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Doored Display Fridges: An Investigation into the Disparity Between the Energy Performance Reported in ISO Testing and that Observed in Live Store Conditions

Dominic SARNO

Aerofoil-Energy
Bollington, SK10 5JB, United Kingdom, info@aerofoil-energy.com
Dominic.sarno@aerofoil-energy.com

ABSTRACT

This paper explores the energy savings achieved by adding doors to an open-fronted multi-deck refrigerator. It explains the disparity between the energy savings reported from ISO testing and the lower savings measured in live stores. This difference, which can be as high as 30%, is due to two main factors: (i) the significantly different ambient temperature and humidity conditions between ISO and store environments; and (ii) the non-uniformity of door openings in a live trading store as compared with the artificial regularity of openings specified under ISO testing criteria.

Keywords: Refrigeration, Doors, ISO, Testing, Evaporators, Energy Efficiency.

1. INTRODUCTION

Increasingly, climate change is dominating the commercial and political landscape such that governments and companies are under pressure to take action to reduce greenhouse gas emissions, especially carbon dioxide (CO2), at a global country, and corporate level. The private sector is at the forefront of the response to government policy. At a legislative level, a combination of incentives and penalties – some generic, others industry-specific – has been introduced to encourage companies to reduce their emissions. For retailers and other public-facing companies, public opinion and ultimately consumer choice are further important drivers for change.

Display fridges of the type used in supermarkets and convenience stores are high energy consumers. In a typical supermarket, refrigeration accounts for around 60 per cent of the total electricity consumed by the store. To put this into perspective: one 3.75 m-length fridge cabinet consumes 25-40 kWh of electrical energy (Energy consumption in display fridges can vary significantly depending on ambient temperature and humidity, product loading and trading behaviour) per day , whereas a typical UK household consumes 8-10 kWh per day. Vasquez-Nicholson (2019) estimates there are an estimated 87,000 grocery stores in the UK , comprising small outlets, convenience stores and supermarkets. Whilst small grocery stores feature fewer display fridges (typically 5-15 per store), a supermarket might have as many as 75 multideck chilled display fridges of various lengths and so consumes electrical energy on a par with 300 households.

Food retailers are therefore seeking to reduce this consumption, both to lower their energy costs and to ameliorate the emissions associated with the carbon intensity of the UK's electricity generation infrastructure. Current options involve the fitting of transparent glass or clear plastic doors on the front of refrigeration cabinets or installing alternative energy-saving technology. In either case, these solutions can be retrofitted in store or added during the cabinet manufacturing process. The decision to invest in these solutions considers their installed and maintenance costs, as well as the energy savings achieved as manifested in both lower energy bills and reduced CO2 emissions.

This study analysed one of these solutions, specifically that of the installation of doors on refrigerated display cabinets. Contrary to the expectations derived from the testing of doored refrigeration cabinets under ISO conditions, retailers have widely reported that actual energy savings are much lower in practice. This potentially compromises their decision to invest in doors, because the expense of installing and maintaining them might not be fully recouped through ongoing savings in energy costs. Moreover, their contribution to a retailer's emissions-reduction targets would also be lower than planned.

2. MULTI-DECK REFRIDGERATION CABINETS

Multi-deck refrigeration cabinets use cooled air to maintain products at a safe temperature. At the base or the rear duct of the fridge, a series of fans direct air across an evaporator coil through which a cold refrigerant is circulated. The coil therefore acts to extract heat from the warmer air blown across the refrigerant pipes. The cooled air is then directed up the rear of the cabinet with a small proportion permitted to leak through the perforated back wall to flow directly over and around products on the shelves. Most of the cooled air is steered up into the roof of the cabinet and turned in the canopy to emerge as a vertical, downward moving 'air curtain' just in front of the shelves. This air curtain serves as an invisible barrier to prevent cold air escaping from within the cabinet and to block the entrainment of warmer, ambient air from the exterior. Finally, the air curtain is sucked back into the base of the cabinet via a return grille, induced by the lower pressure change created by the fans, which in turn recycle the air back through the coil.

