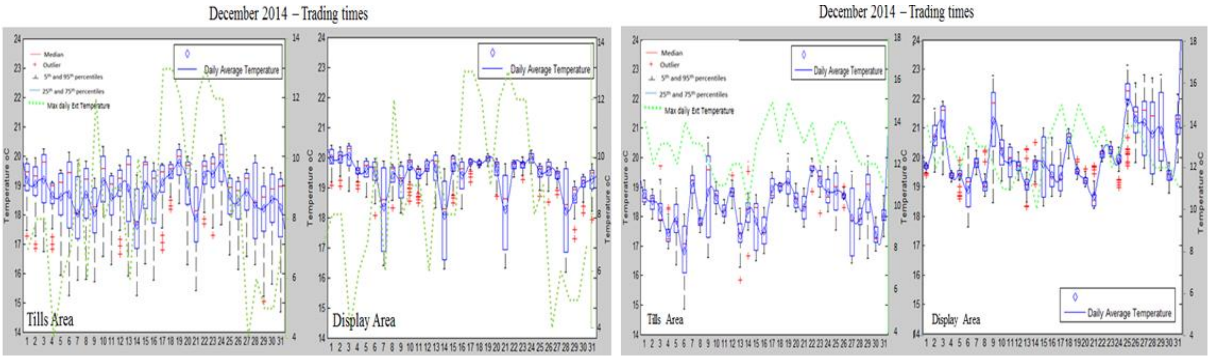


Figure 5: BWM plots of measured air temperature in sales area (tills and display) for December 2014 during trading times (left: CS1, right: CS2)

During non-trading times (Figures 6 and 7), 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^{o}C and 22^{o}C but reached up to 24^{o}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 singificant due to outside conditions permitting and the air temperature of both tills and display area varied between 16^{o}C (which is the minimin setpoint temperature that free night cooling is active) to 18^{o}C.

For CS2, where the ventilation is decoupled from heating and cooling system and the HVAC is in operation 24h, 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 temperatre in the tills area was 1°C lower than the temperaure in the display area.

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

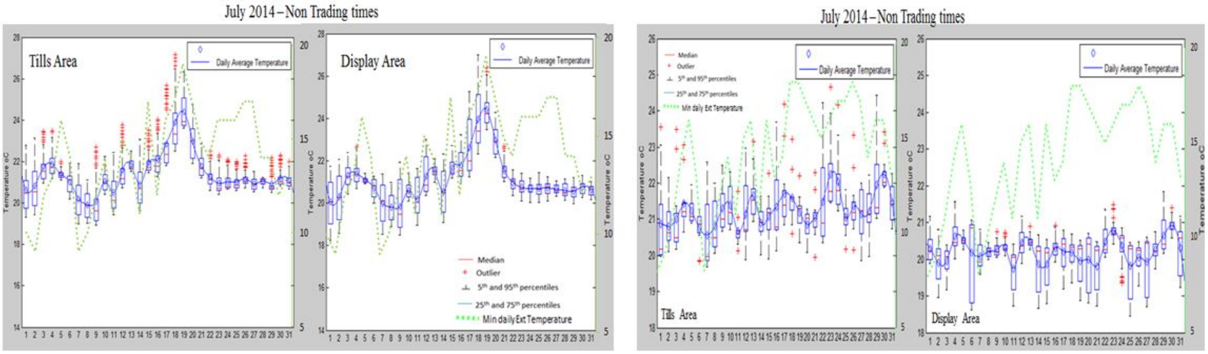


Figure 6: BWM plots of measured air temperature in sales area (tills and display) for July 2014 during non-trading times (left: CS1, right: CS2)

