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Optimization Techniques for the Dosing of Fuels in Parallel Flow Regenerative Kilns

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Abstract. *This work aims at presenting a solution to minimize the cost of fuels by optimizing the dosing of raw-materials and fuels, considering environmental restrictions. As case study, a lime production of a company located in the Center-West region of Minas Gerais was analyzed. The results were compared using three optimization algorithms, that is: Sequential Quadratic Programming (SQP), Teaching-Learning-Based Optimization (TLBO)and Firefly Algorithm (FA). The results obtained with TLBO algorithm were the best ones for the optimization problem, with restrictions. The total cost obtained by this algorithm was R$ 61.00 \ton. At this price, for each 1.78 tons of limestone, 0.0801 tons of petroleum coke, 0.00113 tons of charcoal and 0.00255 tons of coffee hull might feed the kiln*

Keywords: *Lime, Optimization, Fuels, Feedstock.*

1. INTRODUCTION

For the past decades, optimization has become an important tool to obtain the best results in industrial procedures at maximum efficiency.

In lime industry, researches that use optimization techniques are focusing on the conditions of lime hydration processes, such as: Study and Optimization of Calcium Oxide Hydration Reaction (da Silva (2009)).

Lime production is relatively simple, but one of the challenges faced by industries in this industry is the use of alternative renewable fuels, its correct dosing, and the compliance with applicable environmental and quality norms.

Therefore, the lime industry has sought for solutions related to fuels used to produce lime, to the raw material consumed in the production process, to the control of pollutant emission, to environmental restrictions and to lower production costs.

Several researchers have used optimization techniques to solve problems in several areas such as: renewable energy (Bremer *et al.* (2015); Zhang *et al.* (2015)), chemical engineering, production engineering, electrical engineering, among many other areas.

In order to better the process and reduce environmental impacts, without compromising the quality of the end product, it is possible to use optimization techniques to determine the best configuration for the system, improve the production efficiency, and lowering expenses Carpio (2005).

This research aims at contributing to this study by developing an optimization model applied to vertical parallel flow regenerative kilns in lime industry with the use of alternative fuels. With this model, it will be possible to evaluate the effect of alternative fuels on the amount of lime, the environment and the production costs. It will also provide an understanding of the chemical reactions and a study about the influence of the main operational parameters during the operation of the kiln.

2. OPTIMIZATION ALGORITHMS

Several algorithms have been developed and improved such as genetic algorithms (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), Teaching-Learning-based Optimization (TLBO), among many other techniques.

2.1 Interior Point Algorithm

The Interior Point Algorithm, is widely used in linear optimization problems with inequality restrictions.

$$minf\,(x) \tag{1}$$

Subject to:

$$A \cdot x \leq b, \tag{2}$$

where: **A** is the equality matrix and b is a vector.

$$A_{eq} \cdot x \leq b_{eq}, \tag{3}$$

where: A_{eq} is the equality matrix and b_{eq} is an vector.

$$lb \leq x \leq ub, \tag{4}$$

where **lb** is the vector with lower limits of the variables of the search space and **ub** is the vector with superior limits of the variables of the search space.

2.2 Sequential Quadratic Programming (SQP)

The Sequential Quadratic Programming (SQP) algorithm is one of the main local nonlinear optimization methods. The method is based on gradient and is sequential, because, from a set of initial variables, it updates the project iteratively in order to linearize the restrictions and obtain a solution for the quadratic problem (Kim *et al.* (2015)).

Equations 5 - 7 show the means of quadratic approach:

$$\frac{1}{2}d^T Bd + f(x)^T d, \tag{5}$$

Subject to:

$$h_i(x)^T d + h_i\,(x) = 0, \tag{6}$$

$$g_i(x)^T d + g_i\,(x) = 0, \tag{7}$$

where d is the direction vector and B is Lagrange's approach matrix. The optimization process seeks to update the value of x, to obtain an optimal direction vector d as described in Equation 8:

$$x^{k+1} = x^k + \alpha^k \cdot d^K, \tag{8}$$

where k means the iteration number and α is the algorithm step.

2.3 Teaching-Learning Based Optimization (TLBO)

The Teaching-Learning Based Optimization (TLBO) algorithm, proposed by Rao *et al.* (2011), is based on the interaction between students and teachers in the classroom, and may be divided into two phases: the teacher-choice phase and the learning phase.

In the first phase of the algorithm, a teacher is chosen to increase the class' knowledge and average.

In the second phase, a new teacher is chosen. Each student chooses another student to be the teacher and learns new things with them, if they are provided with more knowledge.

3. PROPOSED METHOD

3.1 DATABASE

Data collection was made by analyzing the legislation applicable to restrictions of atmospheric emissions, heavy metals, and dioxins and furans in the product; the characteristics of limestone, fuels and lime quality were obtained by chemical analyses provided by the company under study.

