



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.

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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 (CO₂) [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 warming 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
$\bar{Y}_s$	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 m². This can be classified as a large convenience store (usually up to 280 m²) or a small supermarket (280–2500 m²) 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 m² total gross area and 315 m² 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

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