DIGITAL TWIN MODELING OF REFRIGERATED WAREHOUSES

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1. - INTRODUCTION

The European Commission (EC), based on the European Green Pact (2019) and the Recovery Plan for Europe (2021), proposes that energy efficiency should be the basis for future EU energy priorities [1].

Achieving energy efficiency in the field of cold storage for food is complex, since these are facilities where products of distinct nature are stored, which means that they will have both disparate refrigeration needs and different transport and distribution configurations. Therefore, the logistics operations in these centers, such as product loading and unloading, depend strongly on the type of product stored and have a great impact on energy consumption [2]-[3]. Furthermore, a small variation in the thermal conditions of conservation can lead to losses of accumulated food, so control over these temperatures must be exhaustive, especially in the processes leading to consumption reduction [4]. All these factors affect the energy consumption of these facilities and complicate the implementation of any energy efficiency measures, which increases significantly with the diversity of foodstuffs handled in the center. These difficulties are also economic in nature since the rental price of the cooling areas is highly dependent on its energy consumption [5]-[6].

However, new technologies associated with the Internet of Things are making their way into the field of energy management and in particular the cold storage of food [7]-[8]. Intelligent platforms provide real-time recording, monitoring and control of thousands of variables simultaneously, making them well suited for energy, thermal and economic management in refrigerated warehouse [7]-[9].

This paper analyzes the case of a cold storage center in which an in-cloud platform is implemented with mathematical developments that allow energy management of the facilities in real time, i.e., a digital twin is implemented. By means of this digital twin, control of temperatures and energy consumption is achieved, minimizing food losses or energy cost overruns, which helps the logistics center have fewer emissions while improving economic profitability.

2. - METHODOLOGY

To achieve our goal of creating a Digital Twin of a refrigerated warehouse equipped with a single cooling generation system and cold chambers that are used by different clients with diverse products and cooling needs, the following steps were taken:

1) Temperature sensors and network analyzers were installed in the refrigerated warehouse to respectively monitor the temperature inside the chambers and the overall consumption of the facility.
2) An SQL database was built with the data, with simultaneous recording of power consumption, temperatures in different places and equipment status, among other variables.
3) The set-point temperature of the cold rooms was controlled according to the cooling needs, in order to preserve the quality of the food stored.
4) A mathematical procedure was developed to optimize real-time calculations of the consumption in each refrigerated chamber, using the minimum possible amount of data and thus allowing the automatic supervision to be scalable.
5) The installation and the mathematical algorithms were coded on a programmable cloud platform, accurately simulating the plant and its interactions during its life cycle.
6) Through the cloud platform, the data history and its evolution can be accessed in real time by the different departments, thus yielding the digital twin of the plant.

This innovative development in the application of Big Data techniques to the energy management of cold food storage allows, through a single tool, to improve the sustainability of the process, reduce consumption and improve the competitiveness of companies, adjusting the rental prices of cold storage space to the real cost at all times, of refrigeration in the storage of their various products.

3.- CASE OF USE

The case study is a refrigerated logistics center with more than 140,000m3 of cold rooms for different products and storage temperatures. The chambers have different sizes and refrigeration requirements, with a single central refrigeration system for both cold and frozen foods. This configuration was chosen because it saves energy compared to maintaining an individual cold source in each chamber. However, the lack of knowledge of the actual energy consumption of each chamber and type of food makes business accounting almost impossible to track using conventional procedures.

The cold food storage building we study has 10 storage chambers of 7 different types (see Fig. 1). While all the rooms were built with the same materials, their dimensions are different, so the chambers may have disparate needs depending on the contents they are intended to house and their volume. They have also different interior units to maintain inside the appropriate temperature for each foodstuff. The set point temperatures of the equipment in the chambers thus vary from one to the other and their values are summarized in Table 1.

Zone	Volume (m^3)	Temp. (°C)	No. internal units
1	17,100	4.0	3
2	17,100	6.0	1
3	46,000	4.0	2
4	2,800	3.7	3
5	18,750	-20.0	1
6	2,900	-20.0	2
7	675	4.0	3

Table 1. Volume, set-point temperature and number of internal units for the different zones.

