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ABSTRACT

Studies have shown that the use of Phase Change Materials (PCMs) in secondary refrigeration could improve the efficiency of refrigeration systems. In this study, the focus is made on CO_2 hydrate slurry. Despite the demonstration of the interest of such a system, there is a barrier to their industrial development. The work presented in this paper analyses the behaviour of hydrate slurries in an industrial context, here the air conditioning of supermarket, and proposes a multi-performance evaluation of hydrate slurry systems. Starting from the modelling of the rheological and thermal properties of the slurries established by experimental studies in the laboratory, their theoretical energy behaviour in an industrial case can be analysed. In addition, the environmental, economic and operational performance of the refrigeration system are simulated. This innovative architecture using hydrate slurries is compared to systems already implemented in industry such as centralised direct expansion systems using HFC as primary refrigerant and secondary loop using glycol water.

Keywords: refrigeration, multi-performances, hydrate slurry, secondary loop

1. INTRODUCTION

In recent decades, the world has been increasingly affected by climate change. According to Intergovernmental Panel on Climate Change (IPCC), annual greenhouse gas emissions increased by 80 % between 1970 and 2014 (Blanco *et al.* 2014). The refrigeration industry has been concerned with the environmental issues, banning ChloroFluoroCarbons (CFCs) refrigerants, responsible for the ozone layer depletion, and reducing the use of high Global Warming Potential (GWP) HydroFluoroCarbons (HFCs). However, rising temperatures have increased the need for refrigeration. Today, nearly 20 % of all electricity consumption is used for cold production. This figure is expected to rise with growing demand and is predicted to reach 37 % by 2050 (IEA 2018). In this context, academics and industry have conducted research to develop more sustainable solutions, such as improving the energy efficiency of refrigeration equipment or limiting the use of HFCs. For example, systems with a secondary loop (SL) could reduce the use of high GWP refrigerants. SL systems use secondary fluids to transfer heat. These fluids must be energy efficient. For this purpose, two-phase solid-liquid fluids, especially phase change materials (PCM) dispersed in a carrier liquid, are interesting candidates. Currently, ice slurries are mainly found in the industry as two-phase fluids. However, their generation, based on energy-intensive mechanical processes, is a limiting factor. Gas hydrate slurries, in particular CO_2, are an interesting alternative. Indeed, they are generated by simple gas injection and their latent heat of fusion (374 $kJ.kg^{-1}_{hyd}$) is higher than that of ice (333 $kJ.kg^{-1}$) (Fournaison et al., 2004).

In the literature, there is a growing number of papers showing the technological interest of such fluids. However, these studies do not consider the consequences of this integration on the ground (space needed, accessibility) and the complexity of the market (multiplicity of stakeholders).

It is thus necessary to consider at the same time new technology and socio-economic environment complexity in effective industrial implementation. To address this issue, the present work aims to test the potential of adoption of a low-TRL technology using CO_2 hydrates slurries as secondary fluid for supermarket air conditioning. To do so, a hybrid methodology is used based on classical process engineering approach to evaluate the performance of refrigeration systems, but structured in a research framework from industrial engineering, namely knowledge model or framework. The studied performances include the three pillars of sustainable development (Purvis *et al.*, 2019), environmental, economic, and social. To illustrate the approach, a case study of supermarket air contitioning systems is used. Three configurations are tested (direct expansion system – DX; secondary loop system using single-phase or two-phase refrigerant – SL) using realistic data and air conditioning system design's data from manufacturer and literature.

The ultimate objective of this generic yet realistic approach is to help manage research and development (R&D) and decision making for the implementation of more sustainable technologies.

2. MATERIALS AND METHODS

2.1. General methodology

To ensure better adoption of new technologies through a better understanding of their operation in an industrial space, a knowledge framework was developed to describe the multi-performance evaluation of refrigeration systems.

This framework follows the usual steps of a design process from the definition of the design problem (here the cold need specification) to the design decision based on the refrigeration system performance analysis (Pahl and Beitz, 2013):

- First step: *design problem definition*, also called task clarification, where the system environment and the related requirements (here cold needs for a supermarket air conditioning only) are defined.
- Second step: definition of the feasible solutions, i.e. the system structure with architecture, combination of components and technological innovative clusters, called *conceptual design*.
- Third step: performance assessment of feasible solutions, called *embodiment design*, using mathematical models to link different criteria or performances to each other. In the present model, four categories of performance are evaluated throughout the lifecycle: energy, environmental, economic, and social. This last performance involves the evaluation of operational/industrial conditions according to the system configuration.

Finally, one of the goals of the knowledge framework is to highlight the need for trade-offs in scenarios using real supermarket data. The overview of this knowledge framework is presented in Figure 1.

