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A New Energy Performance Indicator for Energy Management System of a Wheat Mill Plant

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ABSTRACT

In this paper, a predictive tool for the energy consumption of wheat milling process using multiple linear regression and a new energy performance indicator (EnPI) is proposed. This EnPI does not only consider the production of flour but also the particle size of flour and added water for softening wheat. The results of the study, carried out in a wheat mill plant in Cuba, show a good coincidence between the predicted and real energy consumption for the developed model. It also demonstrates the effectiveness of EnPI proposed as a tool for management and energy savings in the company under study. Due to the complexity of the proposed model, for obtaining the baseline and estimating the energy saving potential, a probabilistic method was used. It was statistically demonstrated by the determination index (R^2), that the new proposed model is superior to the conventional model of energy versus production.

Keywords: Energy Performance Indicators, Energy Efficiency, Wheat Milling
JEL Classifications: K32, L94

1. INTRODUCTION

The enhancement of energy management in an industrial process requires good models and the definition of energy performance indicators (EnPI) (Eras et al., 2016), (Madrigal et al., 2018). Nowadays, an effective energy management system (EMS) is recognized as a potential competitive advantage by many companies (Pusnik et al., 2016) because offer many benefits, such as energy consumption and cost reductions, improve company's image and environmental impact reduction (Introna et al., 2014), (Sarduy et al., 2016).

The food industry is divided into several sectors. Among these, the wheat processing sector is considered as an energy-intensive industry consumer because require high and regular energy supply. In flour milling, electricity accounts for almost 75% of total energy use and over 90% of energy costs (Dhotel, 2012), with a consumption that varies between 361 MJ/t and 1186 MJ/t (Steerneman, 2013). Thus, inefficient energy use could lead to huge economic losses as excessive energy consumption adds to the costs of the goods produced.

There is an extensive scientific literature related to energy efficiency on food industry (Todorov et al., 2018), (Bogoviz et al., 2018) and wheat production (Balci, 2017), however, most of them focus mainly on marketing, production planning or quality of product. Studies related to energy consumption in this industry do not provide an adequate tool for energy management (Nabavi-Pelesaraei et al., 2016). In (Aiyedun and Adeyemi, 2008) the analysis is limited to evaluate the energy requirement for operations involved in the processing of wheat while in (Okonigene and Omondaigbe, 2009) it is analyzed how to reduce the peak load and its associated costs. Other researchers have been focusing on the development of energy consumption patterns of various unit operations required for the wheat processing plant (Olaoye et al., 2014).

Some studies report the development of EnPIs corresponding to milling plants (Dróżdż, 2010), (Safa and Samarasinghe, 2011). However, these EnPIs are based on simple models of energy consumption versus. production without considering variables of the wheat production process that affect the energy consumption.

Many factors influence on energy requirements for the size reduction of wheat. Lab tests with an experimental mill were developed to study the correlation between energy consumption and the class of wheat, moisture content, feed rate, fast roll speed, roll speed differential and roll gap (Fang et al., 1998). Other study show that wheat flour relies on proper conditioning to facilitate endosperm and bran separation, for this reason, many mills add moisture to soften the grain and improve efficiency in terms of the energy required to produce the flour (Doblado-Maldonado et al., 2012).

The processing of natural resources depends on their composition, for this reason, it is important to consider the relationship between energy efficiency and the properties of the raw material (Pehlken et al., 2015). The physical properties of wheat (Warechowska, 2014) and technical exploitation parameters of grinding rolls (Fišteš, 2015) have an influence on energy consumption of grinding as well. However, the studies of the plant processes realized focusing in the effect on product quality instead of the energy consumption. In (El-Porai, 2013) the effects of normal and hard milling and different conditioning times on flour properties of wheat were studied, without considering the energy consumption.

In this context, this article aims to present a new EnPI for EMS of a wheat mill plant, based on the ISO 50001 Standard (ISO, 2011). The EnPI is obtained from a multiple linear model that relates the energy consumption with production and other operational variables such as added water, moisture after rest and particle size (PS).