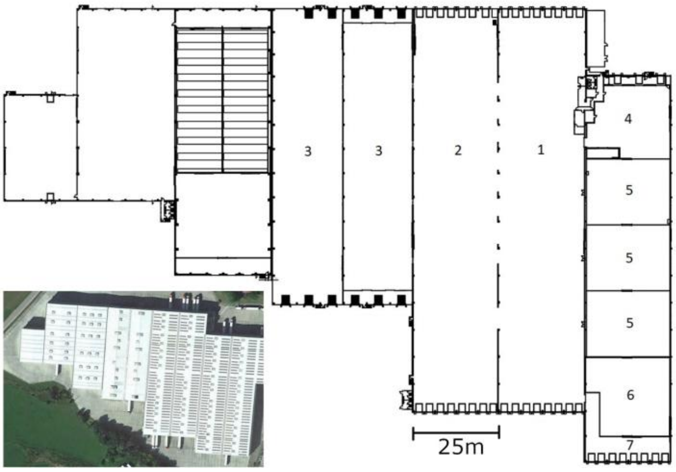


Fig. 1. Floorplan of the warehouse, showing 10 storage chambers of 7 different types. Insert: real photo of the facility.

The chambers, as is the case in most food preservation centres, are rented to 3 different customers, denominated A, B and C. Each customer has rented the following chambers:

- Customer A: zone 3.
- Customer B: zones 1, 2, 4, 6 and 7.
- Customer C: zone 5.

The volume corresponding to each customer is easily obtained by adding the values of the corresponding zones in Table I, yielding 46,000m3 for customer A, 39,900m3 for customer B and 18,750m3 for customer C.

As previously stated, the current configuration presents a problem for the company: having a single centralized climate system, it is only possible to have data of total consumption of the installation, but not of the energy consumed individually by each chamber and consumer. Therefore, the purpose of this article is to show how the construction of a “Digital Twin” will allow to estimate individual consumption of each chamber, and how this solution can be reproduced in analogous facilities.

4.- DIGITAL TWIN CONSTRUCTION.

Following the general methodology, the first step in the construction of a digital twin is the installation of the appropriate sensors to monitor and control the installation. The following figure shows the essential hardware for this process.

Fig. 2. Hardware used for monitoring the facility. Top Left: Adquio Pro programmable controller. Center: Regeltecknik ATF temperature controller. Right: Circuitor CVM-C10 network analyzer. Bottom: Sensors in the actual facility. See the main text for a detailed explanation.

- An Adquio Pro programmable controller from Make Develop, which acts as a concentrator and data processor of the installed sensors and connects to the cloud platform that will create the digital twin of the logistics center. The data received by Adquio are temporarily stored and organized to provide detailed information on environmental and consumption data, according to location, the chamber to which it belongs and the exact date of recording.
- Temperature and humidity sensors inside the chambers, see figure 2, allow an exhaustive control of the environmental conditions, as the temperatures will be controlled in real time and alerts will be programmed in case of a change in the conditions that could affect the quality of the food preserved in each chamber. The hygrometric conditions were controlled with Regeltechnik AFTF sensors.
- A Circuitor CVM-C10 network analyzer has been used to monitor and control the consumption of the cooling generation equipment.

The implementation of the digital twin involves a simultaneous numerical simulation of the system together with real-time data acquisition from the refrigerated storage facility. Thus, the data imported from sensors and the computer simulation of the processes must be embedded together in the same digital cloud platform [10]. In this study we used a programmable cloud platform called Equs [11].

Once the sensors and hardware are installed and connected to the in-cloud platform, the temperature and consumption values of the entire process are displayed on screen in real time, while the database is being built. This database will be used to develop the mathematical models that will show the consumption of each chamber and therefore the costs of renting the space.

An example shall be used to better showcase the construction and implementation of the mathematical model.

The data employed will be from October 2019, recorded every 5 minutes in the facility. During this period, the total power consumption was 207,418 kWh.

The study of the total power demand during 2019 reveals that the base consumption varies throughout the year, as detailed in Table II. To record the temperatures of each chamber, the IoT platform ‘Equs’ is used in addition to the installation of the corresponding sensing devices.

