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Graphical Abstract

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Specific energy consumption values for various refrigerated food cold stores

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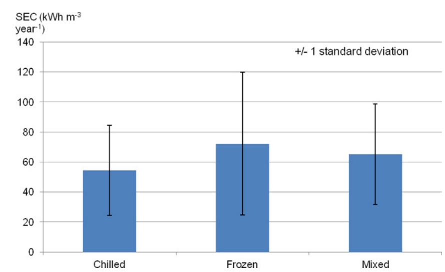

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Highlights

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- Energy consumption of cold stores was compared and benchmarked.
- The work consists of the greatest number of data sets collected and published to date.
- A strong relationship between volume and energy was established.
- A mathematical model was developed to predict energy use.
- The model was used to identify factors affecting energy consumption.

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Specific energy consumption values for various refrigerated food cold stores

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ABSTRACT

Two benchmarking surveys were created to collect data on the performance of chilled, frozen and mixed (chilled and frozen stores operated from a single refrigeration system) food cold stores with the aim of identifying the major factors influencing energy consumption. The volume of the cold store was found to have the greatest relationship with energy use with none of the other factors collected having any significant impact on energy use. For chilled cold stores, 93% of the variation in energy was related to store volume. For frozen stores, 56% and for mixed stores, 67% of the variation in energy consumption was related to store volume. The results also demonstrated the large variability in performance of cold stores. This was investigated using a mathematical model to predict energy use under typical cold store construction, usage and efficiency scenarios. The model demonstrated that store shape factor (which had a major impact on surface area of the stores), usage and to a lesser degree ambient temperature all had an impact on energy consumption. The work provides an initial basis to compare energy performance of cold stores and indicates the areas where considerable energy saving are achievable in food cold stores.

1. Introduction

Refrigeration is one of the most energy-intensive technologies used in the food supply chain and poses a number of sustainability-related challenges. It accounts for about 35% of electricity consumption in the food industry [1], worldwide this equates to a consumption of about 1300 TWh year^{-1} [1].

Energy issues are among the main concerns in Europe today. The main challenge is to meet the binding target set by the Heads of States and Governments of the 27 EU Member States in March 2007 to increase energy efficiency by 20% and to increase the use of renewable energies by 20%, by 2020 [2].

All chilled and frozen food and temperature controlled pharmaceutical products are stored in a cold store at least once during their journey from production to the consumer. Chilled stores generally maintain products at temperatures between −1 and 10 °C whereas frozen stores generally maintain product at below −18 °C. The cold store market is extremely diverse consisting of small stores of 10–20 m^3 up to large warehouses of hundreds of thousands of cubic metres. All cold stores have the function of storing a product at the correct temperature and to prevent quality loss as economically as possible. In Europe there are approximately 1.7 million cold stores totalling 60–70 million m^3 of storage volume. Of these, 67% are small stores with a volume of less than 400 m^3 [3].

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Cold storage rooms consume considerable amounts of energy. Previous unpublished work by the authors has shown that within cold storage facilities, 60–70% of the electrical energy may be used for refrigeration. Therefore, cold store users have considerable incentive to reduce energy consumption. There are few published surveys comparing the performance of more than a few cold stores. In addition surveys rarely differentiate between type of store, storage temperature, location, room size or room function. In 2002 the IIR estimated that the SEC (Specific Energy Consumption) of cold stores was between 30 and 50 $kWh\,m^{-3}\,year^{-1}$ [4]. The minimum value from this study was similar to values from a study carried out in the Netherlands by Bosma [5] which found energy consumption of cold stores to be 35 $kWh\,m^{-3}\,year^{-1}$. In the UK ETSU (Energy Technology Savings Unit) [6] also found that stores consumed at minimum 34 $kWh\,m^{-3}\,year^{-1}$ but that consumption could also be up to 124 $kWh\,m^{-3}\,year^{-1}$. Other studies in the USA by Elleson and Freund [7] and Singh [8] found SECs of between 19 and 88, and 15 and 132 $kWh\,m^{-3}\,year^{-1}$ respectively. In one of the most comprehensive recent surveys carried out in New Zealand by Werner et al. [9] the performance of 34 cold stores was compared. The SECs recorded varied from 26 to 379 $kWh\,m^{-3}\,year^{-1}$ demonstrating that there was a large variation in energy consumed by cold stores. Savings of between 15 and 26% were found to be achievable by applying best practice technologies. This large range in performance was also found by Carlsson-Kanyama and Faist [10] who report data from BELF [11] for energy use for freezers per litre net volume per day to be 1.0 kJ (equivalent to 101 $kWh\,m^{-3}\,year^{-1}$) when food was stored in rooms of 10,000 m^3 whereas in rooms of 10 m^3 the energy was 15 kJ (equivalent to 1520 $kWh\,m^{-3}\,year^{-1}$). In both surveys a factor difference of 15 was apparent.

Limited information has been published on throughputs and storage and often information is difficult to compare due to the metrics used by the authors. Carlsson-Kanyama and Faist [10] report energy used for long-term cold storage of apples may vary between 0.9–1.7 kJ electricity per kg per day. Swian [12] reported figures for potato storage collected over a 3 year period from 8 stores as being between 0.1 and 0.29 $kWh\,tonne^{-1}\,day^{-1}$. On average the energy ranged from 0.12 to 0.15 $kWh\,tonne^{-1}\,day^{-1}$ within each of the 3 years where monitoring took place. The results showed a massive difference in energy consumption between the best and worse stores. It should be noted that the data included all energy used and that in cold weather potato farmers need to heat stores to maintain the potatoes at the usual storage temperatures of 3 °C. In addition there was no information presented on store temperatures and so the stores that appear most efficient may be those that stored the potatoes at a higher temperature.

Previous detailed audits carried out on a small number of cold stores has confirmed that energy consumption can vary considerably and that this was due to a variety of factors [13,14]. These surveys also demonstrated that energy savings of 30–40% were achievable by optimising usage of the stores, repairing current equipment and by retrofitting of energy efficient equipment.

The performance of a large number of cold stores has never been compared in detail and there is little information to compare performance of stores Worldwide. With government targets to reduce energy and emissions of greenhouse gasses (GHG), the need to benchmark and understand potential energy and GHG reductions is of great interest to end users. To enable end users to improve the performance of their cold stores a project called 'Improving Cold storage Equipment in Europe' (ICE-E) was developed with 8 partners from across Europe. The initial aim of the project was to collect data to benchmark the performance of cold stores in Europe.

As part of the ICE-E project, two internet based surveys were developed and data collected to determine energy usage in different cold store types, sizes and configurations. In addition a mathematical model was developed to predict energy used in cold stores. Results from these surveys and the predictions made by the model are presented in this paper and the data analysed to determine whether there were any common factors that affected performance of the cold stores.

2. Materials and methods

2.1. Detailed survey tool

2.1.1. Development of survey tool

The survey was developed using a NET web application. Development was carried out in Microsoft Visual Studio using c# (c sharp) which used .NET Framework 4.0. The data was saved in a Microsoft SQL database. The survey was available in a number of languages (Bulgarian, Czech, Danish, Dutch, English, French, Italian and Spanish). The survey was initially tested on a selected number of cold store operators to ensure the questions were appropriate and relevant. Improvements were then made based on their comments.