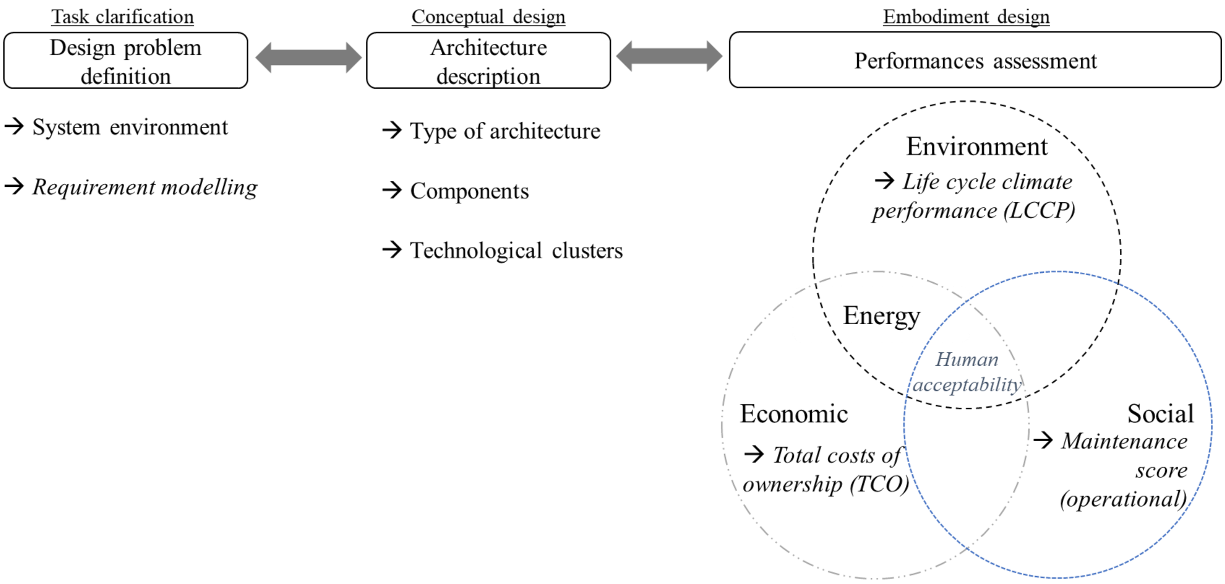

Figure 1. General overview of the process

2.2. Design problem definition

The design problem is defined in engineering design as the representation of the problem scope to be investigated to find a design solution (Gero, 1990). For this purpose, the system environment must first be described as well as the modelling requirements and assumptions.

2.2.1. System environment description

In the present model, the system environment includes all the operational conditions necessary to calculate the air conditioning requirements of the supermarket. It is composed of variables related to the calculation of the internal and external cooling load: location, supermarket description (store area, opening hours, number of employees, customers, description of the walls, display cabinets).

2.2.2. Modelling requirement

For the calculation of the requirements, here the cooling power, some assumptions are taken:

- The air conditioning (AC) set point temperature is assumed to be 21°C.
- AC runs from April to September included.
- The heat losses in pipes are neglected
- Superheating (evaporator) and subcooling (condenser) are 6 °C.
- In secondary loop system, temperature difference between inlet and outlet at the evaporator/heat exchanger is considered 6K for the glycol water and 1.3K for CO_2 hydrate slurry due to the latent heat of the solid-liquid phase change.

The system environment variables allow the cooling power for AC to be calculated. Then, the required cooling capacity is increased by approximately 30 % to follow industrial practices. For example, for a cold need of 30 kW, the industry would purchase a compressor with a maximum cooling capacity of 39 kW to account for error estimations or abnormal peak demands.

The cooling load for air conditioning can be calculated as the sum of the external and internal cooling loads:

$$\dot{Q}_{AC} = \dot{Q}_{external} + \dot{Q}_{internal} \quad (1)$$

In our study, the cooling requirement is based on the supermarket data from (Cecchinato et al., 2012). However, multiple adaptations have been made: the location of the store is in France and the set point temperature is set to 21°C instead of 26°C. Moreover, the required cooling capacity is increased by approximately 30 % as applied by industrial designers who take into account estimation errors or abnormal peak demands. Thus, the calculated AC cooling load is 250 kW.

2.3. Architecture description

2.3.1. Centralized direct expansion system

Most supermarkets use centralized direct expansion system where the cold production is connected to the entire store by a piping system that transports the refrigerant to all the air conditioning evaporators. The cold production is usually located in a machine room, separated from the sales area. A centralized system operates with multiple compressors to achieve the required cooling capacity. The result of this arrangement can be unused compressor capacity if the system is oversized. In the present paper, the refrigerant tested is R404a. Figure 2.a represents a simplified scheme of the modelled centralized system (without fans and control components).

2.3.2. Secondary loop system

Secondary loop (SL) refrigeration systems, also known as “Liquid-Chilling Systems” (ASHRAE 2008), are frequently used in industrial refrigeration and commercial comfort cooling. This architecture was first introduced to limit the use of refrigerants (toxicity/flammability, high GWP). It is composed of two loops (Figure 2.b). The primary loop, a direct expansion system using a primary refrigerant, cools a secondary fluid in a secondary loop via a heat exchanger (Wang et al. 2010). This secondary fluid provides the cooling capacity through heat exchangers, instead of traditional evaporators.

SL allows the containment of the primary loop and the use of climate-friendly secondary refrigerants (also known as heat transfer fluids). It reduces then the amount of primary refrigerant charge and the refrigerant leakage due to shorter circuits. In the present study, the primary refrigerants are R404a. Service and maintenance are easier than a primary centralized system (Horton 2004). The additional cost of the pumps and heat exchanger could be offset by reducing refrigerant charge and copper pipe length (by using plastic pipe for the secondary loop) (DelVentura et al., 2007). Kazachi and Hinde (2006) compared a secondary loop system and a traditional direct expansion system in a supermarket. They confirmed the advantages presented above and identified one disadvantage: additional energy consumption due to the intermediate circulation pumps and heat exchanger.