In Table 1 we present the chemical composition of the fuel, obtained by chemical analysis in the laboratory of the company under study.

Table 1. Chemical composition of the raw-material, in mass (%)

Chemical composition		CaO	Al_2O_3	Fe_2O_3	SiO_2	P_2O_5	MgO	MnO	CO_2
Limestone	X_1	55	0.03	0.07	0.28	0.068	0.54	0.011	40

In Table 2, we present the chemical composition and minimum calorific power of fuels, obtained by chemical analysis in the laboratory of the company under study.

Table 2. Composição química dos combustíveis.

Components	**Petroleum Coke (% in weight)**	**Charcoal (% in weight)**	**Coffee Hull (% in weight)**
	X_2	X_3	X_4
C	85	46.45	11.94
H	4.80	5.70	-
O	2.70	42.65	-
N	2.50	1.41	0.15
S	1.50	0.07	0.05
Minerals	1.00	4.40	15.00
Volatiles	9.00	76.10	30.00
PCI	7.700 kcal/kg	3.941 kcal/kg	5.000 kcal/kg
Arsenic	0 - 1.52 mg/kg	0 - 1.69 mg/kg	0 - 1.71 mg/kg
Cadmium	0 - 1.01 mg/kg	0 - 1.13 mg/kg	0 - 1.14 mg/kg
Plumb	0 – 2,02 mg/kg	0 – 2,26 mg/kg	0 – 2,28 mg/kg
Chrome	0 – 4,55 mg/kg	0 – 62,50 mg/kg	0 – 5,13 mg/kg
Dioxins and Furans	0 - 7,40 ng/kg	-	-

To obtain the results of the mathematical optimization model, MATLAB® version r2016a was used. The optimization algorithms TLBO and bees algorithm were obtained by Yarpiz collection and adapted to the optimization problems with restrictions. SQP algorithm was obtained by Matlab toolbox.

3.1.1 Quality Norms

Lime production industry is regulated by environmental and product quality norms.

The Normative Deliberation Copam 187 of 2013 sets forth conditions and limits of pollutant emissions to the atmosphere, and the maximum limits of nitrogen oxide, sulfur oxide and particulate matter. Table 3, shows the limits established by environmental standards.

3.1.2 Algorithm parameters

To model the aspects mentioned above, it is necessary to count on a calculation procedure that describes the steps to be taken to meet such goals. In Figure 1, we present a flowchart with the sequence of calculations made to obtain the model, when there is a mix of fuels in the lime production process.

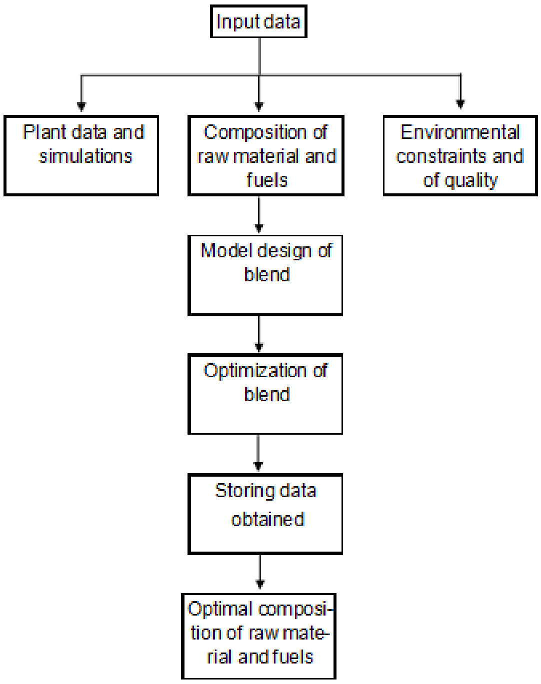
The initial project parameters used for the interior point algorithms were:

- **Number of variables:** 4 variables.
- **Search space:** $1,75 \leq x_1 \leq 2, 0 \leq x_2 \leq 0,5, 0 \leq x_3 \leq 0,5$ e $0 \leq x_4 \leq 0,5$.
- **Maximum evaluation functions:** 500 000.

Table 3. Limits set forth by environmental laws.

Parameter	Limit
Sulfur oxides	470 mg/Nm
Nitrogen oxides	470 mg/Nm
Particulate matter	100 mg/Nm
Arsenic	10 mg/kg
Cadmium	20 mg/kg
Plumb	100 mg/kg
Chrome	200 mg/kg
Dioxins and Furans	500 pg/kg

Figure 1. Optimization method applied to the dosing of fuels.



Source: Elaborated by the author.

- **Maximum number of iterations:** 500 000 iterations.
- **Optimum tolerance: :** 1e-10 000 000.
- **Tolerance step:** 1e-10 000 000.