The main inefficiency in the functioning of this style of fridge is in the performance of the air curtain. In a typical cabinet, the air curtain must move down over a drop of approximately 2 m. In practice, it quickly loses its coherence and can be adversely affected by draughts passing in front of or over the top of the fridge. The resulting turbulence allows warm air to mix with the air curtain and penetrate the display area of the cabinet. In turn, the air eventually reaching the evaporator coil will be warmer and therefore require more energy to cool it to the required temperature. There is a direct correlation between the extent of warm air ingress and the operational duty of the fridge because the duty is determined by the heat load absorbed into the cabinet. Approximately 70 per cent of heat absorption into the case is due to the entrainment of warm air into the air curtain, the other 30 per cent due to radiation and thermal conduction.

Solutions designed to address this phenomenon include air-guiding devices to ensure the air curtain remains laminar as it passes down the front of the cabinet, or the installation of a physical barrier in the form of a door to block warm air entrainment.

3. DOOR DESIGN AND FUNCTIONALITY

Whether or not a supermarket fridge has doors fitted to it, the basic design and functioning of the cabinet is the same; it circulates cooled air in the same way as described above. The doors themselves can be hinged or sliding, the latter being more common in convenience stores where aisle space is at more of a premium. Most larger stores and supermarkets that have installed doors on their refrigeration cabinets employ the hinged type, which is the subject of this study.

Unlike a domestic fridge, refrigerated cabinets used in supermarkets and convenience stores have a significantly larger capacity and are designed to facilitate intensive shopping activity and regular re-stocking. The door on a domestic fridge can be designed for maximum thermal insulation and is therefore thick and opaque with wide surrounding rubber seals. In contrast, doors on supermarket fridges must provide a clear line of sight to products and be easy to open on a frequent basis. They are therefore fabricated from glass or clear plastic and have narrower mounting frames and seals. There are also several doors on any one cabinet, six on a typical 3.75 m fridge. These design trade-offs mean that they provide comparatively lower thermal insulation than a domestic fridge door. There are several other issues that can compromise their performance as follows:

i. The crossflow of air through the perforated back-wall towards the front of the display cabinet creates a localised high-pressure zone behind the closed doors. For the time that a door is open, this local high-pressure zone pushes cold air out of the fridge. The effect is exacerbated in the event of a single door opening due to the relatively small gap through which the air can pass (for example, a sixth of the display window in the case of a 3.75 m fridge). The rapid movement of air from the interior to exterior then creates several areas of low pressure within the cabinet, encouraging warm air from the store to infiltrate into the cabinet.

ii. The action of opening a hinged door creates a 'bellows-effect'; a low-pressure zone in the sweep of the door, which in combination with the relatively high pressure of air inside the fridge causes the refrigerated air to be drawn out and the resulting turbulence to cause warm air to flow back inside.

iii. Door fittings are not designed to be air-tight, in part to overcome the suction effect that would otherwise make them difficult to close and then open in quick succession, but also due to limits on operational tolerances across such a large display area. There are a number of small openings along the front of the fridge, for example the vertical gap between two doors. These gaps can cause localised areas of air movement into and out of the cabinet leading to warm air ingress and product temperature 'hot spots'.

4. IMPACT OF DOOR OPENING ON ENERGY PERFORMANCE – REVIEW OF EXISTING EVIDENCE

Given the challenges in both the design and operation of doors, unsurprisingly their energy performance is highly dependent on the frequency with which they are opened, which is a function of how intensively they are shopped and re-stocked. Previous studies have therefore attempted to measure door openings in a trading environment.

Lindberg et al. (2010) observed that for a deli/meat fridge, door openings over the course of a day averaged 8-10 per hour (Figure 1), whereas doors on a dairy fridge were opened on average 20 times per hour (Figure 2). The observed number of openings for both fridges averaged 15 times per hour.