The secondary fluids tested can be either single-phase or two-phase. In this study, a single-phase fluid (glycol water) and a two-phase fluid (CO_2 hydrate slurries) are tested. CO_2 hydrate have several advantages: they have a high latent heat of fusion, so the slurry flow rate can be reduced to reach the desired power. In addition, the pipework can be reduced. The energy consumption of the secondary loop auxiliaries could thus be reduced. In addition, the high latent heat of hydrates gives thermal stability to the secondary fluid, which reduces thermodynamic irreversibility.

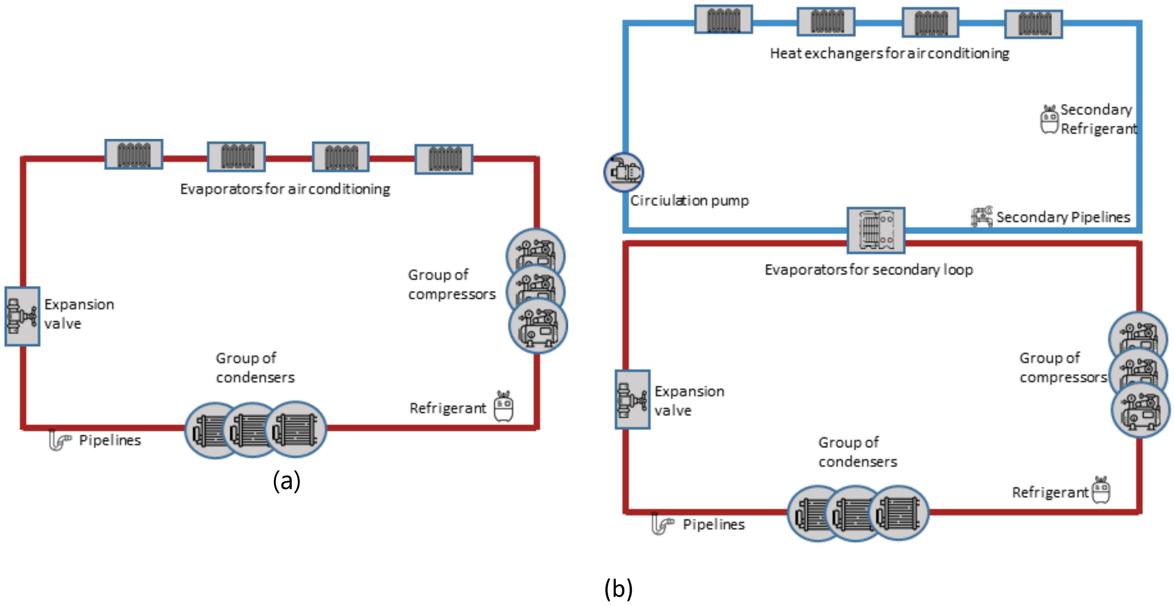

Figure 2. Simplified schemes of the architectures: (a) centralized direct expansion system; (b) secondary loop refrigeration system

2.4. Performances assessment

To assess how a solution fits to one scenario and compare among design solutions, various performances are modelled: energy consumption; environmental impact (Life Cycle Climate Performance – LCCP); financial cost (Total Cost of Ownership – TCO); and maintenance score. As in industrial design approach, the performance analysis is based on the manufacturer's data when available, and on the choice and the sizing of components according to the cooling requirement. Performance modelling steps are illustrated in Figure 3 and detailed in following sections. It should be noted that energy performance is used as an input for both environmental impact and financial cost. In the present study, only the supermarket air conditioning is modelled.

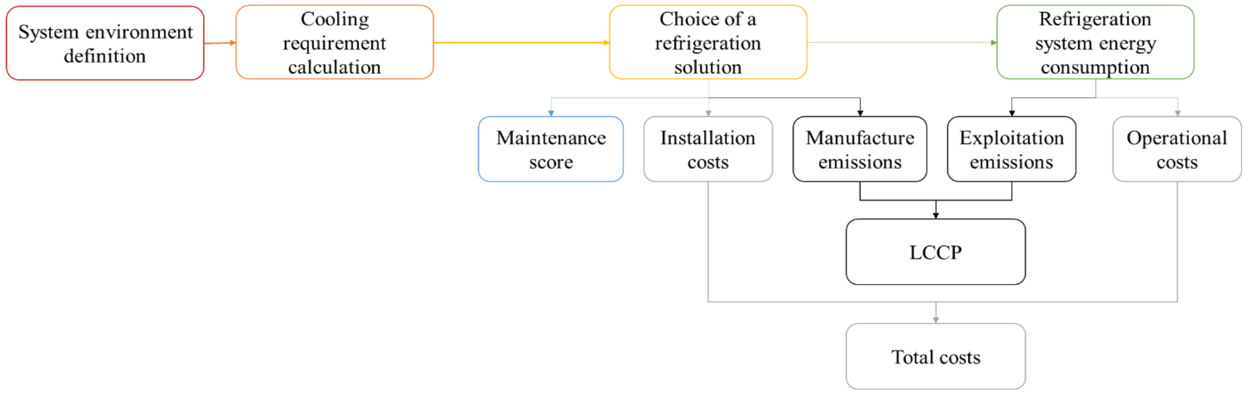

Figure 3. General overview of the system performance modelling

2.4.1. Energy consumption

For a daily energy consumption, E_{si} (kWh/day) is calculated as follows:

$$E_{si} = \dot{W}_{comp\_day} * \Delta t \tag{2}$$

Where Δt is the air conditioning functioning hours, and where

$$\dot{W}_{comp\_day} = \frac{\dot{Q}_{AC}}{COP} \tag{3}$$

With $\dot{W}_{comp\_day}$ the energy consumption by the compressor in kW; $\dot{Q}_{AC}$ the cooling power from equation (1).