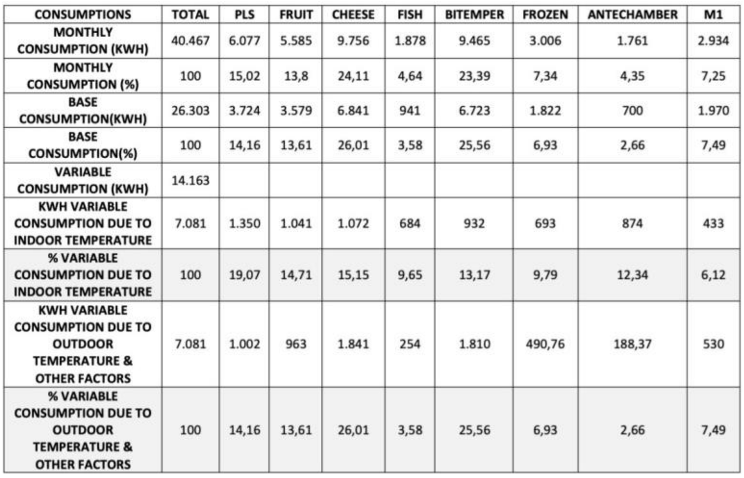
Month	Base (kWh)	Total (kWh)	%
Jan.	87,079.36	156,638.6	55.59
Feb.	109,819.73	142,775.0	76.92
Mar.	140,593.65	167,513.3	83.93
Apr.	134,030.50	170,432.1	78.64
May	134,922.96	190,208.6	70.93
Jun.	157,594.88	211,867.1	74.38
Jul.	199,163.26	259,087.6	76.87
Aug.	191,539.87	248,587.7	77.05
Sep.	168,501.01	213,946.5	78.76
Oct.	149,565.07	207,418.1	72.11
Nov.	126,237.19	177,121.7	71.27
Dec.	125,770.42	173,745.2	72.39
Total	172,4817.9	2,319,341.5	74.37

Table 2: Base and total consumption through the year 2019

To avoid food losses due to not being in optimal preservation conditions, the temperature setpoints of the chambers are programmed so that they remain constant and in the event of any variation, the platform will send a warning by means of programming rules.

With the database created, a mathematical model is developed that will provide a realistic estimate of the consumption of each chamber. As previously mentioned, the consumption of each chamber is the main production cost in a cold logistics center, and to maintain the economic profitability of the process it is essential to know it in real time.

Once the algorithm has been developed, it is programmed in the digital twin so that we can completely control the process of the 140,000 m3 of cold storage from an economic, energetic and food safety point of view.



CONSUMPTIONS	TOTAL	PLS	FRUIT	CHEESE	FISH	BITEMPER	FROZEN	ANTECHAMBER	M1
MONTHLY CONSUMPTION (KWH)	40.467	6.077	5.585	9.756	1.878	9.465	3.006	1.761	2.934
MONTHLY CONSUMPTION (%)	100	15,02	13,8	24,11	4,64	23,39	7,34	4,35	7,25
BASE CONSUMPTION(KWH)	26.303	3.724	3.579	6.841	941	6.723	1.822	700	1.970
BASE CONSUMPTION(%)	100	14,16	13,61	26,01	3,58	25,56	6,93	2,66	7,49
VARIABLE CONSUMPTION (KWH)	14.163								
KWH VARIABLE CONSUMPTION DUE TO INDOOR TEMPERATURE	7.081	1.350	1.041	1.072	684	932	693	874	433
% VARIABLE CONSUMPTION DUE TO INDOOR TEMPERATURE	100	19,07	14,71	15,15	9,65	13,17	9,79	12,34	6,12
KWH VARIABLE CONSUMPTION DUE TO OUTDOOR TEMPERATURE & OTHER FACTORS	7.081	1.002	963	1.841	254	1.810	490,76	188,37	530
% VARIABLE CONSUMPTION DUE TO OUTDOOR TEMPERATURE & OTHER FACTORS	100	14,16	13,61	26,01	3,58	25,56	6,93	2,66	7,49

Fig.3. Example of the final results provided to the costumer by the digital twin.

Since the implementation of the delivery algorithm, the logistics center has adopted the monthly application as the consumption distribution. The algorithm provides a data-based estimation of the consumption of each chamber, used by the logistics center to charge the monthly cost to each Customer. With this distribution, the logistics center has not reported any economic loss.

5.- MATHEMATICAL MODEL DEVELOPMENT FOR INCLUSION IN THE DIGITAL TWIN

As stated in the introduction, the target problem is to find the distribution of the total consumption among the different chambers, taking as input data the overall consumption of all the chambers and the temperature inside each one of them. In Fig. 4 we show daily consumption and the temperatures based on the data obtained during the first week of October 2019 and the whole month, respectively. It's possible to see that it can be divided into two components: a base consumption and a variable consumption.