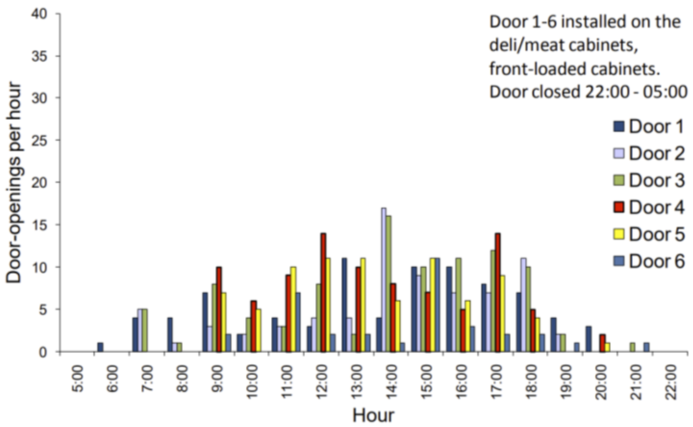

Figure 1: Frequency of door openings for a meat fridge during trading (each of six doors per cabinet measured independently) (Lindberg et al., 2019)

Another study by Mansson et al. (2019) observed that on a particular fridge in a store, door openings averaged 5-7 per hour on Saturday and fewer, 3-5 per hour on weekdays. The scope of this study was, however, limited to one store over a relatively short period of time. Fricke et al. (2010) looked at the impact of door openings on a fridge's energy usage, at the same time observing that door openings in a trading store averaged 6.3 per hour.

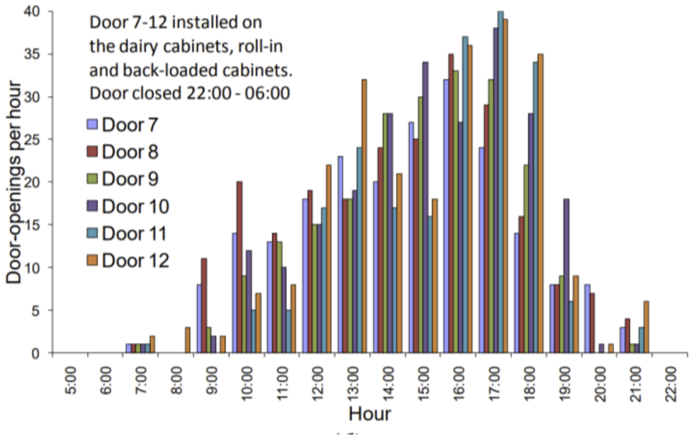

Figure 2: Frequency of door openings for a dairy fridge during the period of trading (each of six doors per cabinet measured independently) (Lindberg et al.,2019)

These studies highlight significant variation in the frequency of door openings depending on the location, day of the week and the type of product on display. Overall, the average appears to sit between five and 20 openings per hour, with a maximum of 40 openings per hour observed by Lindberg et al. (2019) during peak trading.

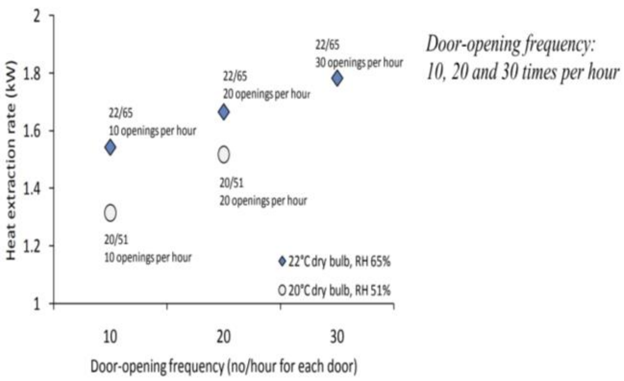

Figure 3: Heat extraction rate as door openings are increased in frequency (Lindberg et al.)