The survey allowed participants to initially register their details and then to enter data on as many refrigeration systems as they wished. It collected information per single refrigeration system that might supply one of several cold stores. The survey was designed to be simple to complete with the aim that it should take a cold store operator less than 20 min to complete the survey. The final survey document consisted of 5 pages collecting basic information, information on the refrigeration system, the food stored, the facility and the refrigeration equipment at the facility. During the initial registration process, cold store operators could ensure that data was anonymous.

2.1.2. Data collected and benchmark analysis of survey tool

The survey parameters collected are shown in Appendix 1. In all cases the users were asked to rate the accuracy of the data they submitted. The collected data was retained on a server where users could return to update information or add further data.

Once users had input data they could then compare the performance of their store through an automatic benchmark analysis. This enabled them to compare the energy used by their cold store system with systems of a similar size and product throughput. In addition users could compare the set point temperatures, food type, room function and refrigerant type with others in the survey. In all comparisons the user had the ability to define the range over which comparisons were carried out.

2.2. Express survey tool

In response to some end users requesting a simpler and more rapid means to benchmark their stores an 'Express Survey' was developed. This required only 5 min to complete.

2.2.1. Development of survey tool

The tool was part of the ICE-E web site and written in HyperText Markup Language (HTML) using a web form to collect the data. As in the detailed survey all data collected was anonymous.

2.2.2. Data collected and benchmark analysis of survey tool

A limited data set of 5 parameters was collected (set temperature, area and volume of the store, food throughput and energy usage per year) which reflected what were considered to be the most important factors affecting energy use in cold stores. In all cases blast freezing of product was excluded from the data collected.

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Once data was submitted the information was input manually into the main benchmark survey and information sent directly to the cold store operator.

For both surveys the data collected was checked and unreliable data excluded. Where possible any unreliable data was cross checked with the cold store operator and any anomalies corrected.

2.2.3. Mathematical model of cold store energy performance

A mathematical model of cold store energy use was developed to predict energy used by cold stores. This was used to compare theoretical energy used by cold stores with the actual energy usage collected in the survey.

The model was steady state, therefore all heat loads were averaged over one day. The cold store was modelled as a fully sealed rectangular box with one entry door. The cold store had enough thermal mass such that door openings did not change the temperature in the cold store. The temperature of the ambient air outside the cold store was not changed by the door openings. There was only one layer of insulation on the walls, roof and floor. Any metal cladding was ignored as the resistance to heat transfer from this was considered negligible. The luminous flux from the lights was divided by the area of the floor and walls to give a uniform luminance. The thermal mass of the forklift trucks were ignored. Therefore if they moved from a warm environment into the store, they did not give up this heat to the store. Energy from fork lift trucks did not include charging the batteries. Any product which changed temperature when loaded into the store did not have a latent load (e.g. freezing and thawing), only a sensible load.

Data was input via a spread sheet. The inputs included;

- Information about each wall (including ceiling and floor) of the cold store, e.g. face area, whether it was in the sun, outside ambient or internal and the type and thickness of the insulation.
- The size of the door, its opening schedule, whether it was protected (e.g. by strip or curtains), amount of traffic through the door and the outside conditions.
- The refrigeration system, refrigerant, type of condenser, condenser ambient, efficiency of compressor and number of compression stages.
- Heat loads inside the store from forklifts, lights, personnel, product, defrosts and evaporator fans.
- Electrical loads from lights, defrosts, evaporator fans and condenser fans.

Full details of the model are contained in Appendix 2.

To better understand the variations in the survey data, 3 usage scenarios were modelled over a range of store volumes between 10 and 350,000 m^3. Store volume was modelled as a cold store of 5 m height with store width and depth equal in all cases. A further set of predictions were made at each store volume for the stores with the minimum and maximum practical surface area (an assumption was made that the store height could not be less than 2 m). For each scenario a chilled store at 2 °C and a frozen store at −23 °C were modelled at the minimum and maximum average annual temperatures in Europe (4.6 °C and 20.6 °C based on data from weatherbase [16]). The 3 scenarios were:

1. A base-line store where all heat loads except those that were essential to the operation of the store were removed.
2. A typical store with average use with a high efficiency refrigeration system.
3. A typical store with high usage with a low efficiency refrigeration system.

Parameters for each scenario were selected based on information from Evans et al. [17]. Full details of the assumptions made for each of the 3 scenarios are listed in Table 1.

3. Results

3.1. Data collected

Data from 329 cold stores was collected. One data point was the mean of 331 cold stores in the UK (i.e. the total data collection encompassed 659 stores). This point was excluded from the analysis as data was not available on the data variance. Therefore, the data point could not be included at an equal weighting to the other data sets and so was used for purely comparative purposes in the analysis. Thirty-four data sets were removed as they were considered unreliable (due to store dimensions being obviously incorrect or product temperatures, throughputs or store temperatures being inconsistent) leaving 294 data sets with the minimum 5 critical parameters recorded (temperature of the store, area and volume of the store, food throughput and energy usage per year).

The data collected covered 21 different countries (Belgium, Bulgaria, China, Czech Republic, Denmark, France, Germany, Greece, Ireland, Italy, Mexico, Netherlands, New Zealand, Portugal, Romania, Serbia, Spain, Sweden, Switzerland, United Kingdom, USA). Seventy percent of the 295 data sets originated from EU countries.

3.2. Cold store type

Cold store function was divided into chilled, frozen or mixed stores (those with both chilled and frozen rooms operating from a common refrigeration system). Analysis of variance (ANOVA) showed a highly significant difference ($P < 0.05$) between the SEC of all store types. Differences between chilled and frozen and chilled and mixed were greater ($P < 0.01$) than between frozen and mixed stores ($P < 0.05$).

3.3. Country

Large variations in SEC were shown between countries. However, this was most likely due to the limited number of data sets for some countries. Analysing the data from countries, where a greater number of data sets were available, did not show any correlation between location and ambient temperature at the location or any factor such as differences in design of the cold stores. Due to the large variability in SEC it was not possible to analyse data from each country separately. Therefore, all further analysis was carried out on data divided into chilled, frozen and mixed stores.

3.4. Impact of store location and ambient temperature

An analysis of ambient temperature at each store location was carried out. Data on ambient temperature was taken from meteorological data for each store location and the mean annual temperature for the year in which the energy data was collected was correlated with energy usage. Correlations between ambient temperature and SEC for chilled, frozen and mixed stores were low (less than 0.17), indicating that mean ambient temperature may have had little impact on energy usage.

3.5. Relationship between energy use and store size

The relationship between store energy consumption and size was investigated using multiple regression. As part of this analysis the data was found to be near to a normal distribution.

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Table 1
Assumptions used in model.