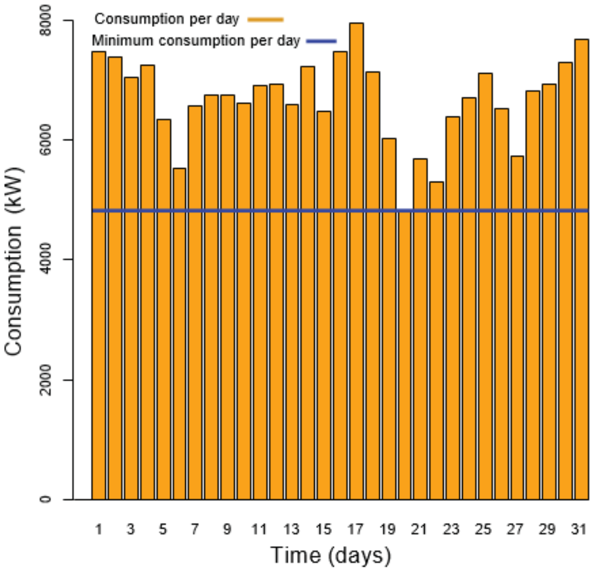


Fig.4. Daily consumption of the facility during October 2019

The base consumption will be distributed according to the physical characteristics of the chambers, and the variable consumption will be divided into equipment consumption, distributed according to the time of use of the machines in each chamber, and the power demand associated with external conditions, also distributed according to the physical characteristics of the chambers.

Therefore, the goal is to code the mathematical formula that will allow us to calculate the power distribution with known data from the installation. To this aim, we must evaluate first separately the base and variable consumption distribution in order to simplify the coding on the in-cloud platform.

Thus, given a time period, let C be the total consumption recorded during the period and $\{C(day)\}$ the set of total daily consumptions for this period, so that the sum of all the total daily consumptions gives rise to the combined total consumption. Thus, the estimate of the base consumption $\boldsymbol{b}$ is constructed as follows:

$$\boldsymbol{b} = \frac{\min\{C(day)\}}{mean\{C(day)\}} C \tag{1}$$

And the remaining consumption, called variable consumption $\boldsymbol{v}$, is given by the following expression:

$$\boldsymbol{v} = C - \boldsymbol{b} = \left(1 - \frac{\min\{C(day)\}}{mean\{C(day)\}}\right) C \tag{2}$$

We will analyze now separately the base and variable consumption between the different chambers.

5.1.- BASE CONSUMPTION.

This is the minimum consumption necessary to maintain the conditions of the chambers. This consumption occurs regardless of the day of the week, the operation being carried out or the type of product. It is estimated on the basis of the minimum daily consumption recorded in the period under study. This depends both on the physical characteristics of the chambers and on the differences between inside and outside temperature. Following Newton’s cooling law, we have the following expression:

$$\boldsymbol{b} = UA\Delta T \tag{3}$$

Where U is the total heat transfer coefficient, A is the total contact surface area of the chamber with the outside and ΔT is the difference between the indoor and outdoor temperature. Therefore, the base consumption of each chamber can be estimated by making use of the terms of the expression given by Newton’s cooling law restricted to each chamber as follows:

$$\boldsymbol{b} = U \sum A(chamber)\, \Delta T(chamber) \tag{4}$$

In which $A(chamber)$ is the area of the contact surface of each chamber and $\Delta T(chamber)$ is the difference between the inside temperature of each chamber and the outside temperature. Note that the heat transfer coefficient will be the same for all chambers since they are constructed with the same materials. Thus, the base consumption of each chamber is given by its specific value of $\boldsymbol{b}$. Since the known data of the installation are the volume and the set-point temperature of the chambers, the volumes and these temperatures will be used for the calculations

Given the volumes $V(chamber)$, it is possible to establish a set of scalars, denoted as $\lambda(chamber)$ satisfying $V(chamber) = \lambda(chamber) \min\big(V(chambers)\big)$ for each chamber. A straightforward calculation shows that these correction factors are given by the expression:

$$\lambda(chamber) = \frac{V(chamber)}{\min\big(V(chambers)\big)} \tag{5}$$

These factors are well defined since the chamber volumes are positive. Similarly, given the set-point temperatures of the chambers, denoted as $T(chamber)$, it is possible to add a set of analogous factors for the temperatures. However, contrary to the volume case, the sign of the set-point temperatures can vary, being negative in the case of the freezing chambers. In addition, since it is a cold store hall, the inside temperature will be lower than the outside temperature, so that a lower set-point temperature will lead to higher consumption. Thus, it is necessary to standardize the temperature data to find the correction factors as follows:

$$\hat{T}(chamber) = -(T(chamber) - T_0) \tag{6}$$

in which T_0 is a constant relative to the outside temperature. In this case, $T_0 = 20^{\underline{o}}C$ will be taken as this is the temperature considered as a normal condition in thermodynamics [8]. Thus, the correction factors for the temperature are given by:

$$\mu(chamber) = \frac{\hat{T}(chamber)}{\min(\hat{T}(chambers))} \tag{7}$$

Using both correction factors, the base consumption of each camera is given by:

$$b(chamber) = U\lambda(chamber)\min\big(V(chambers)\big)\,\mu(chamber)\min\left(\hat{T}(chambers)\right) \tag{8}$$

