27th CIRP Life Cycle Engineering (LCE) Conference

Energy performances assessment for sustainable design recommendations: Case study of a supermarket's refrigeration system

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A B S T R A C T

Nowadays, refrigeration is responsible for approximately 17% of the total electricity used worldwide and around 8% of greenhouse gas emissions. Since the Kyoto Protocols, refrigerants are subject to new regulations which represents a major challenge for the refrigeration industry. Almost half of the energy used in food retail is for cold production and studies have shown that improvement can be done to reduce this part of energy consumption. In this study, the energy consumption of a supermarket refrigeration system is assessed by considering multiple parameters. The results provide recommendations for the design of a sustainable refrigerating system integrating emerging solutions.

1. Introduction

In the last decades, an important demand of electric energy is observed worldwide to respond to the industry's development. Large food stores as supermarkets are energy-intensive buildings. Cold production is responsible for 17% of the world energy consumption. Refrigeration is necessary to maintain cold temperature in display cabinets or cold storage rooms to preserve food. Moreover, most commonly used refrigerants in supermarket are HydroFluoroCarbons (HFC) such as R404. Mostly because of the increasing need for cold applications and despite academics and industrials research to reduce environmental impacts of refrigeration systems and improve efficiency, the direct and indirect emissions (refrigerant leakage and energy consumption) of these systems is growing. Lowering electric consumption is one of the issues that researchers are addressing. Analyzing and understanding the energy consumption of refrigeration systems is necessary to improve their energy efficiency and to lower their environmental impacts by introducing renewable energy. This study aims to assess energy performances of different refrigeration system architectures in a supermarket. The different configurations are presented, analyzed and compared to point out design recommendations.

The literature background presented in the next session has pointed out challenging issues: the lack of holistic perspective on sustainable design for refrigeration systems and the lack of performance assessment of system's configurations for optimal design depending on operating conditions.

The study presented in this paper is based on literature and manufacturers data for a typical hypermarket in Paris, France. The objective of this work is the assessment of operational conditions and system architectures on the energy consumption to give design recommendations depending on the context. This work highlights the importance of refrigeration systems' architecture considered in the design phase for sustainability purpose.

2. State of the art

According to Tassou et al. (2011), approximately 3 to 5% of the annual electricity consumption in North West Europe is used for food refrigeration and between 35 and 50% of the energy consumption in supermarket (display cabinets or food conservation in cold rooms). Many studies on environmental impacts assessment of refrigeration systems have shown that during the lifetime of the system, the most important factor is the electric consumption of the system (Islam et al., 2017; Aprea et al., 2012; Cascini et al., 2016; Bovea et al., 2007; Maykot et al., 2004). Companies do not always have a clear picture of the energy flows of the energy consumption. However, studies were conducted to understand and identify the most influencing parameters. For a supermarket in

Nomenclature

A_{roof}	roof area for PV m^2
COP_{cold}	coefficient of performance
DX C	centralized direct expansion system
DX D	distributed direct expansion system
LT	low temperature application °C
MT	medium temperature application
P	PV nominal power W
$Pinch_c$	cold pinch °C
$Pinch_h$	heat pinch
PI	plug-in cabinet
PV	photovoltaic panel
Q_r	refrigeration power W
SL	secondary loop
T_c	cold temperature °C
T_h	heat temperature °C
$T_{set\,point}$	set point temperature
$T_{outside}$	outside temperature
η	refrigeration system performance
$\dot{W}$	energy required by the system J
W_{PV}	power produced by PV W

Table 1
Initial description of the store.

Store area	10,000 m²
Power for display cabinet (MT)	300 kW
Power for cold room (MT)	150 kW
Power for display cabinet (LT)	100 kW
Power for cold room (LT)	50 kW
Total MT refrigeration power	450 kW
Total LT refrigeration power	150 kW

Table 2
Operational conditions in the store.