And the coefficient of performance (COP) of the refrigeration system is defined as:

$$COP = COP_{theorical} * \eta \tag{4}$$

With η the efficiency of the compressor based on manufacturer data. In this paper, compressor irreversibility is indeed taken into account in this efficiency, as well as pinch in evaporator/condenser (in the COP calculation), and subcooling/superheating (included in cooling power). On the other hand, other irreversibilities such as pressure drop or non-isenthalpic expansion are not considered.

The theoretical COP is related to the cooling power $\dot{Q}_{AC}$, the compressor power $\dot{W}_{comp\_day}$, and consequently the power at the condenser. Moreover, the evaporation temperature is considered 6°C for direct expansion system, and the supply temperatures for the secondary fluids are respectively 5 and 2.9 °C for glycol water and CO_2 hydrate slurry.

To simulate the energy consumed for SL, $E_{cluster}$, several parameters must be considered depending on the type of secondary fluid.

Table 1 resume the main parameters used in this study for glycol water as a single-phase fluid and CO_2 hydrate slurry as a two-phase fluid.

For the hydrate slurry, two main steps are considered:

- Firstly, the amount of hydrates generated depends on the cooling requirement and the desired application temperature. In our case, a hydrate fraction of at least 4.5 wt% must be melted, together with a temperature increase of 1.3K, to achieve a cooling capacity of about 250 kW (Marinhas et al., 2006; Dufour et al., 2019). To ensure the reformation of hydrates in the loop, it is recommended to leave some of the solid fraction in the fluid (slurry). For this main reason, the solid fraction in the slurry is considered to be 7 wt% from the primary/secondary evaporator to the user's heat exchanger.

- Secondly, the calculation of the pumping power is based on the type of slurry in the secondary loop. The viscosity of the slurry depends on the hydrate fraction. Based on the rheological profile of the 7 wt% CO_2 hydrate slurry (Jerbi et al., 2013), the length of the pipe and the flow rate in the loop, a required pumping capacity can be obtained.

Table 1. Secondary fluid parameters

	Glycol water	CO_2 hydrate slurry
ΔT in heat exchangers	6 K	2.1 K
Minimum solid fraction melting (ΔΦ)	-	3.5 wt%
Sensible specific heat (Cp)	3.56 kJ.kg^{-1}.°C^{-1}	3.45 kJ.kg^{-1}.°C^{-1}
Latent heat	-	374 kJ.kg^{-1}.°C^{-1}
Pumping power	1.9 kW	2.3 W

2.4.2. Environmental impact assessment

To assess the environmental impacts of the refrigeration system, the chosen method is Life Cycle Climate Performance (LCCP), characterising the global emissions of a refrigeration system during its whole lifecycle (Hwang et al., 2015):

$$LCCP = \sum DEm + \sum IEm + \sum EEm \tag{5}$$

With DEm the direct emissions; IEm the indirect emissions; EEm the embodied emissions.

In this study, LCCP is expressed in $kgCO_{2eq}$, without considering other categories of environmental impacts such as ozone depletion or eco-toxicity. The detailed equations can be found in Salehy et al. (2023).

The direct emissions (Eq 6) are the sum of the emissions related to the refrigerant leakage occurring during the exploitation phase, also called Middle Of Life (MOL), and the end-of-life (EOL) treatment phases.

$$\sum DEm = DEm_{refleak,MOL} + DEm_{refleak,EOL} +/- DEm_{cluster} \tag{6}$$

The indirect emissions (Eq 7) are the emissions related to the energy (electric) consumption of the system during the MOL.

$$\sum IEm = IEm_{sys,MOL} +/- IEm_{cluster} \tag{7}$$

The embodied emissions (Eq 8) are the emissions related to the manufacture called Beginning of Life (BOL) and EOL treatment.

$$\sum EEm = EEm_{sys,BOL} + EEm_{ref,BOL} + EEm_{sys,EOL} +/- EEm_{cluster} \tag{8}$$

The lifetime of the refrigeration system is considered to be ten years. The necessary properties (GWP of each material manufacture, electricity) were found in EcoInvent v3.8 database (Wernet *et al.*, 2016).

2.4.3. Total costs

To evaluate the cost of the refrigeration system through its lifecycle, the chosen metric is the Total Cost of Ownership (TCO) (Ellram, 1995). It is calculated as the addition of all the direct and indirect costs during the system lifecycle, as illustrated by Figure 3. It consists in the sum of the capital costs (CAPEX) and the operational costs (OPEX).