	Scenario 1		Scenario 2		Scenario 3	
	Chilled	Frozen	Chilled	Frozen	Chilled	Frozen
Cold store shading	Shaded		Not shaded		Not shaded	
Cold store colour	Light		Dark		Dark	
Insulation	100 mm	150 mm	100 mm	150 mm	100 mm	150 mm
Air movement around store	Still air		Windy		Windy	
Under floor heating	None		None		None	
Refrigerant	R717 (ammonia)		R717 (ammonia)		R717 (ammonia)	
Condenser	Evaporative		Evaporative		Air	
Compression/expansion stages	2 Compressor/1 expansion stage		2 Compressor/1 expansion stage		2 Compressor/1 expansion stage	
Isentropic efficiency of compressor	High (0.7)		High (0.7)		Low (0.5)	
Defrost	Off-cycle	Electric	Off-cycle	Electric	Off-cycle	Electric
Product heat load	None		Food loaded at 1 °C above store temperature, loading = 250 kg m^{-3}, product weight loss = zero		Food loaded at 2 °C above store temperature, loading = 500 kg m^{-3}, product weight loss = zero	
			25% of total mass loaded each day	10% of total mass loaded each day	25% of total mass loaded each day	10% of total mass loaded each day
Fork lift heat load	None		1 per 40,000 m^3, size = medium, electric, operated 24 h per day		1 per 30,000 m^3, size = medium, electric, operated 24 h per day	
People heat load	None		2 persons per forklift truck, 24 hours per day		2 persons per forklift truck, 24 hours per day	
Lighting heat load	None		Fluorescent lights, 50 lumens.W^{-1}, 500 lux, operational 24 hours per day		Fluorescent lights, 50 lumens.W^{-1}, 500 lux, operational 24 hours per day	
Infiltration heat load	None		Door height 2.5 m, width 2 m minimum, if > 50,000 m^3 store volume then door width = store volume/10,000, door opening time = 25 sec, volume of traffic during door opening = medium, door seal = good, no protection on door		Door height 2.5 m, width 2 m minimum, if > 50,000 m^3 store volume door width = store volume/10,000, door opening time = 25 sec, volume of traffic during door opening = medium, door seal = good, no protection on door	
			400 door openings per day	200 door openings per day	600 door openings per day	300 door openings per day
Evaporator/condenser fan power	Created from correlation from Evans et al. [17]		Same as for scenario 1		Same as for scenario 1	

3.5.1. Chilled stores

One hundred and twenty-six chilled stores were included in the analysis. These ranged in volume from 57 to 225,000 m^3. Regression demonstrated that 93% of the variation in annual energy consumption was related to store volume (Fig. 1). Multiple regression demonstrated that food type and food throughput had some impact on annual energy but that these factors only increased the R^2 value to 95% and therefore their impact was very low. All other factors collected (including store temperature, store insulation type and thickness, store location and ambient conditions around the store, type of refrigerant and effect of door protection) had no influence on annual energy consumption.

Applying non linear relationships to the data did not improve the regression R^2 value. This indicates that SEC remained relatively constant across the range of cold store volumes examined.

3.5.2. Frozen stores

One hundred and thirty-two frozen stores were included in the analysis. These ranged in volume from 100 to 291,280 m^3. Store volume accounted for 56% of the variability in annual energy consumption of frozen stores when a linear regression was applied. Applying a non linear power function to the data improved the regression R^2 value to 66% (Fig. 2). This showed that for frozen stores SEC reduced as the store size increased.

As with chilled stores none of the factors recorded had anything above a very minimal impact on annual energy consumption. Therefore, approximately 34% of the variability in annual energy consumption was related to a factor that was not collected in the survey.

3.5.3. Mixed stores

Thirty-six mixed stores were included in the analysis. These ranged in volume from 9100 to 180,000 m^3. A number of factors had an impact on mixed store annual energy consumption. As a linear regression, store volume accounted for 67% of the variability, however, if a power function (non linear regression) was applied this increased to 76%. (Fig. 3). In addition throughput, thickness of the store insulation (wall, ceiling and floor) and insulation age also

Table 2
Range in SEC values for cold stores examined.

		Chilled (kWh m^{-3} year^{-1})	Frozen (kWh m^{-3} year^{-1})	Mixed (kWh m^{-3} year^{-1})
All data	Mean	56.1	73.5	61.2
	Minimum	4.4	6.0	15.7
	Maximum	250.4	240.4	115.8
10% upper and 10% lower values removed	Mean	52.2	66.7	52.0
	Minimum	20.7	27.0	29.9
	Maximum	95.3	134.6	107.0
20% upper and 20% lower values removed	Mean	51.5	63.7	55.9
	Minimum	29.6	37.5	37.4
	Maximum	78.0	100.0	87.3

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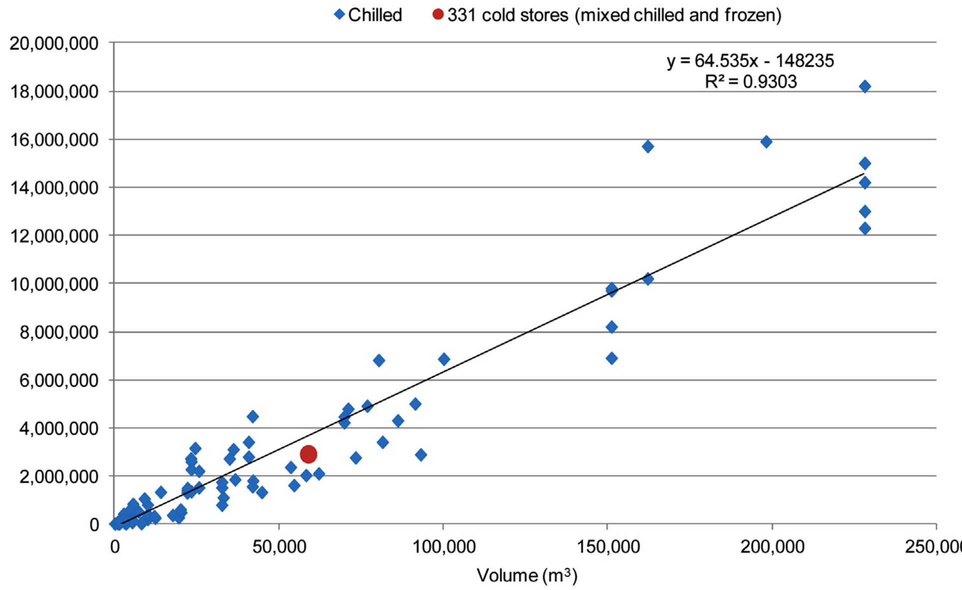

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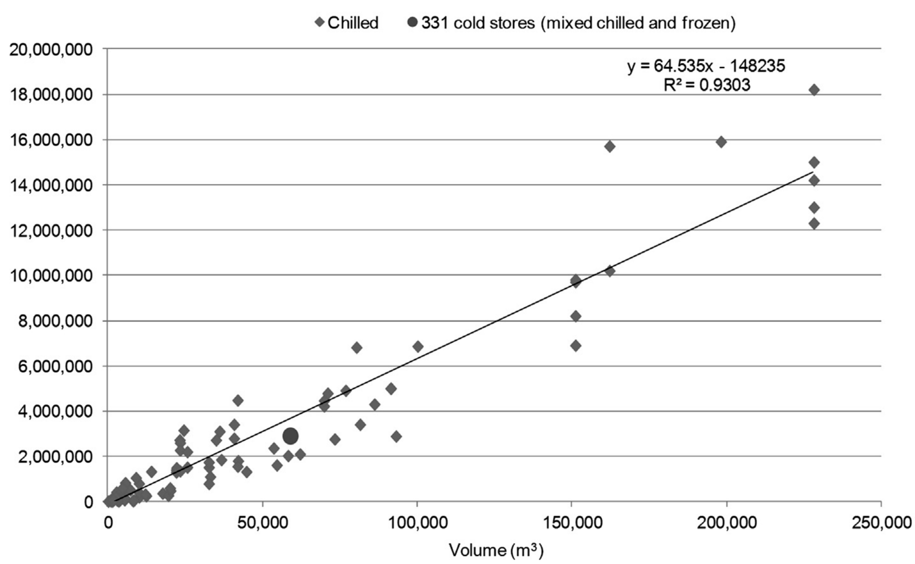

Fig. 1. Relationship between store volume and total energy use per year (kWh/year) for chilled stores.

appeared to have a minor impact on annual energy consumption. However, for these data sets the number of replicates was low and so their impact needs further investigation.

