Predictive tool of energy performance of cold storage in agrifood industries: The Portuguese case study

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A B S T R A C T

Food processing and conservation represent decisive factors for the sustainability of the planet given the significant growth of the world population in the last decades. Therefore, the cooling process during the manufacture and/or storage of food products has been subject of study and improvement in order to ensure the food supply with good quality and safety. A predictive tool for assessment of the energy performance in agrifood industries that use cold storage is developed in order to contribute to the improvement of the energy efficiency of this industry. The predictive tool is based on a set of characteristic correlated parameters: amount of raw material annually processed, annual energy consumption and volume of cold rooms. Case studies of application of the predictive tool consider industries in the meat sector, specifically slaughterhouses. The results obtained help on the decision-making of practice measures for improvement of the energy efficiency in this industry.

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1. Introduction

The sustainability and food safety in the agrifood sector has been a topic of research and study. In the early twentieth century, the world population was about 1500 million people, however just over a century the number of habitants increased to approximately 7000 million [1]. Thus, it is clear that the world demand for food is increasing which is reflected on an enormous strain for the production and conservation sectors of the food chain. So it becomes imperative to find short-term solutions for the agrifood industries that in a macroscopic vision will help the sustainability of the planet. In this context, cooling plays an important role, allowing to store food products in times of increased production when the market has no capacity for product flow, or just make them available when needed. The refrigeration process has the ability to preserve perishable products ensuring their chemical, physical and nutritional properties but it is also indispensable in the processing of perishable foods such as meat, fish, milk, fruit and other. The demand of chilled and frozen food as increased substantially, which leads to new requirements for the efficiency of refrigeration systems [2]. Energy represents a factor of greatest importance not only for a country economy, but especially for the well-being of its citizens. In 1971 there was a global electricity consumption of around 439 Mton·h, and in 2010 this figure rose to 1.536 Mton·h [3]. This increase is related to the population growth, being the industry responsible for about 35.2% of energy consumption worldwide in 2010. The energy consumed globally for the cooling process accounts for 15% of energy consumption [1]. Thus, it is important to develop studies and tools that help the efficiency improvement of these processes to ensure a better sustainability of this industrial sector. There are some results provided by studies and projects in this area, more specifically in the development of predictive tools for the analysis of several points related to the cooling processes (whether energy consumption, environmental impact, among others). The tool FRISBEE CCP (Cold Chain Predictor) [4–6], developed within the activities of FRISBEE (Food Refrigeration Innovations for Safety, Consumers Benefit, Environmental Impact and Energy) project, performs simulations on specific conditions defined by the user, constructs graphs representing the variation of temperature over time and predicts the remaining shelf time of the product. These simulations are performed based on the method of Monte Carlo [4] generating distributions of time/temperature for every stage of the cold-chain and selected product. The results represent realistic scenarios for the behavior of food products, being possible to take corrective actions in order to optimize the efficiency of the cold-chain ensuring product quality and increasing its validity. This tool is intended to provide free information and tools to managers, designers and operators of the
repackaging industry optimizing the efficiency of their companies. In this same context, Foster et al. [7] describes the ICE-E (Improving Cold Storage Equipment in Europe) project [8] devoted to the development of tools with the same goals. This project contributed to reduce the energy consumption and greenhouse gas emissions from the European food cold storage sector through the application of more energy efficient equipment and taking into account the energy and environmental standards of the EU [8–10].

Eden et al. [11] describes a predictive tool, QMRA (Quantitative Microbial Risk Assessment) [12,13], which is combined with the principle of the Hazard Analysis and Critical Control Points (HACCP) to enable the improvement of quality and safety of food in a preventive approach. More specifically, this tool allows to estimate the risk of pathogens growth based on the temperature and chemical and nutritional characteristics of food. As result, the SLP (Shelf Life Predictor) [13] was developed with the ability to predict the true and the remaining shelf life of foods. Apart from the quality and safety of foods, this tool allows tracking (traceability) products in order to know the places where they are in real time so that the consumer can make use of reliable information about the origin of food. It also allows to overlook the manufacturing process from the collection of raw materials to their processing, helping to ensure quality and safety.