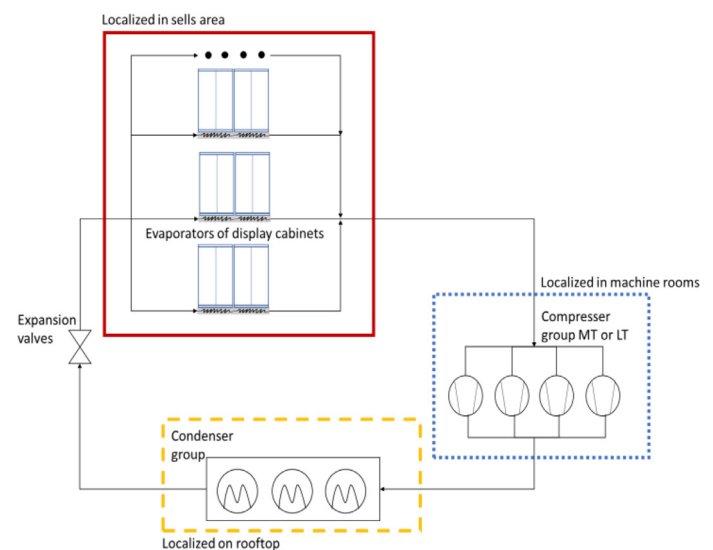|	
Store opening hours	8.30 am–8.30 pm
Indoor conditions	25 °C
Number of opening (per day for the whole store)	12,330
Opening duration per door	5 s
Set point temperature (MT cabinets)	2 °C
Set point temperature (MT cold rooms)	2 °C
Set point temperature (LT cabinets)	−18 °C
Set point temperature (LT cold rooms)	−20 °C

Fig. 1. Simplified scheme of a centralized direct expansion system architecture.

Latvia (Europe), a study was conducted to observe the impacts of customers behavior on the refrigeration system annual energy consumption (Timma et al., 2016). By using a benchmarking method, they observed a large variance of energy consumption per customer.

Bahman et al. (2012) investigated different supermarkets to estimate the sensitivity of the most influencing indoor conditions on energy consumption. They showed that by reducing 5% of the relative humidity in store, the display case refrigeration load is reduced by 9.25%, and that results in total store energy load reduction of 4.84%. Zhang compared environmental impacts, energy consumption and costs related to different configurations of refrigeration systems in a supermarket in the USA (Zhang, 2006).

According to audits carried out in European countries (UK, Italy, Switzerland, Denmark, Bulgaria and Belgium) by Evans et al. (2014), many issues are responsible for energy loss. They have shown that acting on four major parameters as control of compressors, defrost control, condensing pressure and insulation (cabinets and store), 8 and 82% of energy consumption could be saved.

Energy performance assessment of different refrigeration systems configurations and technologies have been deeply investigated by researchers in last decade (Tsamos et al., 2017; Gullo et al., 2016; Suamir and Tassou, 2013; Ge and Tassou, 2011). Moreover, it exists numerous types of systems architectures, refrigerants and promising new technologies such as cold storage with Phase Change Materials (PCMs) (Li et al., 2019; Souayfane et al., 2016). However, even if new technologies can offer better performances in some cases, the questions of how to integrate them in refrigeration system and which configuration to be adopted by industrials are needed to be considered.

3. Case study

3.1. Supermarket and operational conditions description

The energy consumption in a typical supermarket in France has been studied. Commonly there are two levels of temperature for display cabinets and cold storage rooms: medium and low temperatures (MT and LT) for chilled and frozen food. The supermarket's opening hours define the operational conditions. Moreover, customer's behavior, frequency and duration of display cab-

inet's door openings, defrosting frequency and schedule are important parameters for the evaluation of the energy consumption. The Table 1 and 2 present respectively a reference store conditions and the operating conditions. The data are based on an audit conducted by the ADEME, French Environment & Energy Management agency.