Mixed stores appeared to have a similar volume relationship with annual energy consumption as frozen stores and therefore the store SEC reduced for larger stores.

3.6. *All stores*

The SEC for the cold stores examined varied considerably. Data from all stores and for all stores with the 10% and 20% upper and lower values removed are shown in Table 2.

It is interesting to note that mixed and frozen stores had a relatively similar relationship between volume and annual energy (although statistically the regression lines were significantly different at $P < 0.01$). At volumes below 22,000 m^3 chilled store used less energy than frozen or mixed stores but at volumes above 22,000 m^3 chilled stores used more energy than frozen or mixed stores. The stores below 22,000 m^3 were dominated by a cluster of smaller chilled stores that had low energy consumption (several of them were produce stores where there was often intermittent usage). It would be expected that chilled stores would use less energy than frozen stores across the whole range of volumes. However, it may be reasonable to expect that chilled stores have greater usage and greater product heat loads than frozen stores which tend to be used for long term storage of food.

3.6.1. Mathematical model of cold store energy performance

Results from the 3 modelling scenarios are presented in Fig. 4 (chilled stores) and Fig. 5 (frozen stores). The dashed area outlined in each figure represents the range in energy consumption for stores with varied shape factors predicted by the model. Shape factor is related to store surface area and was found to have a large impact on energy consumption and was responsible for increasing energy use from the most efficient shape (lowest surface area to volume ratio, in this case a cube) to the least (a flat plane) by 13 times in a chiller and 10 times in a freezer. The differences between chillers and freezers were due to insulation thickness (most commonly 100 mm in a chiller and 150 mm in a freezer).

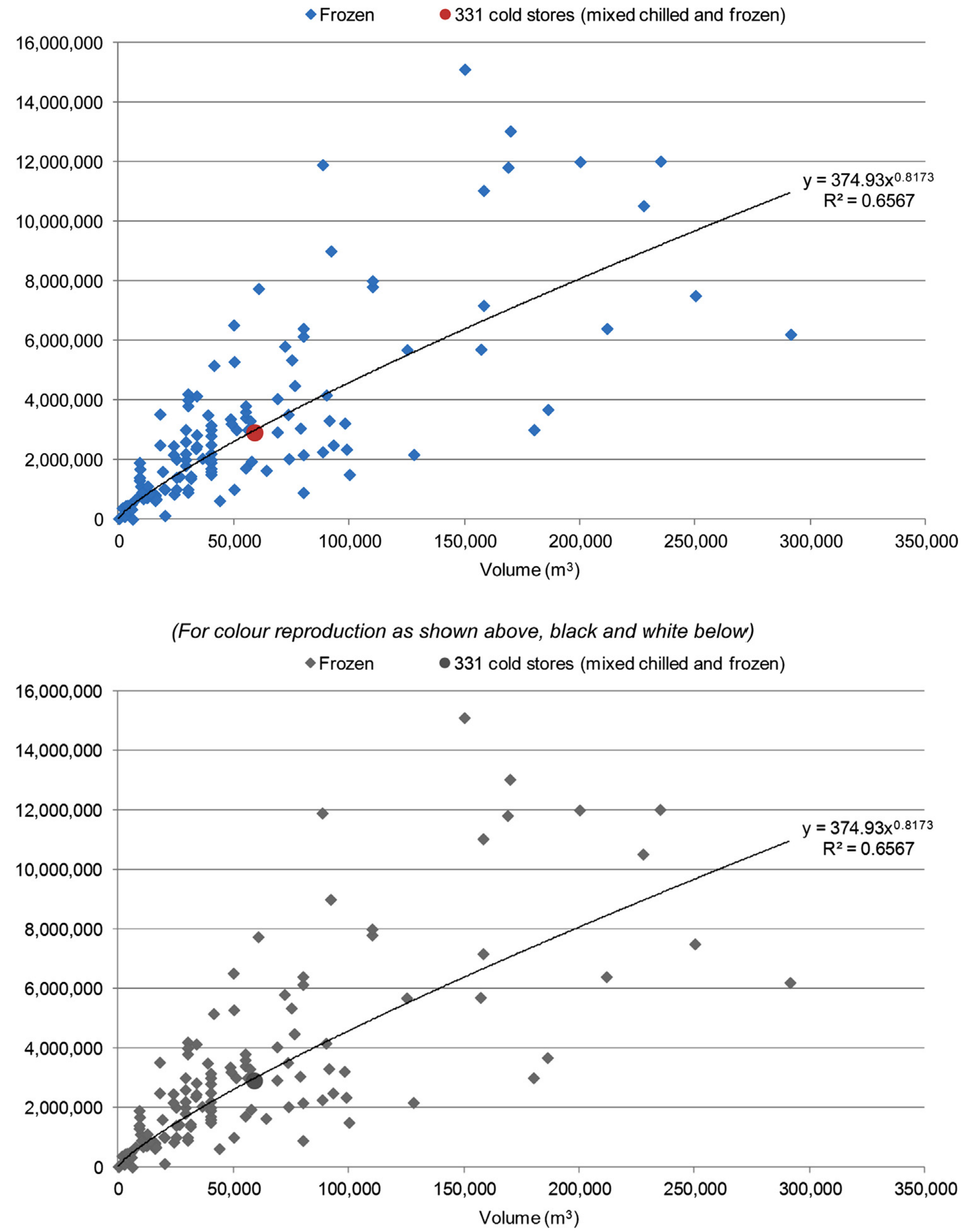

Fig. 2. Relationship between store volume and total energy use per year (kWh/year) for frozen stores (non linear regression).

Ambient conditions around the store had greater influence on frozen stores than chilled stores (due to the greater temperature difference between ambient and store temperature for freezers). Ambient temperature had a greater impact on energy use when usage of the store was high (due to door openings).

If the predications made by the model (including all scenarios and range due to ambient temperature and shape factor) were compared to the data collected in the survey the model predictions covered 83% of frozen stores and 94% of chilled stores. Assuming some inaccuracies in the model (±10%) a further 2% of chilled stores and 6% of frozen stores would be included within the predicted ranges. The stores that were outside of this predicted range were stores with small volumes (less than 8270 m^3 for chilled stores and less than 30,000 m^3 for frozen stores).

SEC decreased as store volume increased but the reduction in SEC was most apparent at low store volumes. The SEC changed by less than 0.5 kWh m^{-3} $year^{-1}$ per 10,000 m^3 increase in store volume for stores with volumes of greater than 10,000 m^3 for chillers and 20,000 m^3 for freezers. Due the minimal change in SEC above certain store volumes the relationship between energy and volume predicted by the model approached a linear relationship when considering store sizes of up to 350,000 m^3.