Van der Sluis [14] describes a software that makes the temperature control of cold stores taking into account the price of electricity and the daily consumption profile of the company. The load management was accomplished considering that compressors will work during time periods of low-cost electricity due to lower demand, in order to accumulate energy in the form of cold to rationally use it during peak hours [15]. However, this procedure is executable only if the facilities have enough cold storage capacity to store the energy demand during the day. Besides the abovementioned works, other computational tools and models have been developed to enhance the operation of refrigeration facilities [16] and system devices, such as compressors and their control, regulation and command [17,18], expanders [19], among others. Additionally, methodologies, strategies and procedures has been developed for optimal control of heat recovery processes in refrigeration systems [16], for the performance evaluation of heat exchangers [20] as well as knowledge based decision making methods for refrigerant selection [21] and energy savings based in energy audits and its detailed analysis [22]. These works are only few examples of recent ongoing research and development focusing the energy improvement of refrigeration systems, which are the main consumers in the agrifood industry.

This paper presents a predictive tool developed for the assessment of the energy performance in agrifood industries that use cold storage. The tool uses mathematical correlations from the greatest number of data sets collected to date in Portugal. Statistical correlations between raw material, energy consumption and volume of cold rooms are used. To show the features and applicability of the tool, several case studies for different sectors of the meat industry are analyzed. The tool results will be useful in the decision-making process of practice measures for the improvement of energy efficiency.

2. Material and methods

2.1. Framework in the context of Portuguese industries

The abovementioned research covers the development of predictive tools aimed to improve the energy efficiency of cold stores since refrigeration is responsible for about 60–70% of electricity consumption of these facilities [23]. Although, Portuguese companies had not been included in the databases. In this context, a project was developed in Portugal focussed in the identification of energy consumption profiles in the agrifood industry. Additionally, it intends to promote and develop actions that contribute to a real improvement of energy efficiency and competitiveness of this sector. The work developed and presented in this paper is part of a project activity and its main objective is the development and implementation of an analysis algorithm to be validated with companies outside the sample of technical audits. As part of the activity, it is aimed the development of a predictive tool to support strategic decisions in companies allowing the estimation of their energy performance and pointing practice measure that lead to an effective improvement of energy efficiency. Note that this project is not aimed for the energy characterization of the cold stores in particular, but to the energy characterization by agrifood category, i.e., meat, fish, dairy, horticultural (fruit and vegetables), wine and vineyard and distribution, in order to obtain real data that was used for the development of the correlations included in the model/algorithm.

The Portuguese industry is mainly constitute by small and medium enterprises. In 2011, it number was around 1.112.000, providing employment to about 78.5% of the Portuguese population [24,25]. A large part of these industries is included in the agrifood sector.

2.2. Sample

This study was conducted based on a sample of 87 agrifood companies: 33 from the meat sector, 31 from the dairy sector and 23 from the horticultural (fruits and vegetables) sector in the central region of Portugal. According to INE [26], this region has the highest number of agrifood companies in Portugal. Additionally, this region has the perfect weather conditions and soil and vegetation properties that allows the development of agrifood practices for a wide range of products from different sectors. Several regional products are manufactured in the region, among which stand out the products in the meat sector (cured meats), dairy products (cheeses) and fruits.

In particular, the meat sector industries, where the predictive tool was applied and validated, were subdivided into three subcategories: Slaughterhouse, Sausages industry and Hams industry. The analysis was conducted in 4 Slaughterhouses plants, 20 Sausages industries and 9 Hams industries. 70% of the ham manufacturing companies are located in this region of the country.

2.3. Data collection

Initially, an extensive survey was developed to carry out a collection of information about the agrifood industries. This survey was used to collect information regarding physical characteristics of plants, activities and characteristics of production processes, high energy-use equipment with special emphasis on cooling systems, cooling and freezing chambers and energy consumption. Besides serving as a support document for data recording, the document ensured a systematic and reliable data collection. Moreover, it was also used as a technical guide to the plants inspection. The inquiry document was used to record the following data:

(i) Identification and location of agrifood plants.