3.2. Refrigeration system architectures

3.2.1. Centralized direct expansion system

Most supermarket refrigeration systems use a centralized direct expansion system (DX C) where the cold production is connected to the entire store through a piping system that circulates and feeds refrigerants to all of the display cabinets' evaporators. The cold production system (usually in the machine room) is separated from the display cabinets' location. For a traditional centralized system to perform adequately, a certain number of compressors must be used in order to respond to the required power. The consequence of this layout may be unused compressor capacity and wasted energy consumption. However, this type of system is the easiest one to be installed due to its simple architecture.
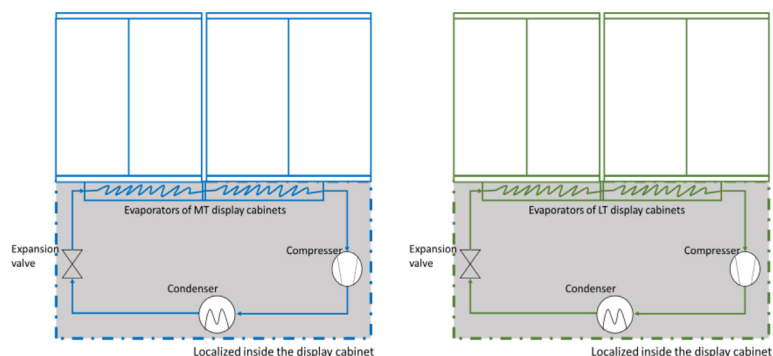
Fig. 2. Scheme of MT and LT plug-in cabinets.

Fig. 1 represents a simplified scheme of the system architecture. To match the reality of such a system, it is necessary to add ventilators and control components, which also consumes electricity.

3.2.2. Distributed direct systems

One alternative to centralized direct expansion (DX D) architecture is to divide the system into different sub groups. Distributed systems split the loads into matched groups, with the compressors physically located closer to the loads they are cooling. This simplifies the field piping and reduces heat losses thanks to a shorter the piping length. A typical distributed system store may have five or more units; each one is matched to a reduced set of loads. The units can be placed along the rear exterior of the store, or on the roof, directly over the loads to which they are connected. Distributed system units are generally smaller than centralized rack systems (often including built-in condensers on exterior-placed units), therefore some versions of the units can be situated in back rooms or on top of cold rooms or coolers (requiring connection to separate condensers). Distributed systems can operate more efficiently and eliminate the need for an in-store mechanical room or a complete exterior machine house.

The same design as the centralized direct system (Fig. 1) is used but the systems are smaller as the refrigerating power is divided by two. The system is composed of the same components as the centralized system, 2 units are for middle temperature range (MT, from 0 °C to 10 °C) and low temperature range (LT, from −25 °C to 0 °C).

3.2.3. Plug-in refrigeration units

Plug-in refrigeration units (PI) (Fig. 2) are direct expansion systems with: compressor, condenser, expansion valve and evaporator. In plug-in cabinets, the refrigeration unit is fitted inside the furniture. Thus, there is no machine room.

3.2.4. Secondary loop refrigeration systems

The secondary loop refrigeration systems (SL) are frequently used in industrial refrigeration and for air conditioning systems. This type of architecture was first introduced to overcome several drawbacks of refrigerants (toxicity, flammability, high Global Warming Potential…) or system incompatibility (ASHRAE, 2008). Indeed, the SL refrigeration system is composed of two circuits: a primary loop with classical refrigerants and a secondary loop to transport cold from the production rooms to the cabinets or cold rooms by using secondary environmental-friendly refrigerants (usually aqueous solution).

The baseline of this architecture is composed of the same components as the centralized system. The primary loop is a traditional vapor compression system and cools the secondary fluid through a heat exchanger. The cooled secondary refrigerant is pumped towards each terminal unit. (Wang et al., 2010). Fig. 3 illustrates the scheme of the loops that generates refrigeration.
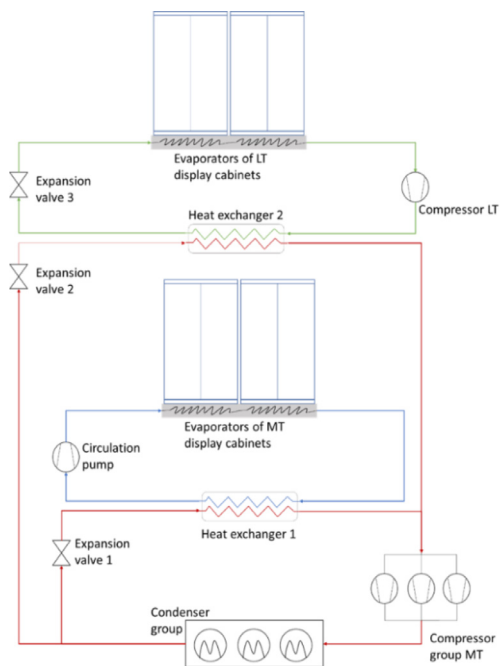