3.6.2. Use of the model to assess the efficiency of cold stores

Using the knowledge gained from the model, the energy used by the survey cold stores could be compared to the modelled energy usage. As the total store surface area was found to be a factor in the energy usage, the energy used across a range of total store surface areas, usage scenarios and ambient temperatures was predicted by the model. Total surface area was obtainable for the cold stores modelled but had to be estimated for the survey data. The floor and ceiling surface area was recorded in the survey (ceiling area was assumed to be equal to floor area). The area of each wall was estimated by multiplying store height (obtained by dividing the store volume by the area) by store depth/width (calculated by taking the square root of the store area). For each cold store

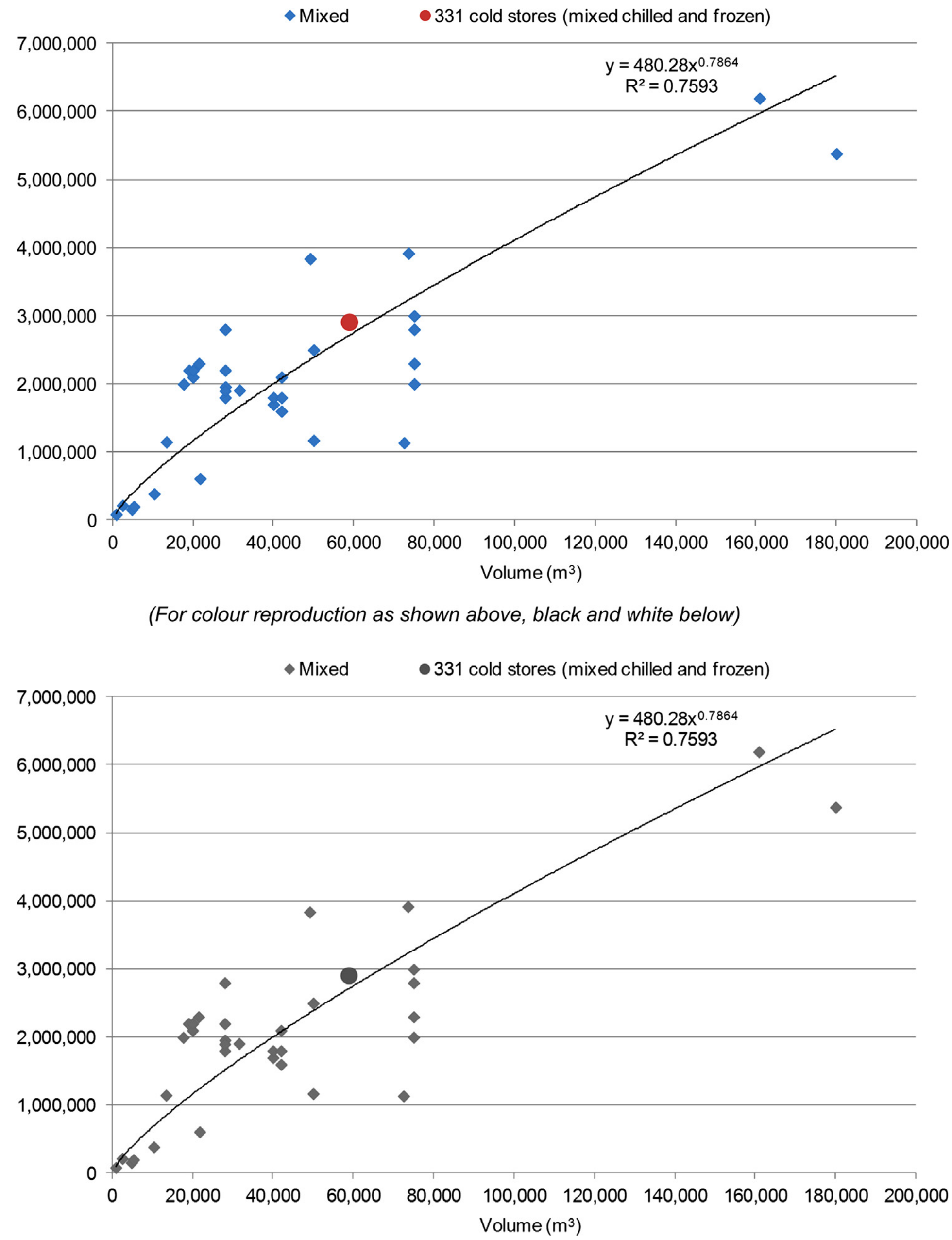

Fig. 3. Relationship between store volume and total energy use (kWh/year) for mixed stores (non linear regression).

survey data point, the average annual ambient temperature for the cold store location was extracted from a weather database (http://www.weatherbase.com/).

The impact of total surface area on the energy consumed for each modelled scenario is shown in Fig. 6 (for chilled stores) and Fig. 7 (for frozen stores). This can then be used to estimate the energy that a cold store should use in a particular ambient location and with a particular usage. The modelled results were compared to the survey data for ambient temperature surrounding the store of 12.6 ± 4 °C and are presented in Figs. 6 and 7. The results show that even though full details of usage for the survey population are not known, that some stores consume considerably more and some less energy than is predicted. By using this methodology the divergence between the energy actually used by a cold store and the energy it should use can be identified. This could be used to provide a metric of energy use per year per square metre that can be used to assess operation of cold stores.

4. Discussion

The data collected showed that there was large variability in the energy used by cold stores. The SEC varied between 4 and 250 kWh m^{-3} $year^{-1}$ for chillers, between 6 and 240 kWh m^{-3} $year^{-1}$ for freezers and between 23 and 157 kWh m^{-3} $year^{-1}$ for mixed stores. The minimum SEC values for chilled and frozen stores were lower than have been reported previously by most authors [4–9] but were not dissimilar to those reported by Carlsson-Kanyama and Faist [10]. However, the maximum SEC values were greater than reported by the IIR [4], Bosma [5], ETSU [6], Elleson and Freund [7] and Singh [8] but less than those reported by Werner et al. [9]. Excluding the upper and lower 10% values gave minimum SECs that were more similar to those previously reported. However, when the data are compared, the results confirm the large range in SECs for cold stores where for chilled and frozen stores the least