(ii) Characterization of infrastructure (location, age, type of materials, dimensions and location of cooling and freezing chambers).

(iii) Characterization of activities (type and quantities of raw materials and final products).

(iv) Identification and characterization of the production process.

(v) Identification and quantification of energy types.
(vi) Characterization of the electricity tariff and consumption (tariff type, electrical power contracted, electricity consumption, power factor).

(vii) Breakdown of electricity consumption by sector and equipment.

(viii) Characterization of cooling and freezing chambers (number, type of insulation material, preservation condition, raw materials/products load).

(ix) Determination of internal and external environmental conditions, of facilities and cooling chambers (air temperature and relative humidity).

(x) Identification and characterization of refrigeration systems (age, location, type of technology and technical characteristics, refrigerant type and nominal electrical powers of compressors).

(xi) Evaluation of the characteristics of compressed air systems.

(xii) Characterization of thermal fluid generators.

(xiii) Evaluation of energy efficiency improvements.

The collected information relates to activities undertaken during 2008. The data collection process was carried out face-to-face, with a visit to the industries, and where the building, the equipment, the technical operations and the manufacturing processes were observed. Data collection was performed during the year 2009.

2.4. Equipment and measurement techniques

In order to measure the environmental conditions inside and outside the cooling equipment, including air temperature a006Ed moisture content, a digital multi-function measuring equipment (Testo 435-2) was used, along with its temperature and humidity probes (±0.3 °C accuracy). The previous equipment with a contact probe with type K thermocouple (±0.5 °C accuracy) was used to measure the walls/surfaces temperature. Temperature data-loggers (Microlite and Lascar electronics with ±0.5 °C accuracy) were used to measure the air temperature inside the cooling and freezing chambers. A thermographic camera Testo 880 (±2 °C accuracy) was used to evaluate the preservation condition of cooling chambers walls, thermal bridges, sealing condition of chambers doors, and insulation of refrigerant suction pipes and of discharge air ducts of air handling units. An ammeter clamp was used for measuring the electrical current and voltage input to the compressor motor, in order to evaluate its electrical power consumption. The electrical power data obtained experimentally was compared with the estimated values available from official catalogues and dedi-
cated software, for the same operating conditions. Close results (deviations below 10%) were found between the two methods in use. Although the energy intakes were quantified by analysis of the monthly electricity bills, a profile analysis of electricity consumption was also performed using an energy analyzer (Elcontrol Energy Explorer).

The physical dimensions of the cooling and freezing chambers were calculated using an infra-red distance meter Bosch-DLE 40 (±1.5 mm accuracy).

2.5. Database

A computer database was built to record all information gathered from the plants. This database was designed to allow data processing and analysis. It also made possible to obtain various performance indicators from each agrifood company and simultaneously to carry out a comparative analysis between different plants in each sector. Additional details of the database can be found in [27].

3. Predictive tool features

3.1. Overview

The predictive tool, Cool-OP (Cooling Optimization Program), was developed in MATLAB [28] making use of GUIDE (Graphical User Interface Design Environment) [29]. This tool provides point-and-click control of software applications, reducing the need to type commands in order to run an application. GUIDE provides tools for graphically design the user interface for applications. The graphical user interface typically contains controls named compo-

ents such as menus, toolbars, radio and push buttons, edit text, static text and check boxes, sliders, among others. Then, GUIDE automatically generates the MATLAB code for the user interface, which was programmed with the behavior expected for the appli-
cation. The computations to be performed by the application were programmed in MATLAB language and the data is display in plots.

The user interface of the predictive tool is extremely simple, intuitive, user-friendly and easy to understand. The aim is to pro-

vide a tool accessible to all professionals in the agrifood industry regardless of their qualifications. Finally, the code generated in MATLAB was converted to an executable file that can run in any computer.

3.2. Algorithms

The predictive tool provides the user with the current state of a company in terms of energy performance and suggests practice measure to improve it.

The correlations focused on several key parameters that charac-
terize companies of agrifood sector, including: the quantity of raw material processed annually, the annual electricity consumption, and the volume of cold rooms.