Lindberg et al.(2019) also analysed energy use as a function of the frequency of door openings. As compared with an equivalent open-fronted cabinet, the retrofit of doors to the deli/meat fridge reduced energy usage by 26 per cent (for consistency, no adjustments to temperature set points were made once the doors had been installed. The study estimated that there would be a 21-39 per cent reduction in the 'cooling requirement' for a doored fridge if temperature set points were raised. This was based on laboratory conditions of ambient temperature of 20-22oC and 50-65 per cent relative humidity). This saving was based on the observed average of 8-10 openings per hour. When this frequency was raised to 20 openings per hour, the energy consumption of the fridge increased by 10 per cent (Figure 3). The implication of this is that the addition of doors to the dairy fridge, which was shopped more heavily in their study, would be realising lower energy savings of only 15-20 per cent against the baseline open-fronted cabinet.

In contrast to most types of cabinet doors, fully sealed doors are rarely used due to their high cost, some interference with product line of sight and their relative difficulty to open. Fricke et al. (2010) measured the energy savings achieved by cabinets with fully sealed doors in a live store as 30 per cent compared with an equivalent open-fronted cabinet (Figure 4). The use of fully sealed doors appears, therefore, to deliver only marginal efficiency gains over standard doors. This was likely due to the need (in 2010 at the time of the study) to install anti-sweat heaters and additional product lighting. Modern alternatives, such as LED lighting, would improve this picture.

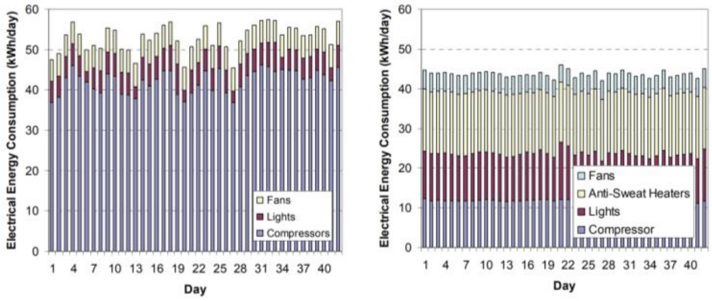

Figure 4: Energy consumption in an open cabinet (left) vs. a cabinet with a fully sealed door (right) (Fricke et al.)

5. ISO TEST CRITERIA

In general, the higher the ambient air temperature and relative humidity surrounding a multi-deck fridge, the harder it must work (and the more energy it therefore consumes) in order to maintain target product temperatures within the display area.

In the UK, multi-deck refrigeration cabinets are subject to ISO test standard 23953. ISO-23953 specifies 'climate classes' defining the ambient conditions in which the cabinet to be tested must be located. The criteria relevant to this study are the ambient air temperature and relative humidity (RH) of the testing environment. Climate Class 3 (CC3) sets these at 25°C and 60 per cent respectively, regardless of whether the fridge is fitted with doors.

CC3 conditions are defined to ensure food temperature integrity is maintained even in the most extreme ambient conditions to which a fridge might be subjected. The CC3 test can, and is, used to provide a comparative test between two of the same types of cabinet. CC3 conditions are extreme and do not reflect typical day-to-day conditions in a store, and so the energy data recorded cannot be used as a guide to actual energy consumption in a store environment (a second climate class – CC0: 20 °C and 50 per cent RH – is defined as more representative of store conditions. The author's own temperature readings taken from trading stores report cooler temperatures and lower humidity in the range of 17-20 °C and 25-50 per cent RH, this is lower than CC0 conditions. In the UK the number of incidences of extreme weather leading to in-store conditions akin to CC3 is statistically insignificant).