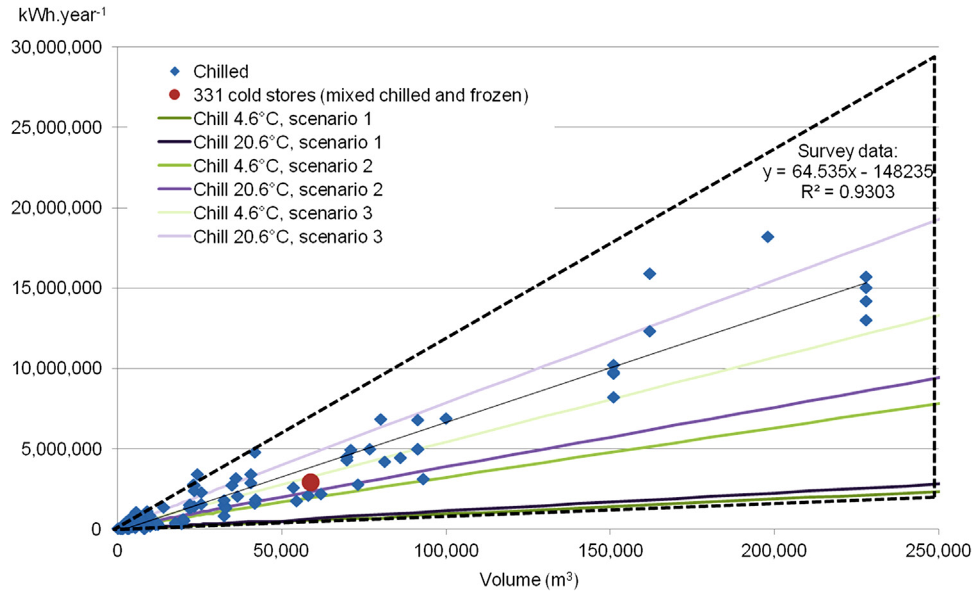

Fig. 4. Predictions from model (scenarios 1, 2 and 3) and range in energy consumption (dashed lines) superimposed onto survey data for chilled stores.

efficient stores used 4–5 times more energy than the most efficient stores. This indicates that considerable energy savings are possible.

Much of this variation can be explained by shape factor of the store, usage and to a lesser extent ambient conditions surrounding the store. When using a mathematical model to understand differences in energy use a large proportion of the survey data could be explained by these factors. When survey data was outside of the model predictions the store sizes tended to be small. This would indicate that use of these stores varied from the scenarios modelled or that a factor of their design affected their efficiency. As most of these stores used more energy than the model predicted it would seem likely that high usage and inefficiency contributed to the high energy usage reported.

The performance of all stores (chilled, frozen and mixed) was statistically different. However, there was more relationship between the performance of frozen and mixed stores than there was between chilled and frozen or chilled and mixed stores. The energy used by chilled stores was less than frozen or mixed stores at volumes below 22,000 m^3 but was higher above this value. This might indicate that large frozen stores tend to be long term stores with less usage and that larger chilled stores have high usage (e.g. large regional distribution centres where food is moved in and out of the store many times per day).

It would be expected that larger stores would be more efficient and have a lower SEC than smaller stores. This was found to be the case by Werner et al. [9]. In this work the indications were that this was only the case for frozen and mixed stores. For chilled stores the relationship between volume and store size was linear. The model demonstrated that SEC did vary with store volume but that it was most apparent at low store volumes and that at store volumes above 10,000 m^3 for chillers and 20,000 m^3 for freezers

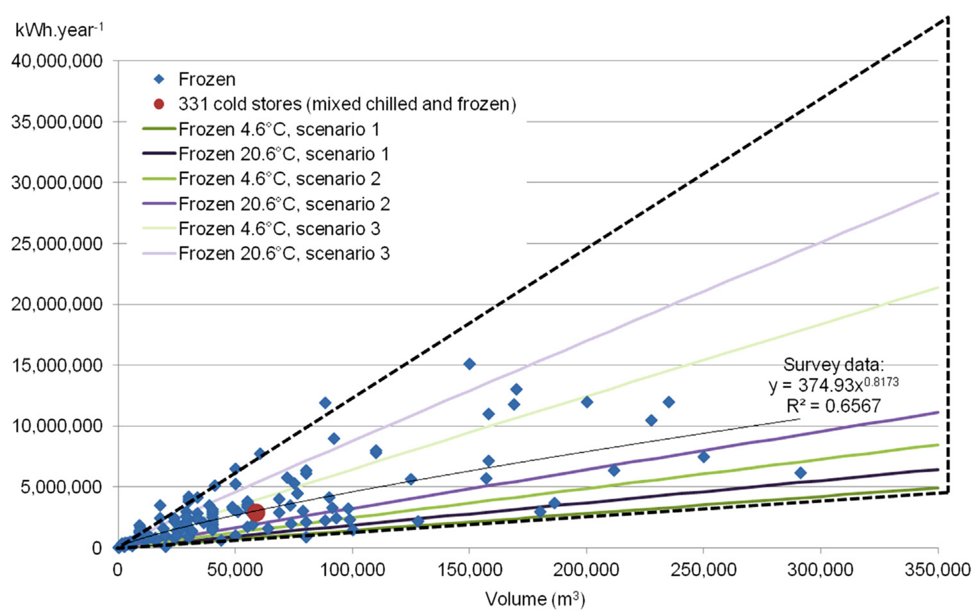

Fig. 5. Predictions from model (scenarios 1, 2 and 3) and range in energy consumption (dashed lines) superimposed onto survey data for frozen stores.

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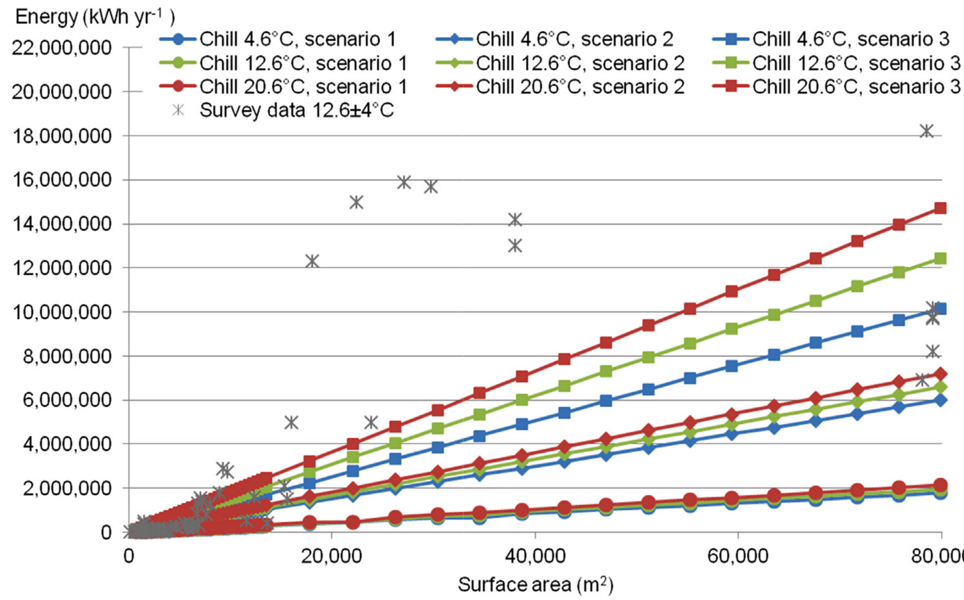

Fig. 6. Modelled impact of store total surface area (for scenarios 1, 2 and 3 at range of ambient temperatures) on annual energy consumption compared to survey data for chilled stores.