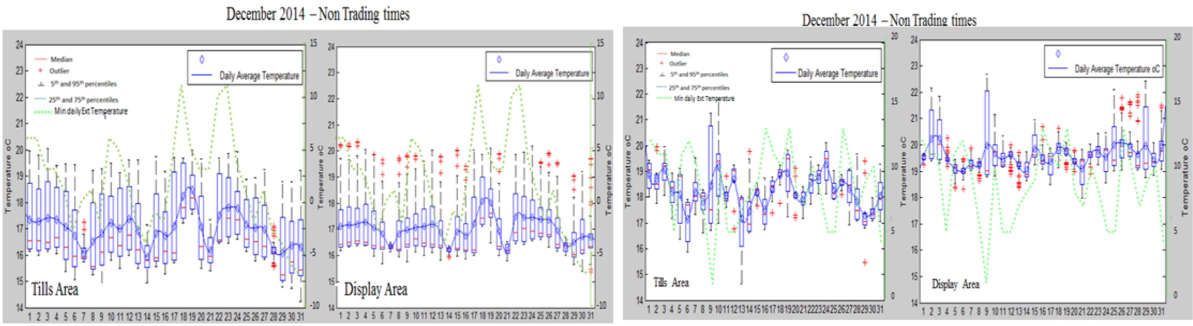


Figure 7: BWM plots of measured air temperature in sales area (tills and display) for July 2014 during non-trading times (left: CS1, right: CS2)

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 (CIBSE, 2015) (ASHRAE, 2013).

4 ENERGYPLUS BASELINE MODEL DEVELOPMENT AND VERIFICATION

The model development of the baseline models and the verification methodology has been presented in (Mylona et al., 2017) 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 %).

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 Mean Squared Error (CVRMSE) are used to evaluate the model uncertainties (ASHRAE, 2002).
According the results, both case study stores EnergyPlus models presented MBE and CVRMSE values within acceptable limits for both energy use and indoor air temperature.

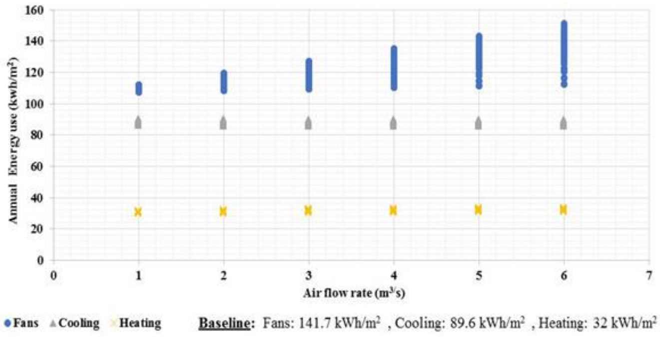
5 RESULTS AND DISCUSSION

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 (Li-Xia Wu et al., 2006). However, studies for offices and other non-domestic building have indicated that three control aspects should be taken into consideration (Kolokotroni, 1998); duration, system initiation and system continuation in order to maximise energy savings. In this case study, the following rules were implemented: i) initiation: $T_{out}<T_{in}$, ii) continuation: $T_{out}<T_{in}$ and $T_{out}-T_{in}<T_{offset}$ and iii) termination: continuation rule and $T_{in}=T_{min}$.
The continuation rule ensures that the outside air brought in is effective in cooling the building. When the temperature difference between inside and outside air (T_{offset}) is low, the incoming air will have little effect on cooling while the ventilation fan energy use will increase the total energy use. However, if the outside air temperature is significantly lower than the inside air temperature, T_{min} will be achieved fast and the duration of night ventilation is decreased (Aria & Akbari, 2007).
Moreover, although NC could increase the total energy savings of the stores, attention should be paid in the air conditions (temperature and RH) brought in store as it may affect the cold surfaces of the cabinets from condensation or it may be harmful to the operation of the refrigeration system or its controls. The stores' LT cabinets are glass lift up lid cabinets which during NC operation remain closed so the evaporator coils are not affected by the ambient air (if hot or humid) and thus crucial problems are not created in the evaporator coils operation. However, action might be taken to prevent condensation on the surface of the glass. Fogging and risk of condensation on the external side of the glass or the multi deck cabinets' curtains might occur in humid climatic conditions while reducing the ambient temperature.

5.1 Coupled HVAC: CS1

NC is already in operation in CS1 during non-trading times. The system is designed to provide free night cooling with 6 m^3/s when the return air and outside air temperature have 1^oC difference and until the inside temperature reaches 16^oC.
The parametric analysis was performed for different airflow rates according to fan speed (1-6 m^3/s), T_{offset} (1-20 ^oC) and T_{min} (10-17^oC). Minimum temperature inside the store was chosen not to fall below 10^oC in order to avoid condensation on the glass cabinets. While setting the T_{min} to the lowest levels (10^oC) and assuming that glass surface temperature does not drop below 0^oC, RH less than 50% would ensure avoidance of condensation.
Figure 8 presents fan, heating and cooling energy use for different air flow rates, T_{offset} and $T_{min;}$ the combinations are integrated and are presented as a range of energy use in the graph. Figure 9 presents the cooling energy use for different T_{offset} and T_{min}. The air flow rate during night cooling plays an important role as the higher airflow increases the fans' energy use. However, low air flow rates could have similar effect on cooling demand with a reduction of heating requirements during the following day. In Figure 8, the fans' annual energy use range is indicated as a result of the different T_{offset}. Higher air flow rate has wider range because the reduction of the internal temperature to T_{min} is achieved fast and the duration of the NC is decreased.