The energy performance algorithm is based in the research developed by Nunes et al. [27,30–32], who performed an intensive collection of field data on energy-related characteristics of a large sample of agrifood industries.

The data was statistically organized, analyzed, and interpreted in order to develop analytical correlations that represent the Portu-
guese average energy performance of meat, dairy and horticultural industries [27]. The statistical program SPSS version 18 was used to assess the data dispersion and to calculate the correlations. The determination coefficient, R², was used to set to correlation type. Based on the results, a linear regression equation was used to obtain the relationships between the relevant parameters. The regression outliers were removed from the sample using the Chau-
venet’s criterion [33].

Fig. 1a shows an example of the correlations developed for the sausages industry. Fig. 1a shows the relationship between raw material processed annually and electricity consumption per year. Fig. 1b shows the relationship between cold room volume and electricity consumption per year.

The correlations developed are shown in Table 1. These equa-
tions express the relationships between the following relevant parameters: electrical energy consumption (annual), E (MWh); raw material (annual), RM (ton); compressors nominal power, CP (kW) and cold room volume, V (m³). Note that the parameter of electricity consumption accounts not only for the energy con-
sumed for cooling or processing food products, but also other sinks as lighting, heating, office, etc.

The correlation between the compressors nominal power and the raw material is not a direct correlation, but it can help the users of the computational tool to evaluate their companies’ performance. The correlation factor has an average value of 71% for the meat industries analyzed. Although the correlation factor value
provides some confidence to the predictions, it is the lowest correlation factor obtained for the selected parameters. The relationship of compressors nominal power with cold room volume as well as the relationship of cold room volume with energy consumption are, in average, the greatest for the meat industries (92%). Evans et al. [10] reached the same conclusion. Thus, these correlations should be preferred when comparing the energy performance of a specific company with the average value for the sector.

The electrical energy consumption per ton of raw material, SEC (kWh ton⁻¹), on an annual basis, is one of the power index among several indicators, which provides information that characterizes the performance of agrifood companies in relation to their electricity consumption. It provides the relationship between the electricity consumption, E, and the processed raw material, RM. This index allows to perform the comparison of the specific electrical energy consumption of similar processes on different agrifood companies. The index evaluation allows to evaluate the performance of agrifood companies and it cooling systems. The differences in this index value can be used to find the causes of energy inefficiencies in agrifood companies by comparison of equipment, infrastructure and processes. Table 1 also shows the average SEC values from the sample for the different subcategories of agrifood companies. Although the three types of industry are processing meat products, the manufacturing processes are different leading to different SEC values for the same amount of raw material (see Table 1). Additionally, the SEC is influenced by several parameters that are part of the manufacturing process. One of these parameters is the rate of cooling. The rate of cooling is very relevant when calculating the SEC and the compressors nominal power depend upon it. For example, in hams manufacturing there is a heating process at the final stage of curing. All these aspects were taken into account during the development of the correlations, which provide different SEC values for the three meat industries.

As the correlations used in the algorithm are the core of the predictive tool and were obtained through real values collected in companies, the predictions validity are limited to a variation domain of each of characteristic parameter. The validity of the predictions are constrained by the values given in Table 2.

3.3. Program flow

The predictive tool presented in this study considers improvements of the tool developed by Santos et al. [34,35] and Neves et al. [36]. Initially, a window containing a brief description of the predictive tool is displayed, informing the user about the necessary input data (inputs) to perform the simulation in the following steps (see Fig. 2).

The user can select in which industry sector fits the company to be analyzed (see Fig. 2a), including meat, fish, horticultural (fruit and vegetables) and dairy products.

There are multiple subcategories within each sector. In the specific case of the meat sector industry, there are (1) Slaughterhouse, (2) Sausages industry and (3) Hams industry as shown in Fig. 2b. Other sectors have also specific subcategories.

Pressing the button of any of the industry subcategories opens a window requesting the inputs (Fig. 2c). Here, the user must input the values of the characterization parameters: amount of raw material processed annually (ton), annual electricity consumption (MWh) and the total volume of cold rooms (m³). Note that it is always possible to return to the previous menu or close the window using the respective buttons (back or exit) for navigation.