Fig. 3. Scheme of the secondary loop system for MT and direct expansion for LT.

4. Refrigeration system design step

4.1. Modeling conditions

4.1.1. Compressor performance

The compressor is chosen depending on the cold demand. In the supermarket, compressors used for refrigeration systems are identical. The most commonly used compressors are piston type as used in this study. For large stores, screw type compressors can be used and for low demand, scroll type compressors are often used. The data are obtained for a typical supermarket compressor types from the manufacturers. The number of compressors is chosen to provide cold for the most demanding day of the year (in the summer).

4.1.2. Condenser and condensing temperature

The cumulated heat is rejected outside through condensers. For supermarket applications, two types of condensers can be found on the store's rooftop: evaporative condensers or air-cooled condensers. The first type is more frequent in dry climates and operates at a lower condensing temperature. Air-cooled condensers are the most commonly used ones due to low needed for maintenance and their reliability. This type of condensers is used in this study.
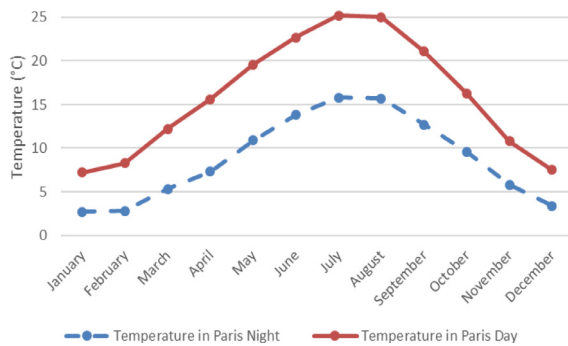
Fig. 4. Outside temperature for one year in Paris, France.

	Day	Night	Mean	Monthly
January	183.2	162.5	172.8	128,591
February	188.3	162.9	175.6	118,004
March	206.2	174.4	190.3	141,611
April	221.9	183.7	202.8	145,996
May	240.3	200.2	220.3	163,882
June	254.6	213.6	234.1	168,543
July	266.1	222.8	244.4	181,871
August	265.2	222.3	243.8	181,357
September	247.2	208.5	227.9	164,067
October	225.1	194.3	209.7	156,002
November	199.8	176.8	188.3	135,551
December	184.6	165.7	175.1	130,304

Fig. 5. Comparison of the energy consumption of different refrigeration architecture for 1 year.

In plug-in units air-cooled condensers are also used and they reject heat in the supermarket. The condensers are sized based on a pinch of 10 °C for both LT and MT. Pinch is the difference between condensing temperature and ambient air. The condensing temperature is maintained above 20 °C.

4.1.3. Evaporating temperature and saturated suction temperature

The refrigeration set point temperature defines evaporating temperature for each display case and cold rooms. When a group of display cases or walk-in coolers are assigned to a multi-compressor refrigeration system, the saturated suction temperature of the system is lower than the lowest evaporating temperature in the group.

4.1.5. Operational conditions

The store is in Paris, France and opened during 12 h from 8.30am. The data for the outside temperature is taken for the whole year using average values of previous years recorded temperatures (data from MeteoFrance).

The energy consumption is calculated differently for the day (store opening hours) and for the night (no activity and colder temperatures). Fig. 4 presents the yearly profile temperature data. In red, the mean of temperature during the day and in blue the mean of temperature at night.