The model was developed in field conditions in a wheat processing plant located in Cuba. The tool is useful to quantify energy performance, energy performance changes and predict the electrical energy consumption. Another important advantage of the method is that variables used are accessible and can be controlled within a certain range to influence on energy consumption, without affecting the product quality.

2. MATERIALS AND METHODS

The method for obtaining the new proposed indicator consists of the following seven steps, described in detail in the following sections.

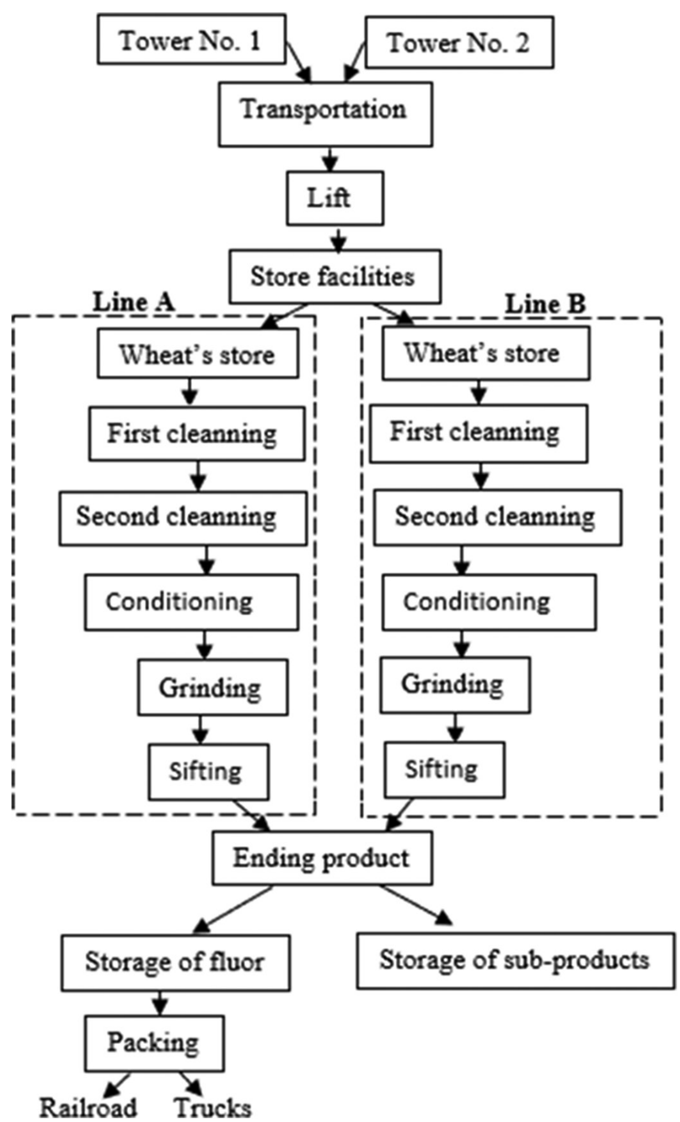
1. General characterization of the wheat flour plant.
2. Preliminary selection of the dependent variable (energy consumption) and independent variables (production parameters), taking as criteria the possibility of obtaining and controlling data.
3. Identification through a statistical analysis the independent variables that influence on energy consumption.
4. Obtaining the mathematical model of energy consumption according to the production variables.
5. Definition of the energy consumption indicator.
6. Validation of the mathematical model and the energy consumption indicator.
7. Obtaining the energy saving potential by applying a probabilistic method.

2.1. Characteristics of the Plant

The wheat mill plant studied produces approximately 420 t of flour daily and 150 Mt/year. It has two cleaning and grinding systems named Mill 1 and Mill 2 with capacities of 18 and 14.5 t/h respectively. The study focused first on the system Mill 1 since it has the highest production capacity and energy consumption. The tool obtained will be afterward replicated by the company in the system Mill 2.