After entering the data according to the SI unit system and considering that the values are within the valid variation domain of each parameter, when the button “Continue” is pressed, the tool starts the computation based on the correlations and displays in a new window the general results that summarize the current state of the company

Table 1

<table>
<thead>
<tr>
<th>Relationships</th>
<th>Industry</th>
<th>Slaughterhouses</th>
<th>Sausages</th>
<th>Hams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity consumption, E (MWh) vs. raw material, RM (ton)</td>
<td>E = 0.2041RM - 138.97</td>
<td>E = 0.2376MP + 24.18</td>
<td>E = 0.9945RM + 159.93</td>
<td></td>
</tr>
<tr>
<td>Compressors nominal power, CP (kW) vs. raw material, RM (ton)</td>
<td>CP = 0.0520RM - 51.46</td>
<td>CP = 0.0702RM + 11.49</td>
<td>CP = 0.1082RM + 86.20</td>
<td></td>
</tr>
<tr>
<td>Cold room volume, V (m³) vs. raw material, RM (ton)</td>
<td>V = 0.5151RM - 265.58</td>
<td>V = 4.3795RM - 87.42</td>
<td>V = 3.8629RM + 785.44</td>
<td></td>
</tr>
<tr>
<td>Electricity consumption, E (MWh) vs. cold room volume, V (m³)</td>
<td>E = 0.4557V - 112.71</td>
<td>E = 0.3243V - 68.84</td>
<td>E = 0.2667V - 228.61</td>
<td></td>
</tr>
<tr>
<td>Compressors nominal power, CP (kW) vs. cold room volume, V (m³)</td>
<td>CP = 0.1102V - 36.72</td>
<td>CP = 0.0572V + 3.41</td>
<td>CP = 0.0323V + 32.05</td>
<td></td>
</tr>
<tr>
<td>Average specific energy consumption, SEC (kWh ton⁻¹)</td>
<td>148.5</td>
<td>660.2</td>
<td>1208.0</td>
<td></td>
</tr>
</tbody>
</table>
of energy performance of a company. In this window (see Fig. 2d), plots that relate the characterization parameters of a company are displayed. All plots have a green shaded background that represents the confidence level of 95% of the statistical correlations. In addition, it is also shown in each plot the value of the percentage deviation of the parameter under consideration: (Company point – red dot) and correspondent correlation value for the Portuguese meat industries (black dot). If the user wants to analyse a particular plot, pressing the button above the plot will open a new and enlarged window.

4. Case study

4.1. Companies presentation

To validate the predictive tool, three companies were selected, hereinafter referred as Company A, Company B and Company C for reasons of business confidentiality, each one for a subcategory of the meat industry: a slaughterhouse, a hams industry and a sausages industry respectively. These companies have not been part of the statistical data used in the development of correlations.

The Company A is a slaughterhouse with 12 years of activity with 13 workers. According to Portuguese legislation is classified as a micro-enterprise and is dedicated to the meat production, pro-

<table>
<thead>
<tr>
<th>Industry</th>
<th>Raw material (ton)</th>
<th>Volume of cold rooms (m³)</th>
<th>Compressors nominal power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slaughterhouses</td>
<td>1000–5000</td>
<td>500–3000</td>
<td>25–300</td>
</tr>
<tr>
<td>Sausages</td>
<td>50–1100</td>
<td>10–1000</td>
<td>10–100</td>
</tr>
<tr>
<td>Hams</td>
<td>50–2500</td>
<td>1500–11,000</td>
<td>80–350</td>
</tr>
</tbody>
</table>
cessing annually 1473 tons of raw materials, particularly cattle and pork meat. There are nine cold rooms with a total volume of 638 m$^3$ in its facilities and its total covered area is 1117 m$^2$. Some cold rooms are built in sandwich panels and others in masonry insulated by polyurethane. The lighting of the cold rooms is of fluorescent type and the refrigeration tubing are insulated by neoprene as shown in Fig. 3a. The refrigeration compressors have a total rated nominal power of 43 kW distributed evenly by four compressors Bitzer (direct central-circuit). The company annual energy consumption is around 209 MWh. It has capacitors installed for the correction of power factor for an actual value of 0.97. This company also has air-conditioned corridors to avoid losses when accessing the cold rooms. Additionally, it has a heat recovery unit and a diesel boiler.