Despite this, the energy savings achievable by fitting doors to an open-fronted multi-deck cabinet are often quoted under CC3 conditions. This artificially accentuates the benefits of fitting doors, as indeed it does with other technologies that mitigate the entrainment of ambient air into the cabinet because the effects of entrainment on the energy consumption of the fridge are much more acute when the ambient air has the high temperature and humidity specified by CC3. It is not uncommon, therefore, to see the energy savings theoretically achievable by fitting doors to an open-fronted multi-deck cabinets quoted as high as 50-65 per cent, because these are measured in CC3 conditions. In contrast, retailers report actual savings in typical store environments of the order of 20-35 per cent, approximately half the energy savings reported at CC3 conditions (The study gathered this data from a range of domestic and international grocers on a confidential basis and so the author is not at liberty to attribute energy data to specific retailers).

The ISO test standard also specifies that, where doors are fitted to a cabinet, they should be opened on a linear basis at a rate of 10 openings per hour, each opening and closing taking 1 second and with the door remaining open for 15 seconds on each occasion. Whilst these criteria are designed to mimic trading behaviour, the studies cited above reveal that the frequency of door openings varies significantly in a store environment at different times of the day and throughout the week. Overall, the average number of openings defined by ISO-23953 is largely representative. However, the non-linear pattern of door openings observed is starkly different.

6. STUDY METHODOLOGY

The objective of this study was to assess whether and to what extent variability in both the frequency and non-linearity of door openings affected the energy consumption of a doored refrigeration cabinet and, therefore, could account for the difference between the energy performance implied by ISO testing and that is observed in a store environment.

A multi-deck refrigeration cabinet has complex aerodynamic and thermodynamic properties and sophisticated control systems to govern the regularity with which refrigerant flows through the evaporator coil. These systems also control how often the fridge needs to 'cycle' to allow for time for frost that naturally builds up on the coil to melt and drain away. Factors such as the thermal inertia of products on the shelves, and the programmed hysteresis controlling the timing and frequency of compressor start-ups, means that the relationship between the number of door openings and energy consumption is not necessarily linear. The study's hypothesis was that an irregular pattern of door openings would provide a more complete picture than previous studies of the reasons for the variability in energy performance of doored refrigeration cabinets.

A baseline energy consumption figure was established on a commonly used open-fronted 2.5 m cabinet, with a Danfoss Inverter Driven Optima Condensing Unit and Variable Speed Drive (VSD) supplying the case with R449a refrigerant. Energy monitoring equipment recorded the power consumption of the compressor and VSD unit. The same cabinet was then fitted with four hinged doors with a central supporting column. Further energy consumption readings were then recorded under a range of scenarios. Both the baseline measurements and the subsequent experiments were undertaken at ambient conditions approximating those typically seen in the chilled aisle areas in a trading store of approximately 19 °C/35 %RH.

The loading capacity was approximately 'half-load' of the loading stipulated in ISO-23953. To obtain product temperature readings Tylose M-packs were used, with thermocouples inserted into the centre of the packs. For each shelf there was a row of M-packs at the very back and at the front of the shelf, with M-Packs arranged on the left, right, middle of each row. In-between each M-pack Styrofoam was used to mimic product thermal load. Each test was performed over a 24-hour period. The energy values reported in this study are an average over the 24-hour period.

For the tests, fully programmable robotic arms were used to open and close the fridge doors with pre-determined frequency and duration. This ensured a high level of reliability and repeatability from one experiment to the next (Figure 5).

Figure 5: Programmable robotic arms were used to conduct door opening and closing in a reliable, repeatable manner

	'Regular' ISO Algorithm	**'Irregular' Store Algorithm**
Interval between door operations	Constant	Variable
Time taken to open or close door	1 second	1 second
Duration of a single door opening	15 seconds	10-30 seconds
Total number of openings in 24-hour period	Identical	
Total time that doors in open position in 24-hour period	Identical	

Table 1: Summary of the profiles used to control operation of the doors on the test refrigeration cabinet

Two types of algorithms were used to control the robotic arms over a 24-hour period. A 'regular' ISO-standard algorithm set them to operate the doors a certain number of times every hour on a regular, linear basis, i.e. with a constant interval between each operation. The 'irregular' algorithm was set to operate the doors in a pattern replicating that of a trading store, i.e. with periods of high operation and other periods of low operation, albeit with a pre-determined number of openings over the 24-hour test period, and such that the total time that the door remained in an open position was the same as for the equivalent regular algorithm.