For lower air flow rates there is a point where the maximum total energy use reduction occurred; energy use starts increasing until reaching the point where NC is not effective (total energy use equals the total energy use when NC is off) (Figure 10). This is due to the increase of the cooling energy which afterwards leads to an increase of the total energy use (Figure 9). This point is observed to range between 5-7°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 (Figure 11). The optimum combinations of parameters leads to up to 3 % of the total energy use from the baseline model – this equates to energy use reduction of 35.3 kWh/m^2/year in the store.



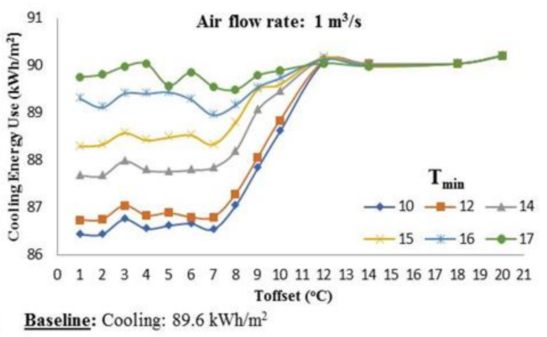


Figure 8: Heating, Cooling and Fans Energy Use for different air flow rates, Figure 9: Cooling Energy Use for different T_{offset} and T_{min}.

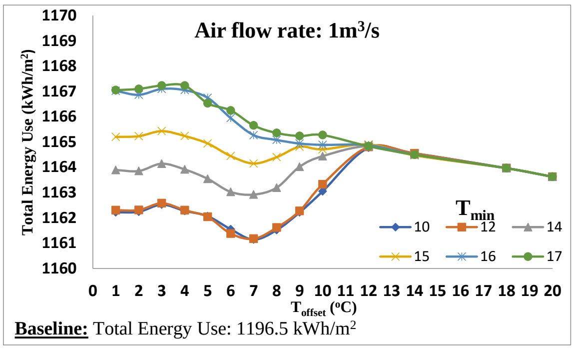


Figure 10: Total Energy Use for different T_{offset} and T_{min}

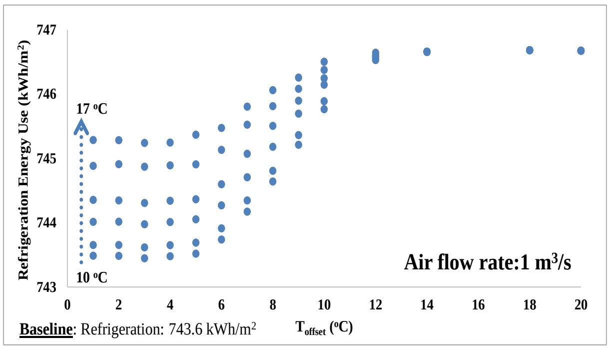


Figure 11: Refrigeration Energy Use for different T_{offset} and T_{min}

5.2 Decoupled heating/cooling from ventilation: CS2

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

For both scenarios the HVAC control strategy of the store changed to facilitate night ventilation as follows: operation between 6:00 to 23:00 for weekdays and Saturdays and 9:00 to18:00 for Sundays rather than 24h of the baseline model. This change alone would save 41 kWh/m^2 sales area per year 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 HVAC system of the CS2, control strategy for exhaust night ventilation resulted to the lowest air flow rates resulting to lower total energy use due to reduced fans energy consumption (Figure 12). Higher air flow rates presented to have strongest correlation with the T_{offset} as mentioned for CS1; while T_{offset} increases, a sharper reduction is occurred and this is because the cold air that is brought inside has bigger effect on the inside air temperature and T_{min} is achieved quickly and thus the duration of the NC is decreased.