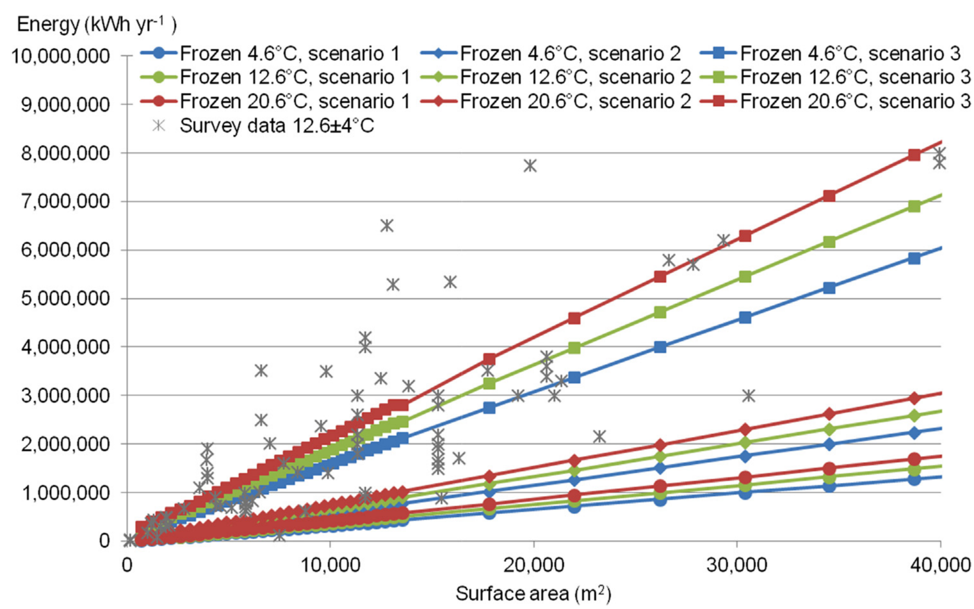

Fig. 7. Modelled impact of store total surface area (for scenarios 1, 2 and 3 at range of ambient temperatures) on annual energy consumption compared to survey data for frozen stores.

the rate of change in the SEC was less than 0.5 kWh m^{-3} year-1 per 10,000 m^3 increase in store volume.

The analysis demonstrated a surprising lack of relationships between the factors recorded (apart from volume) and annual energy consumption. There was for example no relationship for any store types with temperature of the store even though the range in temperatures recorded were relatively wide ranging (13 °C for chilled and 5 °C for frozen) and there was an extensive data set. In other instances the lack of any relationship may have been due to the restricted data sets available. It would therefore be useful to collect further data on the factors that were indicated to be important by the regression analysis and the mathematical model.

5. Conclusions

Survey data demonstrated differences between chilled, frozen and mixed usage cold stores. Store volume was the dominant factor that was related to energy used by the cold stores. The impact of cold store construction or usage had little impact on improving the relationship between store volume and energy consumption. This may have been due to a range of factors influencing energy consumption which themselves had a high correlation with volume. The mathematical model provided a better understanding of the variations in cold store energy consumption and helped to explain how usage, store shape factor and ambient conditions surrounding the store contributed to the range in efficiencies in the survey data.

The model was shown to be a useful tool to estimate energy use of a cold store and provided a mechanism to generate metrics that can be used to assess efficiency of a cold store.

Q2 Uncited reference

[15].

Acknowledgements

The authors would like to thank EACI (Executive Agency for Competitiveness and Innovation) for funding this work and in particular the project officer, Christophe Coudun for his help in managing the project.

Appendix 1. Information collected in survey

Survey page heading	Units
Basic information:	
Total electricity usage for the system in the year reported?	kWh
Does the electricity energy figure of the system submitted include?	
1. Compressor	Yes/No/Don't know
2. Lights	Yes/No/Don't know
3. Fans	Yes/No/Don't know
4. Pumps	Yes/No/Don't know
5. Fork/lift charging	Yes/No/Don't know
6. Blast freezing	Yes/No/Don't know
7. Floor heating	Yes/No/Don't know
If figure supplied includes blast freezing what is energy use	kWh
EXCLUDING blast freezing?	
What is the total volume of the room(s) supplied by the system?	m^3
What was the throughput in the year reported?	Tonne
What is the main function of the room(s)?	Chilled/frozen/mixed storage/blast freezing/loading
What is stored in the room(s)?	Mixed foods/Meat/Fish/Fruit/Vegetables/Dairy/Cereal products
	°C
What is the chilled set point temperature of room(s)?	°C
What is the frozen set point temperature of room(s)?	
Do you plans to invest in energy saving equipment?	Yes/No/Don't know
Refrigeration system:	
Primary refrigerant	Don't know/R22/CO_2/Ammonia/Other
Refrigerant quantity/charge	kg
Amount of refrigerant added to primary system in the year reported	kg
Secondary refrigerant	Don't know/R22/CO_2/Ammonia/Other
Refrigerant quantity/charge	kg
Amount of refrigerant added to primary system in the year reported	kg
Food stored:	
Average intake temperature for chilled products	°C
Average intake temperature for frozen products	°C (for mixed system fill both)
Does the room have controlled atmosphere?	Yes/No/Don't know
Does the room have humidity control?	Yes/No/Don't know
How is the food stored in the area?	Don't know/Pallets/Bins/Dolavs or containers/Placed on shelves
	Kg
How much food can be stored in the storage area	
How many pallets/containers can be stored in the storage area	Number
What is the number of pallets/containers INTAKE in the year reported	Number
What is the number of pallets/containers RELEASE in the year reported	
What is the average size and weight of one pallet/container	Number
	Width/Height/Depth all in m/kg
Facility:	
How many separate rooms does the system supply?	Number
What is the total floor area supplied by the system?	m^2
How much of the floor area is used for:	
• Chilled storage	m^2
• Frozen storage	m^2
• Blast freezing storage	m^2
How many doors (total) are there on the room(s)?	Number
How many times on average will each door be opened per day?	
Do the doors have any protection?	Number
Is product automatically or manually loading into the room?	Don't know/No protection/Strip curtain/Air curtain or Air
Where are the room (s) positioned?	lock/Automatic doors
What is the age of insulation?	Don't know/Manual (hand or fork lift)/Automatic (robot crane)
	Don't know/Inside a building/Outside
What is the thickness of the:	Don't know/ < 5 years/5–10 years/10–20 years/ > 20 years
• Wall insulation	
• Ceiling insulation	mm
• Thickness of the floor	mm
	mm

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Survey page heading	Units
Refrigeration equipment:	
Type of refrigeration cycle?	Don't know/Single stage/Multi stage/Cascade/Absorption cycle/Air
Type of refrigeration system?	cycle
	Don't know/Dry evaporator with thermostatic
Type of compressors?	valve/Flooded-pumped/Flooded-natural circulation
Do you have economised compressors?	Don't know/Reciprocating/Screw or Scroll/Rolling piston/Centrifugal
What is the compressor control system?	Yes/No/Don't know
How are compressors controlled?	Don't know/VSD/Unloading/Other
	Don't know/Suction pressure/Room air temperature/Other
Type of condensers?	Don't know/Air cooled/Evaporative/Water cooled/Cooling tower/Other
Defrost type?	Don't know/Hot gas/Electric/Passive/Other
Do you use any heat from the refrigeration plant?	
• If yes, what for	Yes/No/Don't know
What is the year of installation of the system?	Water heating/Floor heating/Other heating
	Year