Thus, the ratio of the base consumption of each chamber to the total base consumption is given by:

$$\frac{\boldsymbol{b}(chamber)}{\boldsymbol{b}} = \frac{U\lambda(chamber)\min\big(V(chambers)\big)\mu(chamber)\min\big(\hat{T}(chambers)\big)}{\sum U\lambda(chambers)\min\big(V(chambers)\big)\mu(chambers)\min\big(\hat{T}(chambers)\big)} = \frac{\lambda(chamber)\mu(chamber)}{\sum\lambda(chambers)\mu(chambers)} \tag{9}$$

where the base consumption $\boldsymbol{b}$ is given by the sum of the base consumption of all the chambers. Since both the total base consumption and the correction factors are known, an estimate of the base consumption of each chamber can be obtained using the following formula:

$$\boldsymbol{b}(chamber) = \boldsymbol{b}\,\frac{\lambda(chamber)\mu(chamber)}{\sum\lambda(chambers)\mu(chambers)} \tag{10}$$

or, equivalently, using the formula of Equation 1:

$$\boldsymbol{b}(chamber) = \frac{\lambda(chamber)\mu(chamber)}{\sum\lambda(chambers)\mu(chambers)}\,\frac{\min\{C(day)\}}{mean\{C(day)\}}C \tag{11}$$

5.2.- VARIABLE CONSUMPTION.

The variable consumption corresponds to the direct use of the equipment and to external conditions. This consumption depends both on the activity inside the logistics center and on the various loading and unloading processes. To evaluate what part of this consumption corresponds to the use of the installed equipment, the following expressions are assumed to be true:

- The decreases in indoor temperatures are solely due to the use of the indoor refrigeration equipment in the chambers.
- The consumption of the indoor cooling equipment involved is reflected in both the decrease in indoor temperatures and the increase in consumption, corresponding to the variable consumption associated with the equipment.
- The variable consumption associated with the use of equipment will only increase if the equipment is in use.

Thus, there is a direct relationship between the use of indoor cooling equipment and the variable consumption associated with it, as well as an inverse relationship between equipment use and indoor temperature. Therefore, the part of the variable consumption corresponding to the use of equipment is given by the correlation between the variation in equipment use and the variation in variable consumption.

Although the equipment usage data is not known, it can be estimated thanks to the sensing of the chamber. An equipment is considered switched on if and only if the temperature in its area is decreasing. By means of sensing, it is possible to divide the period into five-minute intervals and compare the values taken by the indoor temperature at the beginning and at the end of each interval. Thus, the following piecewise time-dependent function can be constructed for each equipment:

$$\delta(equipment, interval) = \begin{cases} 1 & if \quad \Delta T < 0 \\ 0 & if \quad \Delta T \geq 0 \end{cases} \tag{12}$$

This function describes the operation of each piece of equipment, giving the value 1 in the intervals in which the equipment is on and the value 0 in the intervals in which it is off. The function δ describing the total use of the equipment in the chamber is obtained as the sum of the functions δ of all the equipment. Thus, the correlation between equipment uses and variable consumption is given by the Pearson correlation coefficient $R = R(\boldsymbol{v}, \delta)$ between the variable consumption $\boldsymbol{v}$ and δ.