Company B manufactures hams. It has 24 years of experience, employing 15 technical workers. It has a covered area of 3000 m$^2$. According to the Portuguese legislation it is classified as a small-enterprise, dedicated to the production of meat, annually processing about 2029.5 tons of feedstock (exclusively pork meat). In its facilities there are 18 cold rooms (freezing, cooling and drying) with a total volume of 6668 m$^3$. Eight cold rooms are made of masonry with cork insulation and the remaining ten rooms are built in sandwich panel with polyurethane insulation (see Fig. 3b). The lighting in the masonry made rooms’ uses incandescent lamps, and the others uses fluorescent lamps. The corridors have no air-conditioning system although the facilities include a heat recovery unit. The compressors of Company B have a total rated power of 221 kW distributed by 18 compressors from the following brands: Bitzer, Copeland and Dorin (individual cooling circuits). The annual global energy consumption is 1662.1 MWh and the company has a power factor of 0.91 corrected by capacitors. The company also has a diesel boiler.

Company C has 15 years of activity, employing only 4 workers. According to the Portuguese legislation it is classified as a micro-enterprise, devoted to the production of dry-cured sausages. It processes annually 44.8 tons of raw material, mainly pork meat. The company has three cold rooms with a total volume of 142 m$^3$. However its covered area is 600 m$^2$ since the facilities include rooms for manufacturing the sausages and a smokehouse for drying the products. The cold rooms are made with polyurethane sandwich panels with fluorescent lighting (see Fig. 3c). The compressors have a total rated power of 10.5 kW distributed by four Bitzer compressors (individual cooling circuits) and the annual global energy consumption is 21.2 MWh. The power factor of the company is 0.86. The facility has not a capacitors system for power factor correction. This particular company does not have a stove either a boiler.

The details of each industry are gathered in Table 3.

### Table 3: Companies characterization and activity.

<table>
<thead>
<tr>
<th>Company</th>
<th>Company A</th>
<th>Company B</th>
<th>Company C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company activity</td>
<td>Slaughterhouses</td>
<td>Hams industry</td>
<td>Sausages industry</td>
</tr>
<tr>
<td>Meat subsector</td>
<td>1473.0</td>
<td>2029.5</td>
<td>44.8</td>
</tr>
<tr>
<td>Electricity consumption (MWh)</td>
<td>209.0</td>
<td>1662.1</td>
<td>21.2</td>
</tr>
<tr>
<td>Total volume of cold rooms (m$^3$)</td>
<td>638</td>
<td>6668</td>
<td>3000</td>
</tr>
<tr>
<td>Compressors nominal power (kW)</td>
<td>43</td>
<td>221</td>
<td>10.5</td>
</tr>
<tr>
<td>Company characterization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Company age</td>
<td>12</td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td>Number of workers</td>
<td>13</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>Company size</td>
<td>Micro company</td>
<td>Small company</td>
<td>Micro company</td>
</tr>
<tr>
<td>Number of cold rooms</td>
<td>9</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>Covered area (m$^2$)</td>
<td>1117</td>
<td>3000</td>
<td>600</td>
</tr>
<tr>
<td>Lighting</td>
<td>Fluorescent</td>
<td>Fluorescent/incandescent</td>
<td>Fluorescent</td>
</tr>
<tr>
<td>Tube insulation</td>
<td>Neoprene</td>
<td>Neoprene</td>
<td>Polyurethane</td>
</tr>
<tr>
<td>Chambers insulation</td>
<td>Polyurethane</td>
<td>Polyurethane/cork</td>
<td>Polyurethane</td>
</tr>
<tr>
<td>Capacitors battery</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.97</td>
<td>0.91</td>
<td>0.86</td>
</tr>
<tr>
<td>Boiler</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Air-conditioned corridors</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

5. Analysis and discussion of results

The tool allows predicting the energy performance of a particular company in relation to the Portuguese national average.
(a) Electrical energy consumption vs. Raw material.
(b) Compressors nominal power vs. Raw material.
(c) Cold room volume vs. Raw material.
(d) Specific energy consumption.
(e) Electrical energy Consumption vs. Cold room volume.
(f) Compressors nominal power vs. Cold room volume.