In Figure 1 it is shown the process flow chart of the production system Mill 1. This system is divided into two similar production lines named Line-A and Line-B respectively. The main steps of the flow chart are:

Figure 1: Flow diagram of production system (Mill 1)



1. Input of raw material (wheat).
2. Cleaning.
3. Conditioning. In this step water is added to the wheat to soften it (normally, the moisture content of wheat is increased by 4–6%).
4. Grinded with roller mills.
5. Sift to reduce the size of the particle.
6. Storage of products and sub-products.
7. Delivery of flour through packing in sacks for transport by truck and railroad.

The plant has a centralized electric power meter and electric power meters on each distribution boards of production lines. The measurements are recorded and stored in the control room of plant.

2.2. Multiple Linear Regression (MLR) Model

According to ISO 50001 and ISO 50006 standards, several variables that affect the energy consumption can be introduced to obtain an EnPI (ISO, 2011), (ISO, 2014). With this purpose, in this study the general model of MLR represented in equation (1) is applied.

$$\hat{Y} = a_0 + \sum_{i=1}^{n} a_i x_i \tag{1}$$

Where $\hat{Y}$ represents the response variable, $a_0 \ldots a_n$ are coefficients of the equations, x_i are predictor variables and i represents the i-th observation of data sample.

In the model, energy consumption is the dependent variable and independent variables are following:

- Production (P): Flour produced in a work period of 8 h, in T.
- Added water (W): Difference between moisture content of wheat after spraying it with water for its softening and input moisture of the wheat, in %.
- Moisture after rest (M_{ar}): Moisture content of the wheat after the rest time in the holding bin, in %.
- PS: Percent of flour that has PSs more than 250 µm. This percentage is obtained in the lab from a 100 g sample. The material captured in the sieves is weighed and the result is recorded as a granulation. This magnitude defines the quality of the product.

Considering that the two production lines have similar technologies, a common EnPI was obtained for both lines, from the production and consumption data merged. This implies the use of an average EnPI model, which is less accurate than using an EnPI for each line but is easier and more practical to apply.

For the study, a sample of 290 data corresponding to March, April and May of 2015 was used. The reports are organized according to the work shifts of the plant (7:00 a.m. to 3:00 p.m.), (3:00 p.m. to 11:00 p.m.) and (11:00 pm to 7:00 am.).

To obtain the EnPI, a multivariable linear model was used applying the "multiple regression" tool of the software "Statgraphic". Several models were evaluated considering as dependent variable energy (E) and various combinations of the independent variables (P, W, M_{ar} and PS). For the evaluation of the models, the statistical parameter determination index (R^2) were used. This statistic measures the proportion of the variability in E which is explained by the model.

Table 1 shows the results of fitting various multiple regression models to describe the relationship between E and the four independent variables. Models are sorted by determination index (R^2). For better understanding, the independent variables were coded with the letters A, B, C and D. According to results, the best model with greater determination index (R^2) (65.43) was the combination 1, in which are correlates the energy (E) with production (P), added water (W) and PS.

Where independent variables are encoded as: A=P, B=W, C=Mar and D=PS. Number of complete cases equal to 290 and number of models fit equal to 14.

Table 2 shows the P-value statistic corresponding to each independent variable obtained from evaluation of the model with all the independent variables included. If the P-value statistic is ≤ 0.05, means that for a confidence level of 95%, the variable is not statistically significant, that is, it does not affect the behavior of the dependent variable. Because of the analysis, the table shows that the independent variable (Mar) has P > 0.05, therefore they do not influence on energy consumption and can be eliminated from the model.

Table 3 shows the statistical difference of the models when considering only P as an independent variable (Identifier E_1) and when considering the independent variables P, W and PS (Identifier E_2). For this analysis, 11 outliers of the 290 initial measurements were eliminated. Outliers are those that are outside the range of plus/minus three times the standard deviation (Madrigal et al., 2018).