For the secondary loop system, the airflow in each display case is cooled by the secondary fluid circulating inside a heat exchanger.

4.2. Calculation

The energy consumption, the energy consumption of each system is calculated. Thus, based on Ge and Tassou (Ge and Tassou, 2011) hypothesis, the total energy consumption of a refrigeration system in a supermarket is the sum of the consumption of the various subsystems. First, the theoretical COP (Coefficient of Performance) is calculated with Eq. (1):

$$COP_{cold} = \frac{T_c}{T_h - T_c} \tag{1}$$

With $T_c = T_{set\ point} - Pinch_c$ and $T_h = T_{outside} + Pinch_h$. $Pinch_c$ and $Pinch_h$ are respectively the difference between the air temperature and the evaporating or condensing temperature. The cold and heat pinch in the case study equals $Pinch_{c/h} = 10$ °C.

Then, Eq. (2) calculates the real COP.

$$COP_{carnot} = COP_{cold} * \eta \tag{2}$$

With η the efficiency of the refrigeration machine. In the case study, the typical efficiency equals $\eta = 0.5$.

The calculation of the amount of needed energy $\dot{W}$ to produce the refrigeration power is finally calculated by Eq. (3):

$$\dot{W} = \frac{Q_r}{COP_{carnot}} \tag{3}$$

COP_{carnot} is the coefficient between the heat extracted or cold demand power Q_r and the needed work. For example, in a supermarket of 10 000 m², for the medium temperature applications MT $Q_r(MT) = 450\ kW$ and for low temperature applications, $Q_r(LT) = 150\ kW$.

For plug-in units, the hypothesis of Glavan et al. (2016) is used: the energy consumption has been calculated for one cabinets and multiplied by the number of cabinets in the store.

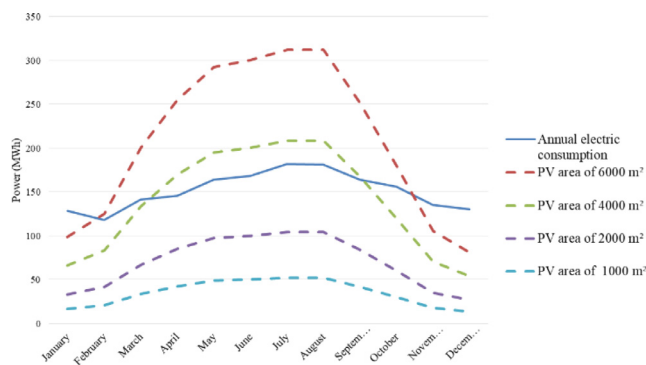## 5. Results

5.1. First calculation results

Table 3 shows the calculation of electric energy consumption of the reference refrigeration system for a typical year in France. As expected, for each architecture, the cold demand increases during the summer to maintain the mandatory conservation temperature in the cabinets.

The energy needs for the reference architecture (direct expansion system as it is the most frequently used system) in the supermarket are presented in Table 4. Fig. 5 shows a comparison of the annual consumption of different architectures. Plug-in cabinets show the most important consumption. This type of refrigeration system is however used frequently in supermarkets in northern Europe (UK, Sweden) (Kolokotroni et al., 2019). This is explained by the important heat released by such systems. Indeed, less energy is used to heat the store and thus balances the electric energy consumption.

Table 4
Comparison of energy required and power delivered by photovoltaic panels depending on the surface installed.

	Energy for food conservation kWh	Energy by PV kWh/m²	Needed surface m²	rooftop surface/ store area
January	128,591	16.5	7793	109%
February	118,004	20.8	5658	79%
March	141,611	33.4	4234	59%
April	145,996	42.5	3432	48%
May	163,882	48.8	3360	47%
June	168,543	50.1	3361	47%
July	181,871	52.1	3493	49%
August	181,357	52.1	3482	49%
September	164,067	41.9	3913	55%
October	156,002	29.9	5204	73%
November	135,551	17.6	7700	108%
December	130,304	13.5	9622	135%

Fig. 6. Energy needed compared to energy produced by photovoltaic panel during a year.