Fig. 4. Company A: Predictions of energy performance.

(a) Electrical energy consumption vs. Raw material.
(b) Compressors nominal power vs. Raw material.
(c) Cold room volume vs. Raw material.
(d) Specific energy consumption.
(e) Electrical energy Consumption vs. Cold room volume.
(f) Compressors nominal power vs. Cold room volume.

Fig. 5. Company B: Predictions of energy performance.
Depending on the results, the tool also provides practice measures to improve the energy efficiency. Thus, it can be used on energy-decision making process in order to improve the energy efficiency if required and/or desired.

This work shows the application of the predictive tool in case studies of industries in the meat sector, particularly, in a slaughterhouse, a hams industry and a sausages industry. The values of the parameters shown in Table 2 (company activity section) for each case study were entered in the predictive tool.

Figs. 4–6 show the overall results of the energy performance of each case study.

Based on the predictions, all companies have values of specific electrical energy consumption below average, characterizing them as competitive businesses. In the case of Company A, as shown in Fig. 4, note that all plots show a small increment comparing to the national average, such as the energy consumption vs. raw material, where the value is 23% above average (see Fig. 4a). From this plot it appears that for the annual energy consumption of the company, 209 MWh, it would be expected to process more raw material (about 2000 tons). The plot relating the volume of cold rooms vs. raw material predict that cold rooms are capable of storing more 23% of the processed meat annually. An important feature is related to prediction values within the confidence interval of 95% (shaded green). Finally, the plot of specific energy consumption shows the SEC value of the company under study in relation to the average SEC in this meat companies’ subcategory (i.e., the average SEC value of the sample). In this case, and although the remaining plots are above the predicted values by the correlations, the result indicates that the company under study has a SEC value that lies 5% below the average value of this companies’ subcategory. Therefore it is considered more efficient, having competitive advantage over others with higher energy consumption, and thus being able to practice more competitive prices. If the company processes more raw material, the value of the nominal power of compressors in relation to the amount of raw material processed and volume of cold rooms would be adjusted according to prediction correlation values. The compressors power is 22% higher than expected, which allows concluding that this particular industry can increase the volume of cold rooms or load (raw material) using the installed power. However, based on the audit results there were identified certain issues that may improve the efficiency of this industry, such as the replacement of fluorescent lamps by LED lamps. Furthermore and according to the data collected there is in average one person per hour inside the cold rooms. Despite the air conditioned systems of hallways, this condition increase the thermal load of the cold rooms that lead to an increased energy consumption due to increased working time of compressors to compensate this thermal load. Another negative indicator was the poor condition of the boiler’s insulation. On the other hand the power factor of the company assumes a value close to ideal, being an asset to the energy performance of this industry.

The Company B is the largest from the case studies having a higher number of technical staff than others. At a first glance, it is shown in Fig. 5 that most of the prediction values displayed in the plots for this industry are within the confidence interval.

In the first plot (see Fig. 5a), where energy consumption is related with the raw material processed, it is predicted an energy consumption 31% lower than the average, which allows pointing out that this is a competitive industry. Additionally, the compressors nominal power for the same amount of raw material is 38% lower than the national average. This condition arises from the fact that Company B processes more raw material than the national average for the same volume of cold rooms as shown in Fig. 5c. Thus, the specific values related to the raw material processed are below the national average resulting in a lower SEC. Regarding the energy consumption and nominal power of compressors related to the volume of cold rooms (see Fig. 5e and f), the values are 7% above and 12% below average, respectively. It should be noted that these
latter values lie within the confidence interval, so the uncertainty of the predictions is reduced by the overall analysis of the correlations. The SEC of Company B is 32% below the national average being therefore the more efficient company analyzed in this case study. The cold storage of raw material is considered as a great advantage in this kind of industry. During the audit, some inefficiencies were detected, namely the lack of insulation in the boiler, the absence of air-conditioning in the hallways and the type of illumination used. Regarding the power factor, the capacitors system ensures that this value remains within the normal parameters.