Table 1: Statistical evaluation of the models

Combinations	Independent variables	Determination index (R^2)
1	ABD	65.4302
2	AD	65.3899
3	ABCD	65.3711
4	ACD	65.3469
5	AB	64.8005
6	ABC	64.7745
7	A	64.7278
8	AC	64.7244
9	D	6.5995
10	BD	6.36209
11	CD	6.35557
12	BCD	6.10425
13	C	0.0
14	B	0.0

Table 2: P value of independent variables corresponding to the model with all the independent variables included

Parameter	P-value
P	0.0000
W	0.0274
PS	0.0155
Mar	0.4749

PS: Particle size

Table 3: Results of curve fit for the operational variables data sets

Identifier	Parameter	Estimation	Standard error	T-Statistic	P-value	R^2
E_1	Intercept	430.491	105.487	4.08099	0.0001	80.92
	P	47.7935	1.394	34.2852	0.0000	
E_2	Intercept	637.332	121.26	5.25591	0.0000	82.59
	P	46.2911	1.36932	33.8058	0.0000	
	W	8.33988	10.6897	0.780178	0.0436	
	PS	−98.843	19.6482	−5.03065	0.0000	

PS: Particle size

As seen in the table, consider the variables W and PS in addition to P, improve the model correlation since the value of determination index (R^2) is higher than when only considering P. Figure 2 shows the observed values versus predicted values. The excluded points are marked with red crosses. The equation of model E_2 represented in Figure 2 is:

$$E_2=63733+4629\ P+834\ W-98.84\ PS \qquad (kWh) \qquad (2)$$

The model E_2 obtained is very useful because allows to predict the energy consumption of the company and is the basis of the proposed indicator. In addition, as it considers the operational variables W and PS that can be controlled, it can influence with greater flexibility in the energy consumption if the quality of the production is not affected.

2.3. Verification of Model Quality

Figure 3 shows the behavior between the actual energy values measured and those estimated by the model. As it is observed, there is a very similar qualitative behavior.

The quantitative evaluation of the forecast accuracy was done by calculating the mean absolute percentage error (MAPE). This statistical parameter gives a global idea of the difference between the predicted and actual values. MAPE is calculated using Equation (2). For this case, the MAPE is equal to 5.33%. This low error indicates the good quality of the model as a tool to forecast energy consumption.

$$MAPE=\left(\frac{1}{n}\sum_{i=1}^{n}\left|\frac{(P_i-A_i)}{A_i}\right|\right)\cdot 100 \qquad (3)$$

Where n is the number of observations of the test period, and P_i and A_i are the i^{th} predicted and actual values, respectively.

2.4. New EnPI for Each Production Line

The new EnPI expressed in energy consumption per production unit is obtained from equation (1). For this, both members of the multiple regression equation are divided by production (P) as:

$$\frac{E}{P}=\frac{637.33+46.29\cdot P+8.34\cdot W-98.84\cdot PS}{P} \qquad (kWh/t) \qquad (4)$$

It can be expressed as:

$$EnPI=\frac{46.29+(637.33+8.34\cdot W-98.84\cdot PS)}{P} \qquad (kWh/t) \qquad (5)$$