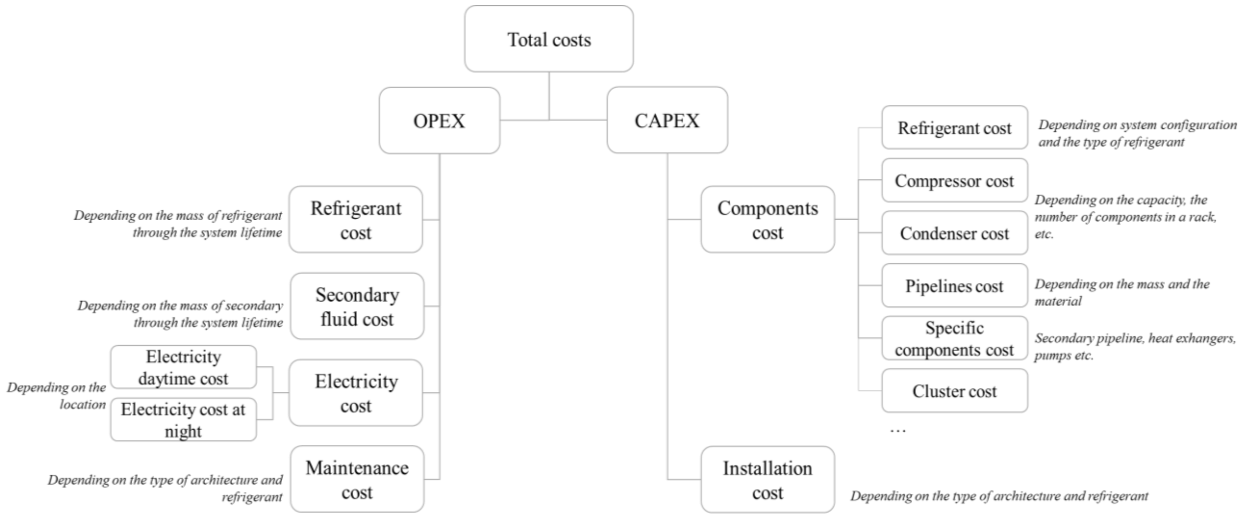

Figure 3. Calculation of the TCO metric

The TCO is calculated based on the following equations:

$$TCO = CAPEX + OPEX \tag{9}$$

Where the installation costs depend on the cooling requirement in kW and the type of architecture installed. The maintenance costs depend on the system architecture.

2.4.4. Maintenance evaluation

Refrigeration system maintenance is an important part of the exploitation phase in the life cycle. It ensures the efficiency of the machines and avoids breakdowns and accidents. The maintenance activities are standardized, i.e. should respect guidelines (number per year, certifications for operators according to the refrigerant, procedures, reports, etc.).

The latest studies on maintenance assessment for refrigeration systems or building highlights that the most widespread and easy quantitative method to assess maintenance is by cost analysis. For example, Alrwashdeh and Ammari (2019) establish a life cycle cost analysis, including in their model costs of acquisition, energy, repair, maintenance and disposal for two types of refrigeration system. In the present paper, this maintenance cost is already included in the TCO assessment.

However, it is not simple to qualitatively evaluated maintenance, due to the complexity of the systems, the organizations involved, the technologies and the standards that govern it (Amrina et al., 2020). By extending the field of research to ergonomics, another way to assess maintenance based on a qualitative approach can be considered. In this paper, the maintenance is evaluated both quantitatively by the TCO and qualitatively as a score that depends on the architecture and the refrigerant. It is based on four sub-classes from Geng *et al.* (2013): accessibility, error proofing, ergonomic and physical injury. Some evaluation elements, such as ergonomics is adapted for refrigeration systems, as well as rank illustrations according to an illustration table detailed in Salehy et al. (2023). The higher the score, the more difficult the system is to be maintained and installed. The maintenance score is evaluated as follows:

$$Maintenance\ score = Architecture\ score + Refrigerant\ score + Cluster\ score \tag{10}$$

Where

$$\begin{aligned} Architecture\ score \\ &= accessibility\ score + \ error\ proofing\ score + \ ergonomic\ score \\ &+ \ physical\ injury\ score \end{aligned} \tag{11}$$

$$Refrigerant\ score = \ error\ proofing\ score + \ physical\ injury\ score \tag{12}$$

And $Cluster\ score$ is the score of the other technological clusters included (for example CO2 hydrate slurry in our case study).

3. RESULTS

3.1. Model verification

To check if the modelling method is well implemented, the energy consumption of a refrigeration system only for air conditioning was simulated and compared to experimental data taken from a case study of a simulated supermarket (Cecchinato et al., 2012).

The surface area of the supermarket is approximately 3 000 m². The air conditioning is considered active during the summer period from April to September inclusive, 14 hours per day, 6 days per week. The set temperature is 26°C and the relative humidity is 60 %. The total energy consumption obtained in their study for air conditioning only from April to September is approximately 53 500 kWh. In the proposed model, the total energy consumption obtained is 50 681 kWh. Thus, there is a relative difference of 5 %, which is considered acceptable.

3.2. General results

In the following sections, the results include the monthly and yearly energy consumption for air conditioning, the lifecycle climate performance (LCCP), the total cost of ownership (TCO) and the maintenance scores.

3.2.1. Energy consumption

Figure 4 represents the yearly energy consumption for air conditioning from april to september in supermarket for the three studied architectures: centralized direct expansion using R404a (DX) in blue, secondary loop using CO_2 hydrate slurry (SL HYD) in yellow and secondary loop using glycol water (SL GLY).

The cooling requirement and the weather is the same for all architecture so the energy consumption depends mainly on the architecture and the associated components. Secondary loop system using CO_2 hydrate slurry as secondary refrigerant is the most efficient system according to our model. Indeed, this can be explained mainly by the fact that the heat exchanger temperature differential for CO_2 hydrate slurries is about 4.5 times lower than for water glycol for example. This means that the power of the primary circuit is much lower than with water glycol. In addition, it is interesting to note that centralized systems using R404a as primary refrigerant consume slightly more power than those with a secondary architecture. The evaporators of the centralized system are modelled in series, which causes a significant degradation that affects the temperature of the primary fluid, and thus a higher compressor requirement.