Appendix 2. Cold store model

Nomenclature

A	surface area (m^2)
e	efficacy of the lamps ($lm\,W^{-1}$)
COP	coefficient of performance of the compressor
E	effectiveness of door protection or blockage
F	density factor
g	acceleration due to gravity (9.81 $m\,s^{-2}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
l	latent heat of fusion for water ($J\,kg^{-1}$)
L	height of cold store door (m)
LF	luminous flux ($lm\,m^{-2}$)
m	mass flow rate ($kg\,s^{-1}$)
n	stage coefficient
N	number
M	weight loss from product and packaging ($kg\,day^{-1}$)
P	electrical power
q	heat flow (W)
r	respiration
t	duration
T	temperature (°C)
U	overall heat transfer coefficient ($W\,m^{-2}\,K$)
x	fractional vaporisation of refrigerant in evaporator on expansion from liquid to saturation at discharge
X	concentration of water in air

Greek

α	empirical constant for different refrigerants
Δ	thickness (m)
ρ	density ($kg\,m^{-3}$)
μ	efficiency

Subscripts

ad	air through door
c	condensing
comp	compressor
d	door
do	door opening
ds	door seals
do24	door openings per 24 h
de	defrost
e	evaporating
f	floor
fl	fork lifts
fu	fusion
i	inside
l	lights
m	motor
o	outside
ot	other
pe	personnel
pr	product
T	total
v	vapour
w	wall

Model

The model was steady state, therefore all heat loads were averaged over one day. The shape of the cold store was a rectangular box. There was only 1 door and the cold store was otherwise fully sealed. The cold store had enough thermal mass such that door openings did not change the temperature in the cold store. The temperature of the ambient air outside the cold store was not changed by the door openings. There was only one layer of insulation on the walls, roof and floor. Any metal cladding was ignored as the resistance to heat transfer from this was considered negligible. The luminous flux from the lights was divided by the area of the floor and walls to give a uniform luminance. The thermal mass of the trucks was ignored. Therefore if they move from a warm environment into the store, they do not give up this heat to the store. Energy from fork lift trucks did not include charging the batteries. Any product which changed temperature when loaded into the store did not have a latent load (e.g. freezing and thawing) only a sensible load. Respiration was included for all vegetable and fruit product above 0 °C.

Data was input via a spread sheet. The inputs included;

- Information about each wall (including ceiling and floor) of the cold store, e.g. face area, whether it was in the sun, outside ambient or internal and the type and thickness of the insulation.
- The size of the door, its opening schedule, whether it was protected (e.g. by strip or curtains), amount of traffic through the door and the outside conditions.
- The refrigeration system, refrigerant, type of condenser, condenser ambient, efficiency of compressor and number of stages.
- Heat loads inside the store from forklifts, lights, personnel, product, defrosts and evaporator fans.
- Electrical loads from lights, defrosts, evaporator fans and condenser fans.

Heat loads

The total heat load, q_T, on the cold store was given by Eq. (1):

$$q_T = q_w + q_{do} + q_{de} + q_l + q_{fl} + q_{pe} + q_{pr} + q_m + q_{ot} + q_f \quad (1)$$

The heat load through the cold store wall was calculated using Eq. (2):

$$q_w = U \cdot A_w \cdot (T_0 - T_i) \quad (2)$$

The overall heat transfer coefficient, U was calculated from Eq. (3). A surface heat transfer coefficient of 9.3 W $m^2 K^{-1}$ was used for h_i and h_o. If the weather was selected as windy, h_o was increased to 34 W $m^2 K^1$.

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o} + \frac{\Delta w}{k_w} \quad (3)$$

The heat load through the door opening, q_d, was calculated using the sensible and latent heat exchange caused by mass flow of air during door opening and through the seals when the door was closed (Eq. (4)). The latent heat of fusion, $l_{fu} = 0$ when the evaporating temperature was >0 °C.

$$q_{do} = (m_{do} + m_{ds}) \cdot [c_p(To - Ti) + (Xo - Xi) \cdot (l_{fu} + l_v)] \quad (4)$$

Q3 The mass flow through an open door was calculated using the Gosney and Olama model (Eq. (5)) [21]. An effectiveness value was used to reduce the infiltration for door protection devices and traffic obstructing the opening as detailed by Chen et al. [19]. The mass flow through the seals was a function of the condition and length of the door seal.

$$m_{do} = (1 - E) \cdot 0.221 \cdot A_d \rho_i \left(1 - \frac{\rho o}{\rho i}\right)^{0.5} (g \cdot L)^{0.5} \cdot F \quad (5)$$

The density factor was calculated according to Eq. (6).

$$F = \left(\frac{2}{1 + \left(\frac{\rho_i}{\rho_o}\right)^{0.333}}\right)^{1.5} \quad (6)$$

The heat load due to people was calculated from ASHRAE [17,18] (Eq. (7)).

$$q = 273 - 6 \cdot T_i \quad (7)$$

The heat load from forklifts trucks was calculated from Eq. (8). The model provided values for small, medium or large trucks, electrically or internal combustion powered.

$$q_{fl} = N_{fl} \cdot P_{fl} \cdot t_{fl} \quad (8)$$

The product load was calculated based on flow of product into the store and the sensible heat it added or removed (Eq. (9))

$$q_{pr} = m.c.(T_p - T_i) + q_r \quad (9)$$

The heat load of the condenser and evaporator fan motors, q_m was given in Eq. (10). Where the electric motor were mounted outside of the cold store, $\mu_m = 1$.

$$q_m = \frac{N_m P}{\mu_m} \quad (10)$$

The heat load from the defrost was given by Eq. (11):

$$q_{de} = \left(\frac{1}{\mu_{de}} - 1\right) \cdot \left(\frac{m_{ad} \cdot (X_o - X_i) \cdot l \cdot t \cdot N_{do24}(M.l)}{24 \cdot 3600}\right) \quad (11)$$

Electrical power

The total electrical power was the sum of all the electrical loads (Eq. (12))

$$E_T = E_{comp} + E_{cond} + E_{evap} + E_{def} + E_f + E_o \quad (12)$$

An electrical energy of the compressor, E_{comp}, was derived from the total heat load (Eq. (1)) using a calculated coefficient of performance (COP) (Eq. (13)). The COP of the refrigeration system was calculated using the formula given in Cleland et al. [20] (Eq. (14))

$$E_{comp} = q_T.COP \quad (13)$$

$$COP = \frac{(T_c - T_e)}{(273 + T_e)(1 - \alpha.x)^n \mu_{comp}} \quad (14)$$

The electrical power of the condenser and evaporator fan motors, E_m was the same as the heat load given by (Eq. (10)).

For electric defrosts, the electrical power of the defrost heater was given by Eq. (15). If the defrost was hot gas or natural $E_{de} = 0$.

$$E_{de} = \frac{1}{\mu_{de}} \frac{\{[m_{ad}.(X_o - X_i).l.t.N_{do24}] + (m_{wat}.l)\}}{(24.3600)} \quad (15)$$

The electrical power of the lamps E_l was given in Eq. (16).

$$E_l = Lf.\frac{A_f + A_w}{e} \quad (16)$$

The total calculated heat load was presented plus individual heat loads from transmission, infiltration (door opening), defrost, lights, fork lift trucks, personnel, product, evaporator fans and other heat loads. The total electrical energy was presented plus the individual electrical loads from the refrigeration compressor, defrosts, condenser and evaporator fans, lights and floor heating.

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