Figure 2: Observed values versus predicted values for E_2 model

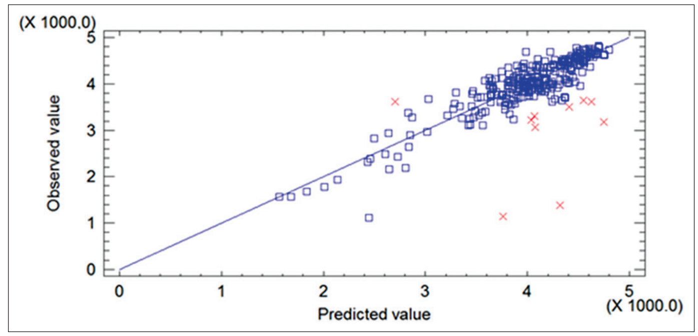
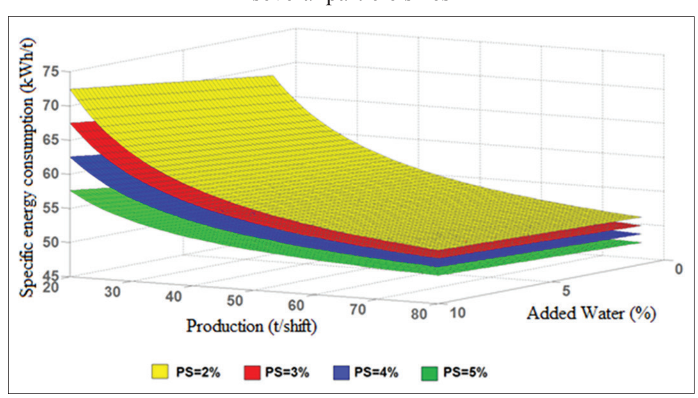


Figure 3: Comparison between prediction by multiple linear regression model and real energy consumption

Figure 4: Graphic representation of the proposed new indicator for several particle sizes



The new indicator defined by Equation (5) represents a family of surfaces, with one surface for each PS as shown in Figure 4. This model is more complex in relation to traditional linear models proposed. However, as explained, allows greater control of energy consumption and with current technology, it can be easily implemented in any electronic spreadsheet or embedded in other applications.

3. RESULTS AND DISCUSSIONS

3.1. Application of New EnPI

To describe the application of the new EnPI, plant operational data of April 29th 2016 in the work shift from 7 a.m. to 3 p.m. were analyzed. This shift was considered because it is where the highest production of the day is concentrated.

The screen of electrical measurement system for this day is shown in Figure 5. The red curve corresponds to the electrical power demand of Line-A, and the yellow one to Line-B. The corresponding production operational parameters per shift to each production line is shown in Table 4. The power demand of Line-A is lower than that of Line-B because in Line-A flour with bigger PS is produced and therefore its roller performs less work.

The results and curves family obtained from Equation (5) for work shift from 7 a.m. to 3 p.m of Line-A for different PSs and 3% of added water, are plotted in Figure 6. In this figure the actual value of specific consumption is 52.21 kWh/t (red point) and the theoretical value obtained by the proposed model for a PS of 2.95% is 51.15 kWh/t (gray curve). According to this result, evaluating energy performance from EnPI, there was an over-consumption of energy (OCE) in this work shift of 88.88 kWh calculated as:

$$\text{OCE}=(\text{Actual value}-\text{Theoretical value by the proposed model})\ \text{Production} \quad (6)$$

$$\text{OCE}=(5221\ \text{kWh/t}-51.15\ \text{kWh/t})\ 76.3\text{t}=80.88\ \text{kWh} \quad (7)$$

These losses are explained because as observed in Figure 5, close to 3 p.m., an electric power of 240 kW for 20 min was connected without production, representing losses of 80 kWh. In this industry and others, it is a common practice to keep the equipment working at not load condition when the supply of raw material is interrupted (Santos et al., 2016), (Quispe et al., 2018).

For Line B, Figure 7 shows that for 7 a.m. to 3 p.m. shift, the actual energy required for production for PS = 0.5 and 5.6% of added water was (54.32 kWh/t) and the new proposed model predicts an energy consumption of 54.15 kWh/t.

The similarity between the theoretical value obtained by the model and the real one in Line B, and the results of Line A, shows the effectiveness of the proposed model, as a tool for energy management.

3.2. Determination of Energy Saving Potential for Each Production Line

Because the proposed indicator is made up of a family of curves, a statistical model is presented as a baseline. Points above baseline represents an inefficient operation due to malpractices such as: Keep plant equipment's connected at zero load for long time periods, operative interruptions, broken equipment due to lack of maintenance, etc. Points below baseline mean that the plant is operating efficiently.