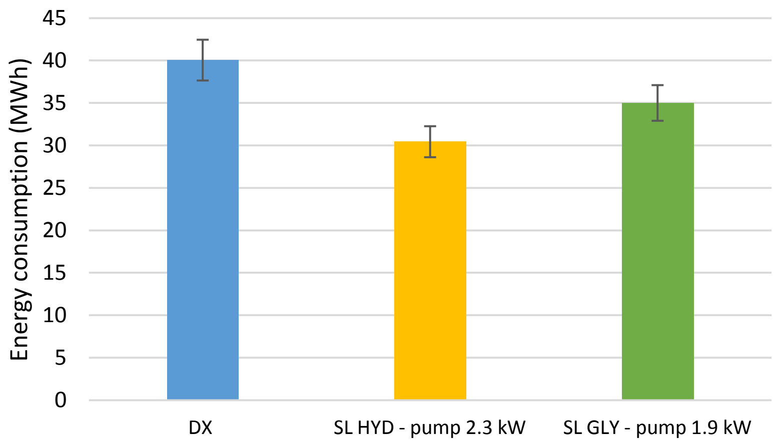

Figure 4. Yearly energy consumption for the three architectures: DX; SL HYD; SL GLY

3.2.2. LCCP

Figure 5 represents the LCCP calculated over ten years for the three architectures. Energy consumption is the most significant factor when calculating environmental impacts. As the power consumption of the DX is higher than that of the other two architectures, it has a greater environmental impact.

Furthermore, the notable difference between DX and SL systems is explained by the type of primary fluid used, which has a high GWP (R404a) and is used in greater quantities than in SL systems. In environmental impacts calculation, the type of fluid and the leakage during the different life cycle phases are two important factors influencing significantly the LCCP. Indeed, the GWP in the use phase of R404A is 3922 kg CO_2 eq / kg of fluid. The environmental impact of its production is about 130 kg CO_2 eq / kg of fluid, according to Ecovent v3.8 data. The GWP of glycol water in the use phase is 3 kg CO_2 eq / kg of fluid and its production is about 0.51 kg CO_2 eq / kg of fluid. For CO_2, the GWP of production is higher that the usage GWP 1 kg CO_2 eq / kg of fluid. A limitation of this work is the consideration of the manufacture of the hydrate slurry. Indeed, it is considered in this work that the slurry is already formed and circulates in the secondary loop. In practice, additional energy input and several auxiliary components would be required to form hydrates and then circulate them in the transport loop. However, it is recognized that the LCCP over a ten-year period is largely due to the operation phase and, to a lesser extent, the manufacturing phase.

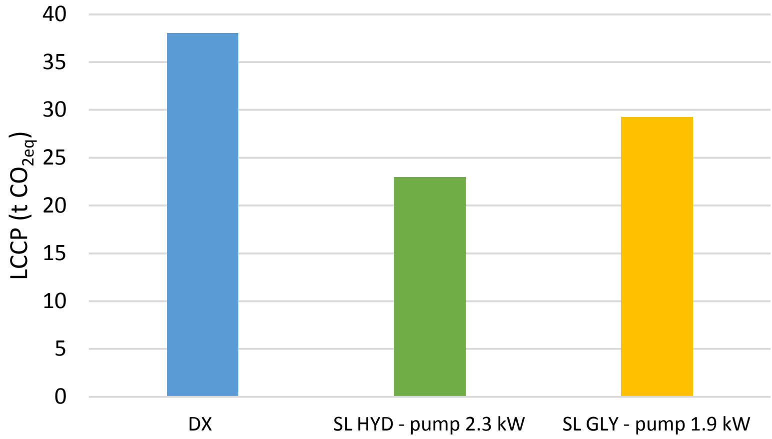

Figure 5. LCCP calculated over ten years for the three architectures: DX; SL HYD; SL GLY

3.2.3. Total Cost of Ownership (TCO)

Figure 6 presents the comparison histogram of the average annual TCO calculated over ten years for the three architectures. As a reminder, TCO is an economic approach to calculate the total costs of a system during its entire life cycle (from manufacture to end-of-life treatment). In this case, the calculation of TCO is presented in section 2. First, the TCO for all three architectures are highly depending on the electric consumption of the systems. This is why the OPEX of DX system is higher than SL systems.

Moreover, several factors can explain why SL GLY and DX are almost as expensive. Firstly, the fluid R404 used as primary refrigerant in this study is about 4 to 10 times more expensive than glycol or CO_2. The mass of the fluid used in DX and the high leakage rate, 15-25% for DX versus 5-10% for both SL, impact the OPEX. Indeed, OPEX for SL is lower than for DX. However, the SL installation and maintenance costs are much higher than those for DX. Thus, a balance is achieved.

In this study, it is considered that systems with CO_2 hydrate slurry have the same maintenance parameters as systems with glycol water. However, to ensure that the hydrates are properly formed and still present in the system, more regular maintenance should be considered as well as training for operators in this type of system. Finally, the cost calculations do not take into account the auxiliary components needed to form and maintain the CO_2 hydrate slurry, which may influence the trends.