Since the base consumption is constant, the total consumption varies over time in the same way as the variable consumption. Therefore, the correlation coefficient between variable consumption and equipment usage is equivalent to the correlation coefficient $R = R(C, \delta)$ between total consumption and equipment usage and therefore the variable consumption associated with the use of equipment is given by:

given by:

$$\boldsymbol{e} = \boldsymbol{v}\, R, \tag{13}$$

Or equivalently, according to the equation 2,

$$\boldsymbol{e} = \left(1 - \frac{\min\{C(day)\}}{mean\{C(day)\}}\right) C\ R \tag{14}$$

And so, the variable consumption associated with other factors is given by:

$$\boldsymbol{o} = \boldsymbol{v} - \boldsymbol{e} = v(1 - R) \tag{15}$$

or equivalently,

$$\boldsymbol{o} = \left(1 - \frac{\min\{C(day)\}}{mean\{C(day)\}}\right) C\ (1 - R) \tag{16}$$

Once the variable consumption associated with equipment, $\boldsymbol{e}$, has been estimated, it is possible to estimate the consumption that corresponds to each equipment by comparing the time they have been working. Given the functions δ defined above, it is possible to construct an equipment-dependent function $D(equipment)$ as the sum over all the intervals of the functions δ, so that for each equipment, $D(equipment)$ gives the total number of intervals in which the equipment has been switched on. One can also define the function for chambers, $D(chamber)$, as the sum of $D(equipment)$ for all equipment in each chamber. With this function it will be possible to find what proportion of the variable consumption $\boldsymbol{e}$ corresponds to each chamber, as follows:

$$\boldsymbol{e}(chamber) = \boldsymbol{e}\ \frac{D(chamber)}{\sum D(chambers)} \tag{17}$$

The distribution of the variable consumption can be associated with external factors, like the weather. Given that the chambers share the same location and have been built with the same materials, the distribution of this consumption will be carried out following the weightings obtained from the correction factors for Newton's Law of cooling in the section on base consumption.

Therefore:

$$\boldsymbol{o}(chamber) = \boldsymbol{o}\ \frac{\lambda(chamber)\mu(chamber)}{\sum \lambda(chambers)\mu(chambers)} \tag{18}$$

5.3.- TOTAL CONSUMPTION.

The total consumption of each chamber is given by the following expression, representing the sum of the three parts described above:

$$C(chamber) = \ \boldsymbol{b}(chamber) + \boldsymbol{v}(chamber) = \boldsymbol{b}(chamber) + \boldsymbol{e}(chamber) + \boldsymbol{o}(chamber) = \frac{\lambda(chamber)\mu(chamber)}{\sum \lambda(chambers)\mu(chambers)} \frac{\min\{C(day)\}}{mean\{C(day)\}} C + \left(1 - \frac{\min\{C(day)\}}{mean\{C(day)\}}\right) C\ R \frac{D(chamber)}{\sum D(chambers)} + \left(1 - \frac{\min\{C(day)\}}{mean\{C(day)\}}\right) C\ (1-R) \frac{\lambda(chamber)\mu(chamber)}{\sum \lambda(chambers)\mu(chambers)}. \tag{19}$$

A direct calculation shows that this expression can be reduced to the following:

$$C(chamber) = C\left[R\left(1 - \frac{\min\{C(day)\}}{mean\{C(day)\}}\right)\left(\frac{D(chamber)}{\sum D(chambers)} - \frac{\lambda(chamber)\mu(chamber)}{\sum \lambda(chambers)\mu(chambers)}\right) \frac{\lambda(chamber)\mu(chamber)}{\sum \lambda(chambers)\mu(chambers)}\right] \tag{20}$$

Once this final expression for the total consumption of each chamber is coded in the cloud platform, the digital twin is constructed.

6. – CONCLUSIONS

The in-cloud platforms offer the possibility of creating Digital Twins for logistics centers. The digital twin makes it possible to manage the facilities of logistics centers as well as food preservation with a single application. The ability to program mathematical algorithms in the digital twins, to model the processes in real time, allows for improved monitoring of the activity and advanced management of the refrigeration logistics centers. This study has made clear the great possibilities offered by digital twins with real data, improving cold storage processes from all perspectives:

- Digital thermal control management: Temperature control every minute with an alarm system for out-of-control detection, allowing to prolong the shelf life of the food and avoid wastage.
- Digital energy management: Control of consumption at intervals ranging from every 5 minutes to every month allows us to propose strategies to improve energy efficiency by accurately accounting for the consumption of all the processes carried out in the facility, together with the operations in the plant. The digital twin is a very powerful tool for energy optimization, and it guarantees the sustainability of the cold storage production process, reducing consumption and CO2 emissions in a food-safe way. Controlling temperature, energy needs and pollutant emissions at the same time is an adequate way to optimize energy without losing product by varying its conservation conditions.

Thus, by solving a multidimensional problem in real time, our digital twin can contribute to increase the sustainability of refrigerated warehouses, reducing CO2 emissions, in a safe and economical, way using Industry 4.0 technologies that are easy to implement in current facilities.

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