The energy goal is calculated probabilistically as differences between predicted values of energy from baseline and actual energy consumption (ΔE). The set of ΔE values, better adjust to a Lognormal distribution with the distribution parameters for each production line shown in Table 5.

As ΔE follows a Lognormal distribution, ln(ΔE) has a normal distribution with mean μ and variance σ^2. For this reason, the variable x is:

Figure 5: Electrical power demand for each production line, April 29th 2016

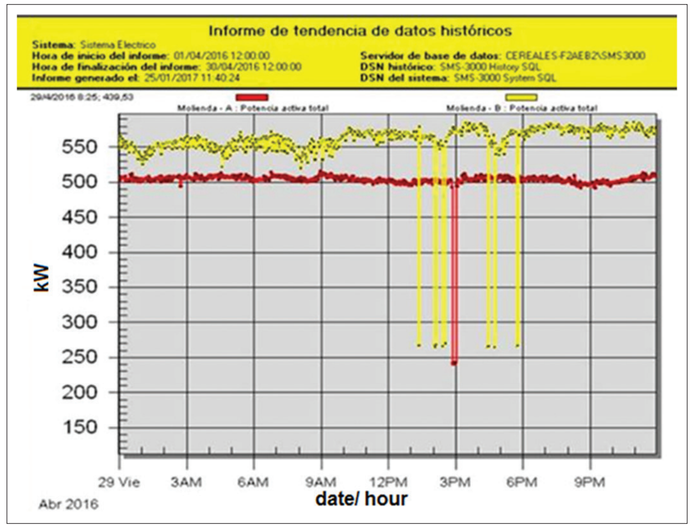


Figure 6: Specific energy consumption versus production for line-A. April 29th, 7 a.m. to 3 p.m. with 3% of added water

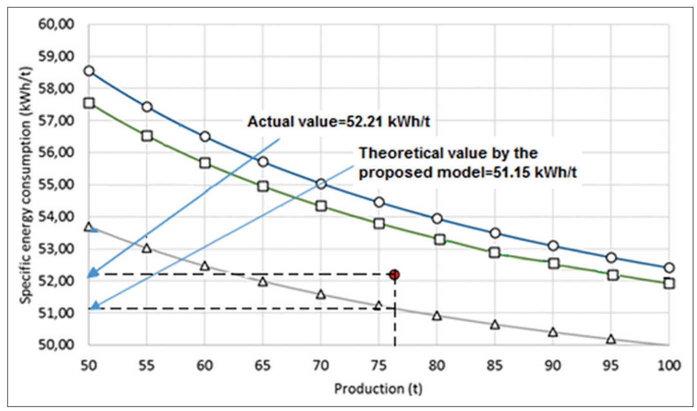
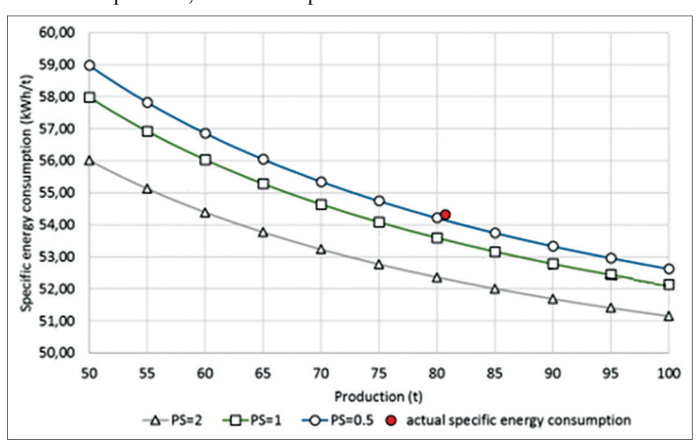


Figure 7: Specific energy consumption versus production for line-B. April 29th, 7 a.m. to 3 p.m. with 5.6% of added water



$$x = \frac{\ln(\Delta E) - \mu}{\sigma} j \tag{8}$$

Variable x is a reduced variable with mean 0 and a standard deviation equal to 1. Hence, the probability that $\Delta E > \Delta E_O$ can be described as:

$$P(\Delta E\_O)=1-\varnothing(x) \tag{9}$$

Where is the function of the cumulative distribution of the reduced normal.