5.2. Impact of photovoltaic panels (PV) power production

The 2015 United Nations Climate Change Conference, COP21, has set the goal in the European Union of 27% of renewable energies. The French objective is to reach 32% of renewable energies in the electric production by 2030. The number of food retail stores in France has been increasing since the beginning of the century and has reached today 27,000 stores. A considered and interesting solution to reach the goal is the installation of PV on the store's roof to become as self-sufficient as possible and in some cases also to provide electric energy to the households located around or to the grid. The PV are installed on the supermarket's roof. The roof is considered flat and robust to support PV weight. The data is provided by the PV panel manufacturers. The amount of energy produced by PV depends on the area of the installation A_{roof} as follows. The nominal power P for the used PV panel is 331 W_p/m².

$$W_{PV} = P * A_{roof} \qquad (4)$$

Table 4 and Fig. 6 show the results for an installation of PV on the supermarket roof for different panel surfaces. The energy produced is compared to the refrigeration energy required. The electric consumption of supermarkets is more important during the day than during the night and thus the usage of PV for self-consumption is very compatible. However, some issues have been detected: for a case of renovation or an update, the roof must be adapted and must support the weight of the panels. Moreover, in these cases, the French regulation (La ministre de l'écologie du développement durable et de l'énergie Delphine Batho, 2012) constrains the company to renovate also the building's insulation which can significantly increase the renovation costs. It's thus better to install PV on a new building. Nowadays, some lighter panels are available, and it can be interesting to install them on existing buildings. In this case study, it is shown that the store cannot be self-sufficient the whole year. Due to the French regulation, it can be interesting to install PV on newly designed parking shack. The objective is to maximize self-sufficiency of the store. In this study, the table shows the importance of PV during the summer to compensate the energy required for food conservation. However, the energy produced by PV exceeds the energy needed by the refrigeration system, energy storage becomes a very interesting solution to investigate. Indeed, to prevent the surplus of energy to be reinjected in the network (less profitable for companies), thermal energy storage (cold storage tank) or electric energy storage (with batteries) are suitable solutions. Some newly developed technologies such as PV-T (photovoltaic-thermic) can not only bring thermal energy to the building but also the electricity produced by the PV. An advantage is the use of the same rooftop surface for both applications.

6. Conclusion

The cold industry has a large negative environmental impact mostly due to the energy consumption of systems during its use phase. This study aimed to focus on the influence of the supermarket operational conditions to give specific recommendations for refrigeration systems design. The electric consumption of different refrigeration architectures has been calculated for a typical hypermarket in the north of France. The different architectures were compared, and the distributed direct system was proven to be more interesting for energy consumption. However, the secondary system may have a longer lifetime and the secondary refrigerants are environmental-friendly. The use of PV for the store's self-consumption has been studied for different surface areas installed on the rooftop.

The study shows that trade-offs between environmental impacts, costs and performances of the systems need to be found depending on external conditions. General recommendations cannot be relevant for every food retail store even in the same country as the type of architecture, technology and expectations can be different. For sustainable purpose, reducing energy consumption of refrigeration systems is important as the running period is the most impactful life cycle phase. Thus, to optimize the design of those systems, the external conditions and the chosen boundaries of the study need to be considered in the final design. The perspectives of this work are to generalize and automatize the calculus to give adapted recommendations for refrigeration systems in food retail stores for new system design or renovation considering upcoming regulations on cold production systems. Therefore, it is necessary to integrate economical performances, environmental impacts, regulation, customer behavior... Even though the article focuses on the use phase of refrigeration systems' life cycle, it will be necessary to include in future work waste treatment aspects as it will have an impact on the design's choice.

CRediT authorship contribution statement

Yasmine Salehy: Writing - original draft. **Hong Minh Hoang:** Supervision. **François Cluzel:** Supervision. **Yann Leroy:** Supervision. **Anthony Delahaye:** Supervision. **Laurence Fournaison:** Supervision. **Bernard Yannou:** Resources, Supervision.

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