In general, when energy-saving technology is applied to a refrigeration cabinet, it has the combined effect of reducing its cooling duty and lowering product temperatures within the display area. When comparing the experiments with the baseline test, the relative energy consumption figures can therefore be calculated in two ways:

i. Unadjusted' – this is the energy consumed by the fridge based on its automated control system. The cabinet is fitted with commonly used air-temperature probes and based on this data the control system alters the regularity and duration with which the fridge calls for cooling duty. There is no manual adjustment to temperature set points, and so product temperatures are generally lower than in the baseline test.

ii. 'Temperature Adjusted' – this is the energy consumed by the fridge after the temperature set points have been adjusted such that product temperatures are returned to those observed in the baseline test. Consequently, the requirement for cooling is reduced further and energy consumption commensurately lower (analysis of store energy monitoring data suggests that increasing the temperature control set point by 1oC reduces the fridge's energy consumption by 3-5 per cent). In general, retailers specify a maximum product temperature on which they then base their control set point. The temperature-adjusted energy consumption figures recorded in our tests were therefore taken after setting the control set point back to match the maximum product temperature observed in the baseline test.

Energy consumption figures were translated into relative energy savings with reference to the baseline test and on an unadjusted and temperature-adjusted basis respectively.

7. RESULTS

The baseline open-fronted refrigerated cabinet consumed 1294W on average over a 24-hour period with a maximum product temperature of 7.5^{o}C. Doors were then installed on the cabinet and data collected from a range of tests. Table 2 summarises the energy consumption and product temperatures observed in the tests where the doors were operated using the regular algorithm, firstly with the doors fully closed for 24 hours, and then with them opened 10, 20, 30 and 40 times every hour over a 24-hour period.

The test with the doors fully closed was an artificial scenario (for a supermarket during opening hours) but was conducted to show the maximum possible energy saving achievable. In subsequent tests, as the average number of door openings per hour was increased, the energy consumption of the cabinet increased and so the energy savings in comparison with the baseline test gradually diminished. Fitting doors also resulted in a drop of between 3^{o}C and 5^{o}C in maximum product temperatures, which therefore translated into greater energy savings when temperature set points were adjusted accordingly.

Case	Average Energy Usage (W)	Max Product Temp (degC)	Energy Saving (%) (to Baseline Open)	Energy Saving % Range Adjusted for Temp (to Baseline Open)
Baseline (Open Fronted)	1294	8		
Baseline + Doors Closed	768	3	41	54 to 60
Baseline + Doors 10/hr	813	4	37	46 to 52
Baseline + Doors 20/hr	898	4	31	40 to 46
Baseline + Doors 30/hr	986	4	24	33 to 39
Baseline + Doors 40/hr	1065	5	19	23 to 29

Table 2: Summary of energy and temperature data from experiments conducted with a regular algorithm controlling door operation

Importantly, the tests where doors were operated in line with ISO-23953, (i.e. 10 times an hour at equal intervals), returned energy savings of 37 per cent (unadjusted) and 48 per cent (adjusted) in comparison with the baseline open-fronted fridge. Hence, the transition from CC3 conditions to the store-like ambient conditions of our test laboratory, accounts for a large part of the disparity between the energy savings purportedly offered by doors of 50-65 per cent and that reported by retailers when they have undertaken energy monitoring before and after installing doors on the fridges in their stores.