The present study aims to determine the energy savings potential with a probability of 80%. Then $P(\Delta E_0) = 0.80$ and from equation (8), $ø(x) = 0.2$. Substituting these values in a normal distribution table, it is obtained that $x = -0.84$. With this value and from equation (6), the energy saving potential is obtained probabilistically as:

$$\Delta E_O = e^{(-0.84 \cdot \sigma + \mu)} \tag{10}$$

Substituting the data of Table IV in Equation (8), it can be affirmed with a probability of 0.80 that the energy saving potential in the Linea-A is at least 61.56 kWh per shift. This could represent 5540 kWh per month. Similarly, we can affirm with a probability of 0.80 that the energy saving potential in the Line-B is at least 28.67 kWh per shift which could represent 2580 kWh per month.

This potential represents a reduction of 1% of the monthly consumption. This may be an initial goal without considering investments, but the standardization of good practices obtained in the shifts of better energy performance.

Table 6 shows the energy saving potentials obtained by the probabilistic method considering different probabilities. As it is observed, while estimating the savings with greater probability, that is, seeking better precision, a lower energy saving potential is obtained and vice versa.

Table 4: Production operational parameters per shift, April 29th 2016

Shift	Line A (7 a.m.–3 p.m.)	Line B (7 a.m.–3 p.m.)
Production (t)	76.3	80.7
Input moisture content of wheat (%)	12.0	12
Moisture content of wheat before rest (%)	15.0	17.6
Moisture content of wheat after rest (%)	13.5	13.6
Added water (%)	3.0	5.6
PS (%)	2.95	0.5
Energy consumption (kWh)	3984	4384
Actual specific energy consumption (kWh/t)	52.21	54.32

PS: Particle size

Table 5: Parameters of adjusted distribution for ΔE

Parameters	Lognormal distribution	
	Line-A	Line-B
μ	4.96	4.49
σ	1.00	1.35

4. CONCLUSIONS

The proposed new EnPI is a useful tool for energy management in wheat mill plants. The added value of this tool is that it is not only based on a simple correlation of energy versus production but consists of a surfaces family that considers production operation variables as added water (W) and PS.

The advantage of using indicators with several independent variables including production parameters, is that it allows managing energy with greater flexibility. However, to obtain the indicator with these characteristics, it is essential to use a rigorous statistical analysis that allows defining the variables that influence on energy consumption and disregard those that do not have any relation with this parameter.

The proposed indicator was obtained and validated in two lines of production of a real wheat flour plant from the data of production and consumption of energy. The application of the indicator allowed to identify in one of the lines, the OCE by keeping equipment operating in vacuum for long time and in the other line, prediction and actual values were very close. These results demonstrate the validity of the proposed tool for energy management. It was also demonstrated statistically by the determination index (R^2), that the proposed model is superior to the conventional model of energy versus production.

To obtain the baseline and estimate the potential for energy savings, a probabilistic method was proposed that allowed identifying, for a probability of 80%, a potential energy saving of 1% without apply investments. Considering the high consumption of the plant, this value represents a considerable annual saving in the costs associated with the energy consumption of the company.

Table 6: Probability of potential of energy saving for both lines

Probability	Line A		Line B	
$P(\Delta E_O)$	ΔE_O (kWh/shift)	Energy saving potential (kWh/month)	ΔE_O (kWh/shift)	Energy saving potential (kWh/month)
0.95	27.66	2489	9.74	877
0.90	39.65	3568	15.83	1424
0.85	50.40	4536	21.89	1970
0.80	61.56	5540	28.67	2580
0.75	72.97	6567	36.07	3246
0.70	84.77	7629	44.17	4011

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