The initial project parameters used for TLBO algorithms were:

- **Number of variables:** 4 variables.
- **Search Space:** [0 3].
- **Maximum number of iterations** 500 iterations.
- **Population number:** 10 000.

The initial project parameters used for SQP algorithm were:

- **Number of variables:** 4 variables.
- **Search space:** $1,75 \leq x_1 \leq 2, 0 \leq x_2 \leq 0,5, 0 \leq x_3 \leq 0,5$ e $0 \leq x_4 \leq 0,5$.
- **Maximum evaluation functions:** 500 000.

- **Maximum number of iterations:** 500 000 iterations.
- **Optimum tolerance: :** 1e-10 000 000.
- **Tolerance step:** 1e-10 000 000.

3.2 MATHEMATICAL MODEL

The function "cost objective" presented in Equation (9) consists of the costs of raw material (W_1) and costs of fuels (W_2, W_3 e W_4) during the process. The raw material used in this optimization model is limestone. As fuels, we evaluated Petroleum Coke, Charcoal Residue and Coffee Hull.

Regarding atmospheric emissions of particulate matter, sulfur oxides and nitrogen oxides, we analyzed the applicable law to elaborate the restrictions. Restrictions related to the amount of lime are represented by the content of heavy metals, dioxins and furans.

Equation (10) e (11) , presents the restriction related to calcium oxide ($CaCO_3$)

Equation (12) presents the restriction related to aluminum oxide (Al_2O_3).

Equation (13), presents the restriction related to iron oxide (Fe_2O_3).

Equation (14), presents the restriction related to Silicon Dioxide (SiO_2).

Equation (15), presents the restriction related to Phosphor Pentoxide (P_2O_5).

Equation (16), presents the restriction related to Magnesium Oxide (MgO).

Equation (17), presents the restriction related to Manganese Oxide (MnO).

Equation (18), presents the restriction related to Carbon Dioxide (CO_2).

Equation (19), presents the restriction related related to the calorific value of fuels that are Charcoal and Coffee Hull.

Equation (20), presents the restriction related to Petroleum Coke, which should be responsible for 50% of the kiln calorific power which equals 3800 kJ/kg.

$$Minimize \ W_1 \cdot x_1 + W_2 \cdot x_2 + W_3 \cdot x_3 + W_4 \cdot x_4, \tag{9}$$

$Subject\ to:$

$$55 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 \geq 89, \tag{10}$$

$$55 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 \leq 100, \tag{11}$$

$$0.03 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 \leq 1.50, \tag{12}$$

$$0.07 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 \leq 0.2, \tag{13}$$

$$0.28 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 \leq 1.50, \tag{14}$$

$$0.068 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 \leq 1.00, \tag{15}$$

$$0.54 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 \leq 1.60, \tag{16}$$

$$0.011 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 \leq 0.01, \tag{17}$$

$$40 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 \leq 2, \tag{18}$$

$$0 \cdot x_1 + 0 \cdot x_2 + 16489.14 \cdot x_3 + 20920 \cdot x_4 = 1900, \tag{19}$$

$$0 \cdot x_1 + 32216.80 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 = 1900, \tag{20}$$

4. RESULTS AND DISCUSSION

In Table 4, we present the results of the total cost obtained by different types of optimization algorithms for 10 runs. SQP had the best result (R$ 60.9\ton of lime produced).

Table 4. Results obtained for different optimization algorithms.

Optimization Algorithm	**Best**	**Worst**	**Mean**	**Standard Deviation**
Interior Point Legacy	76.00	76.00	76.00	0.00
SQP	75.00	75.00	75.00	0.00
TLBO	60.9	63.00	61.71	0.73

In Table 5, we present the results for amount of raw-material and fuels that should enter the lime kiln to reach the best result obtained by the optimization process. According to the results obtained by SQP, for 1.78 tons of limestone, 0.0801 tons of coke, 0.00113 tons of charcoal and 0.00255 tons of coffee hull should be in the kiln.

Table 5. Amount of raw-material and fuels that should be used to reach the best results under the optimization algorithm.

Optimization algorithm	$\mathbf{X_1}$	$\mathbf{X_2}$	$\mathbf{X_3}$	$\mathbf{X_4}$
SQP	1.78	0.0801	0.00113	0.00255

5. CONCLUSION AND FUTURE STUDIES

As mentioned above, optimization is an important tool used by several companies to solve daily problems.

In order to optimize the mixture of raw-materials and fuels, a model was elaborated considering environmental restrictions and quality of the product. Three types of algorithms were used in order to minimize the total cost of the mixture. The best results were obtained by Sequential Quadratic Programming (SQP) algorithm (R$ 60.9 \ton of lime produced).

For future studies, we intend to compare new optimization algorithms, as well as the variations in initial project parameters

6. ACKNOWLEDGEMENTS

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