The sausage industry examined within this case study is Company C, the smallest one. It is a micro company and the values of the input parameters for predicting the energy performance are in the limit of validity domain of the results.

Fig. 6a shown an energy consumption 64% lower than the national average for the amount of the raw material processed. In the remaining plots, the conclusions are similar and all predicted values are below average. The compressors power and the volume of cold rooms are lower than expected by 39% and 23% respectively for the raw material processed when compared to the national average. Fig. 6e–f compares the energy consumption and the nominal power of compressors with the volume of cold rooms. In these plots is noted that the predicted values are below the average 86% and 10% respectively. The prediction in Fig. 6e (86%) is outside the confidence interval due to an amount of raw material processed 23% lower in relation to the volume of the cold room. This condition is verified by the low energy consumption. Considering again Fig. 6a, it is clear that if the company handles more quantity of raw materials, the energy consumption will increase. Finally, by evaluating the plot comparing the SEC with the national average is predicted a value 28% lower than the estimated average. It is important to point out that this company uses electricity for heating water. This condition contributes to the low power factor (0.86) which increases the cost of electricity due to the increased reactive power. This problem can be easily solved by installing a small capacitor system. Notice that although the results obtained in the simulations are valid, the value of the amount of raw materials is slightly below the valid domain what can compromise the prediction results, hence the variation between the values of different plots (86% maximum in Fig. 6e and −10% minimum in Fig. 6f).

The predictions results as well as the conclusions obtained from the audits are indicative but allow managers of agrifood companies to be aware about the positioning of their company in relation to the national average in terms of energy performance. However, any change in the company or in the processes require a detailed in-situ study about the energy consumption of different devices that are part of manufacturing and cooling processes, taking into account the various inefficiencies that may exist. Nevertheless, the results obtained by the tool for the prediction of energy performance of meat industries are in line with the failures or inefficiencies detected in the fieldwork. The predictive tool here presented can be adapted to another country or sector, requiring only the modification of the correlations as well as the limit range of application and the confidence intervals.

6. Conclusions

This paper presents a predictive tool of the energy performance of agrifood industry. The main features and workflow of the tool are presented. Three case studies of its application are provided. The selected industries belong each one to a different meat subsector, respectively, slaughterhouse, hams industry and sausages industry. The case studies validate and demonstrate the applicability of the predictive tool. Some conclusions obtained from the graphical analysis of predicted results about the positioning of each company performance in relation to the Portuguese national average are presented. This predictive tool allows performing an evaluation of the energy performance of companies in the agrifood sector comparing the most relevant parameters such as raw materials processed annually, annual energy consumption and volume of cold rooms with the national average. The predictions allows the user to conclude which are the possible weaknesses or strengths of its company. The plot of specific energy consumption is very conclusive since it relates the energy consumption per ton of raw material. It can be seen as a competitiveness indicator. However it should be mentioned that the developed tool only helps managers of agrifood industries in the analysis of the energy performance. It is necessary that the user has sensitivity to identify possible problems of technical origin on the company facilities. Thus, the analysis does not discards the need for a more detailed study to determine particular conditions that can be improved. This conclusion arises from the comparison of results obtained from the simulations and the experimental results from audits.

The current state of the predictive tool allows the user to manually enter the data of annual energy consumption, raw material processed annually and volume of cold rooms. With this performance assessment, the user can decide how to improve the energy performance of his company. The practical application of this tool demonstrates its usefulness in helping decision-making in the implementation practice measures for the improvement of energy efficiency. This tool includes also correlations for other sectors of the agrifood sector, such as fish, milk, vine and wine and distribution. Moreover, the predictive tool delivers automatic suggestions for the improvement of energy performance depending on the prediction results. This tool can be used in any country or sector, requiring only the modification of the correlations as well as the limit range of application and the confidence intervals.

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References