It is also observed that for low air flow rates there is a specific T_{offset} where the total energy use starts slightly increasing (T_{offset} >5°C) . After that point, where the optimum total energy use reduction occurs, the cooling energy demand increases and with higher T_{offset} the cooling energy use increases more significantly as the NC is not more effective (Figure 13). For higher air flow rates this T_{offset} increases up to 7 °C. The optimum combinations of the parameters lead to 3.6% reduction in the total energy use which equals to 40.8 kWh/m^2 per year. Refrigeration energy use was found to follow the same pattern with what was analysed for CS1; after a specific T_{offset} refrigeration energy use increases to the levels that NC is no more effective.

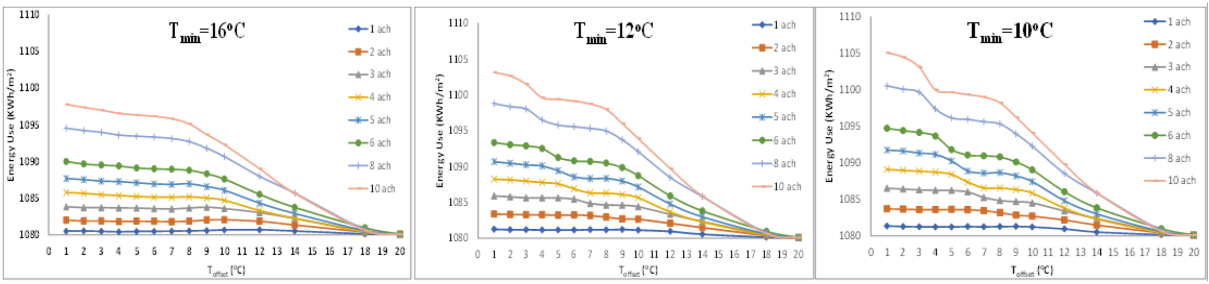
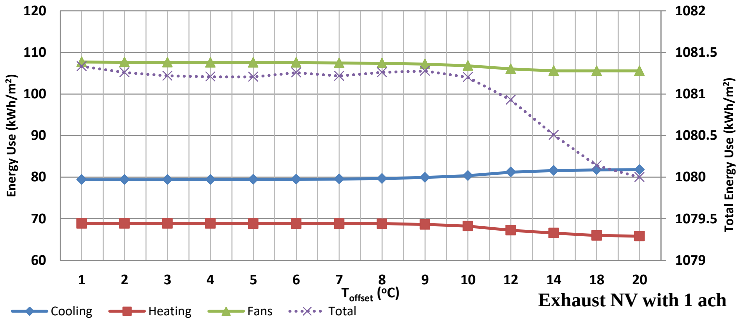


Figure 12: Total Energy Use with different air flow rates for different T_{offset} and specific T_{min}.



Baseline: Cooling: 95.4 kWh/m^2, Heating: 71.1 kWh/m^2. Fans: 130 kWh/m^2, Total: 1121.943 kWh/m^2

Figure 13: Cooling, Heating and Fans Energy Use for different T_{offset} for T_{min}=10°C and with 1 ach air flow rate

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

6 CONCLUSIONS

Two frozen food supermarkets were monitored (energy use and environmental conditions), EnergyPlus models were developed and validated against measurements and night ventilative cooling, taking into account interaction with HVAC and refrigeration systems, was explored as a strategy to reduce energy use. The two stores have the same refrigeration system but different HVAC; the bigger and the older (CS1) uses all air HVAC system with heating and cooling coupled with ventilation, the smaller and the newer (CS2) uses a different system providing heating and cooling (VRF) decoupled from ventilation.

- Energy use of both stores is similar and internal air temperature does not fluctuate significantly from setpoints. CS2 had more constant conditions than CS1.
- NC 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 NC plays an important role as proved in CS1 where NC is already in operation but with better controls bigger reductions are achieved.
- CS2 is cooled during the night to maintain the setpoint 24hrs. Implementing free exhaust or intake NC leads to a reduction in the total energy use.
- Simulations indicate that longer period of NC 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 NC parameter. Parametric analysis indicated that optimum savings occurred if the air inside the stores has 5-7^{o}C difference with the outside air. The higher the air flow rate, the higher this difference should be for better changes.
- With NC, 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 ^{o}C, refrigeration energy use starts increasing until it reaches energy use without NC.
- Although NC 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.

7 ACKNOWLEDGEMENTS

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