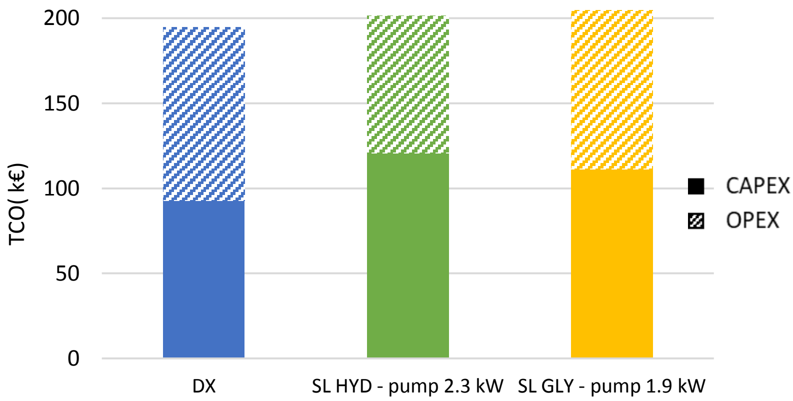

Figure 6. Average annual TCO for the three architectures: DX; SL HYD; SL GLY

3.2.4. Maintenance score

The maintenance score for each architecture and refrigerant is presented in Table 2. Maintenance was already taken into account quantitatively in TCO sections. In this section, the maintenance is assessed based on the qualitative analysis of the domain experts from French installation and maintenance companies. The architecture maintenance score is based on the installation, maintenance and EOL handling of the system.

DX or SL GLY systems are the most frequently used system for supermarket due to their ease of installation, and better operator experience. However, the maintenance is more frequent because of high-GWP refrigerant usage. Moreover, condensers located on the rooftop require a secured accessibility for the operators.

SL HYD are more complicated to assess as they are not yet industrialized. SL HYD uses CO_2 gas and should therefore be subject to pressure equipment regulations in the same way as CO_2 systems (e.g. transcritical, subcritical), which increases the score obtained. In addition, the risks associated with the use of this new technology are reflected in the much higher score than for the other two proven systems. Moreover, the EOL treatment parties are not yet prepared for such system (Salehy et al., 2021). The score for SL HYD is thus expert-based.

Due to lack of knowledge for each component of the system, the score is assessed only depending on the architecture and refrigerant used. It should be completed with the scores of each component, for example type of installed compressor or condenser.

Table 2. Maintenance score

Category	DX	SL GLY	SL HYD
Ergonomic	2	2	2
Error proofing	4	2	6
Marking	2	4	4
Operation space	0	0	0
Reachability	2	2	2
Physical hurt preventing	0	2	4
Visibility	2	0	0
Total maintenance score	12	12	18

4. CONCLUSION AND PERSPECTIVES

This paper proposes a multi-disciplinary (process engineering, industrial engineering) modelling of air-conditioning systems in supermarket. Three main modelling steps are defined for multi-performance analysis: task clarification with system environment modelling; conceptual design with solution/architecture definition; and embodiment design with performances assessment.

This work sets up a methodological structure to test different scenarios towards more sustainable systems. For this purpose, four performances are defined according to the pillars of sustainability: energy consumption, environmental impact through Life Cycle Climate Performance (LCCP), economic through Total Cost of Ownership (TCO) and social through maintenance scores. Although the maintenance score and TCO have a high level of uncertainty and should be discussed carefully, they are given as an indication toward the development of innovative technological cluster. The feasibility of the proposed approach has been demonstrated. It would allow to test different innovative technologies in refrigeration to analyse their performance in real industrial cases or to highlight scientific or technical levers to their industrial maturity.

In this study, architectures and components already developed industrially are used to test the proposed approach. Main outcomes of this work are listed below.

The results show interesting performance for CO_2 hydrate slurry as a secondary fluid in terms of energy efficiency and environmental impacts, compared centralized direct expansion using R404a and secondary loop using glycol water. The presented study allows to evaluate the behaviour of CO_2 hydrate slurries in a real industrial case by raising questions of operability. To go further in this analysis, it would be interesting to test other system configurations, to take into account the generation of hydrates as well as the necessary auxiliary components in the modelling process. It could be used to highlight critical issues toward the industrial development of such systems.

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NOMENCLATURE

GWP	Global Warming Potential	LCCP	Life cycle climate performance
$\dot{Q}_X$	Heat flows	DE_m	Direct emissions
$\dot{W}_x$	Compressor power	EE_m	Embodied emissions
Δt_x	Functioning hours	IE_m	Indirect emissions
E_{si}	Electric consumption	TCO	Total cost of Ownership
COP	Coefficient of performance	$CAPEX$	Capital costs
T_x	Temperature	$OPEX$	Operational costs
η	Efficiency		

REFERENCES

Alrwashdeh, Saad S., and Handri Ammari. 2019. ‘Life Cycle Cost Analysis of Two Different Refrigeration Systems Powered by Solar Energy’. *Case Studies in Thermal Engineering* 16: 100559. https://doi.org/10.1016/j.csite.2019.100559.

Amrina, Elita, Insannul Kamil, and Dhova Aridharma. 2020. ‘Fuzzy Multi Criteria Approach for Sustainable Maintenance Performance Evaluation in Cement Industry’. *Sustainable Manufacturing - Hand in Hand to Sustainability on Globe: Proceedings of the 17th Global Conference on Sustainable Manufacturing* 43 (January): 674–81. https://doi.org/10.1016/j.promfg.2020.02.125.

ASHRAE. 2008. ASHRAE Handbook—HVAC Systems and Equipment. ASHRAE Atlanta, GA.