The results pertaining to higher numbers of door operations per hour illustrate the increasingly detrimental impact on the fridge's energy consumption for the reasons discussed earlier, namely the pressure differentials inside and outside the cabinet along with the bellows-effect occurring each time a door is opened. However, even when the doors were operated 40 times an hour (mimicking a highly intensive trading period), they still conveyed an energy saving of 18 per cent (unadjusted) in comparison with an open-fronted cabinet.

Table 3 summarises the energy consumption and product temperatures observed in a test where the doors were operated using the irregular algorithm, i.e. to more accurately reflect real-life store trading activity. This is compared against the equivalent test using the regular algorithm and the same overall number of openings over a 24-hour period. It shows clearly that opening the doors in an irregular fashion akin to that observed in a trading store, albeit with the same number of total operations and identical overall duration of opening, reduces the energy savings achievable to 27 per cent (unadjusted). This figure aligns closely with the average saving reported by retailers.

Case	Average Energy Usage (W)	Max Product Temp (degC)	Energy Saving (%) (to Baseline Open)	Energy Saving % Range Adjusted for Temp (to Baseline Open)
Baseline (Open Fronted)	1294	8		
Baseline + Doors 10/hr	813	4	37	46 to 52
Baseline + Doors 10/hr - Store Frequency	944	4	27	38 to 44

Table 3: Summary of energy and temperature data from an experiment conducted with an irregular algorithm controlling door operation

8. CONCLUSIONS

Open-fronted multi-deck refrigerated cabinets used in supermarkets and convenience stores have a significant footprint in terms of their energy consumption and related greenhouse gas emissions. Some retailers have installed glass or plastic doors on the front of fridges to reduce energy costs and contribute towards their wider sustainability goals and net zero emission targets. However, the actual energy savings recorded by retailers is universally much lower than expectations arising from ISO-23953 laboratory tests which indicate that fitting doors to an open-fronted cabinet could reduce energy consumption by as much as 65 per cent. In contrast, retailers report actual savings in typical store environments in the range 20-35 per cent.

This study provides an explanation for this disparity, some of which is due to misrepresentation of data from ISO testing, and the balance due to the inherent vagaries of a trading store environment as compared with the prescribed testing criteria of ISO-23953.

The energy savings from door installations as determined from ISO tests at CC3 conditions are rather artificial as CC3 conditions are rarely encountered in stores in practice. The very high ambient temperature and humidity levels defined under CC3 test criteria are designed to ensure the fridge maintains satisfactory product temperatures at these extremes. For this reason, they are not a very meaningful basis for measuring and comparing energy consumption, because the cooling requirement of a fridge in such extremes will inevitably be much higher than in the lower ambient temperature and humidity levels of a live store environment.

Our study shows that moving from CC3 test conditions to those more typically observed in a supermarket or convenience store, reduces the energy savings achievable from doors to approximately 37 per cent. This figure is more representative of the level that could be expected albeit it is still based on the somewhat unrealistic pattern of regular door openings specified under the ISO test standard.

The most appropriate regime for a more complete understanding of the energy savings achievable with doors, would be to test using a profile of door openings that closely mimics that of a trading store, i.e. where the number and duration of door operations varies significantly throughout the day. Our testing on this basis resulted in an energy saving of 27 per cent (unadjusted), which is within the range of actual savings reported by retailers.

In conclusion, whilst ISO-23953, and in particular CC3, serves a purpose in ensuring food safety, it is not appropriate as a predictor of the energy consumption in a trading store environment and even less useful as an indicator of the energy savings achievable by installing doors on open-fronted cabinets. Given the high capital cost of installing doors and the ongoing costs associated with their maintenance, it is essential that retailers obtain a meaningful estimate of the energy savings so that their investment decision is properly informed. Similarly, to the extent that their decision is also driven by a desire to reduce the greenhouse gas emissions associated with their refrigeration assets, it is vital to obtain an accurate picture of the benefits achievable by door installations. This can only be done under a more realistic set of testing criteria.

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