Blanco, Gabriel, Reyer Gerlagh, Sangwon Suh, John Barrett, Heleen C. de Coninck, CF Diaz Morejon, Ritu Mathur, Nebojsa Nakicenovic, Alfred Ofosu Ahenkorah, and Jiahua Pan. 2014. ‘Drivers, Trends and Mitigation’, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, .

Cecchinato, L., Corradi, M. and Minetto, S., 2012. Energy performance of supermarket refrigeration and air conditioning integrated systems working with natural refrigerants. *Applied Thermal Engineering*, 48, pp.378-391.

DelVentura, Robert, Celena L. Evans, and Ira Richter. 2007. ‘Secondary Loop Systems for the Supermarket Industry’. *Bohn White Paper Setembro De*.

Dufour, T., Hoang, H.M., Oignet, J., Osswald, V., Clain, P., Fournaison, L. and Delahaye, A., 2017. Impact of pressure on the dynamic behavior of CO2 hydrate slurry in a stirred tank reactor applied to cold thermal energy storage. *Applied Energy*, 204, pp.641-652.

Ellram, Lisa M. 1995. ‘Total Cost of Ownership’. *International Journal of Physical Distribution & Logistics Management* 25 (8): 4–23. https://doi.org/10.1108/09600039510099928.

Finckh, O., R. Schrey, and M. Wozny. 2011. ‘Energy and Efficiency Comparison between Standardized HFC and CO2 Transcritical Systems for Supermarket Applications’. In *Proceedings of the 23rd IIR International Congress of Refrigeration, Prague, Czech Republic*, 21–26.

Fournaison, L., Delahaye, A., Chatti, I. and Petitet, J.P., 2004. CO2 hydrates in refrigeration processes. *Industrial & engineering chemistry research*, 43(20), pp.6521-6526.

Geng, Jie, Dong Zhou, Chuan Lv, and Zili Wang. 2013. 'A Modeling Approach for Maintenance Safety Evaluation in a Virtual Maintenance Environment'. *Computer-Aided Design* 45 (5): 937–49.

Gero, J. S. (1990). Design Prototypes: A Knowledge Representation Schema for Design. *AI Magazine*, 11(4), 26. https://doi.org/10.1609/aimag.v11i4.854

Horton, William Travis. 2004. 'Modeling of Secondary Loop Refrigeration Systems in Supermarket Applications.'

Hwang, Y., C. I. Ferreira, and C. C. Piao. 2015. 'Guideline for Life Cycle Climate Performance'. *International Institute of Refrigeration, Paris*.

IEA. 2018. 'The Future of Cooling'. Paris: International Energy Agency. https://www.iea.org/reports/the-future-of-cooling.

Jerbi, S., Delahaye, A., Oignet, J., Fournaison, L. and Haberschill, P., 2013. Rheological properties of CO2 hydrate slurry produced in a stirred tank reactor and a secondary refrigeration loop. *International Journal of Refrigeration*, 36(4), pp.1294-1301.

Kazachki, Georgi S., and David K. Hinde. 2006. 'Secondary Coolant Systems for Supermarkets'. *ASHRAE Journal* 48 (9): 34–47.

Marinhas, Sandrine, Delahaye, Anthony, Fournaison, Laurence, Dalmazzone, Didier, Fürst, Walter, Petitet, Jean-Pierre, 2006. Modelling of the available latent heat of a CO2 hydrate slurry in an experimental loop applied to secondary refrigeration. *Chemical Engineering and Processing: Process Intensification* 45:184-192. https://doi.org/10.1016/j.cep.2005.08.002.

Pahl, Gerhard, and Wolfgang Beitz. 2013. *Engineering Design: A Systematic Approach*. Springer Science & Business Media.

Purvis, Ben, Yong Mao, and Darren Robinson. 2019. 'Three Pillars of Sustainability: In Search of Conceptual Origins'. *Sustainability Science* 14 (3): 681–95. https://doi.org/10.1007/s11625-018-0627-5.

Salehy, Yasmine, Delahaye, Anthony, Hoang, Hong Minh, Fournaison, Laurence, Cluzel, François, Leroy, Yann, Yannou, Bernard, 2023. Choosing an optimized refrigeration system based on sustainability and operational scenarios applied to four supermarket architectures in three European countries, *Journal of Cleaner Production* 392, 136307.

Salehy, Yasmine, Yannou, Bernard, Leroy, Yann, Cluzel, François, Fournaison, Laurence, Hoang, Hong-Minh, Lecomte, Robin, Delahaye, Anthony. 2021. 'Diagnosis of Development Opportunities for Refrigeration Socio-Technical System Using the Radical Innovation Design Methodology'. *Proceedings of the Design Society* 1: 1263–72.

United States. Congress. Senate. Committee on Foreign Relations. 1993. *Amendment to the Montreal Protocol on Substances That Deplete the Ozone Layer : Report (to Accompany Treaty Doc. 103-9)*. [Washington, D.C.?] : [U.S. G.P.O.], [1993]. https://search.library.wisc.edu/catalog/999803377502121.

Wang, Kai, Magnus Eisele, Yunho Hwang, and Reinhard Radermacher. 2010. 'Review of Secondary Loop Refrigeration Systems'. *International Journal of Refrigeration* 33 (2): 212–34. https://doi.org/10.1016/j.ijrefrig.2009.09.018.

Wernet, G., Bauer, C., Steubing, B. et al. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21, 1218–1230 (2016). https://doi.org/10.1007/s11367-016-1087-8