OPTIMIZATION IN THE CO-PROCESSING OF WASTES IN CEMENT INDUSTRY COMPRISING COST, QUALITY AND ENVIRONMENTAL IMPACT

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Abstract. *Nowadays the high degree of the industrial activity as well as the increasing society life standard have been accompanied by a growing waste generation which represents one of the most serious environmental problems. The possibility use of some industrial wastes in the cement production, as an alternative source of secondary raw materials, as well as of alternative secondary fuels has been a viable path to reduce the cement industries production cost. The main concern about the use of these fuels is the effects in the cement performance and the possible environmental impacts that they can cause. Through an optimization model the influence of these fuels in the cement Portland properties are analyzed. In this model the Sequential Quadratic Program (SQP), Genetic Algorithm (GA) and Differential Evolution (DE) are applied taking account the raw material and fuels cost, the clinker quality and the environmental impact, such as the consumption of the energy requested in the grinding for the cement production.*

Keywords: *optimization, co-processing of industrial waste, cement industry*.

1. Introduction

The industrial growth along with its waste residues increasing (hazardous or not) has been representing a challenge to be overcome and constitute one of the great problems related to the environment in the last years, mainly for the industries that generate hazardous residues. According to the Brazilian Association of Treatment, Recovery and Disposition of Special Residues Companies (Abetre), 2.9 million tons of hazardous industrial residues is generated annually in Brazil. Only 600 thousand tons, about 22%, receive appropriate treatment. The remaining 78% are deposited improperly in landfills without any type of appropriate treatment. (Abetre, 2003).

The co-processing is a solution that satisfies the current demands for environmental control (CONAMA, 1999), because it is possible to take advantage of the thermal energy contained in the residues, avoiding the unnecessary burn of non renewable fossils, besides giving an appropriate destination of them.

The use of residues as fuels in the cement production is not new. This process is used thoroughly in Europe and in the United States, and every day is being more used in Brazil. In the USA, since 1969, several cement industries has been using residues as alternative inputs obtaining an annual economy around a million tons of coal (Sitivesp, 2002).

With the co-processing, 100% of the industrial residues are destroyed without generating any liquid or solid effluent due to the burn. Also, the organic compositions are destroyed in the process due to the high burn temperature. The solids are kept in high temperature by several minutes, the necessary time for the clinker formation, the main representative of the cement, which is responsible for its hydraulic properties.

The clinker, a basic component of the Portland Cement, is obtained from the grinding, homogenization and burning (high temperatures $\approx$ 1450 ^oC) processes inside the rotary cement kiln starting from a raw mix originating from the raw material: limestone, clay, sand, iron ore. The main chemical elements that constitute the clinker are: calcium oxide (CaO) and silica oxide (SiO_2), which react between themselves forming calcium silicates, which are the main actives components of the cement. A sketch of the manufacture process of the Portland Cement is shown on Fig. 1.

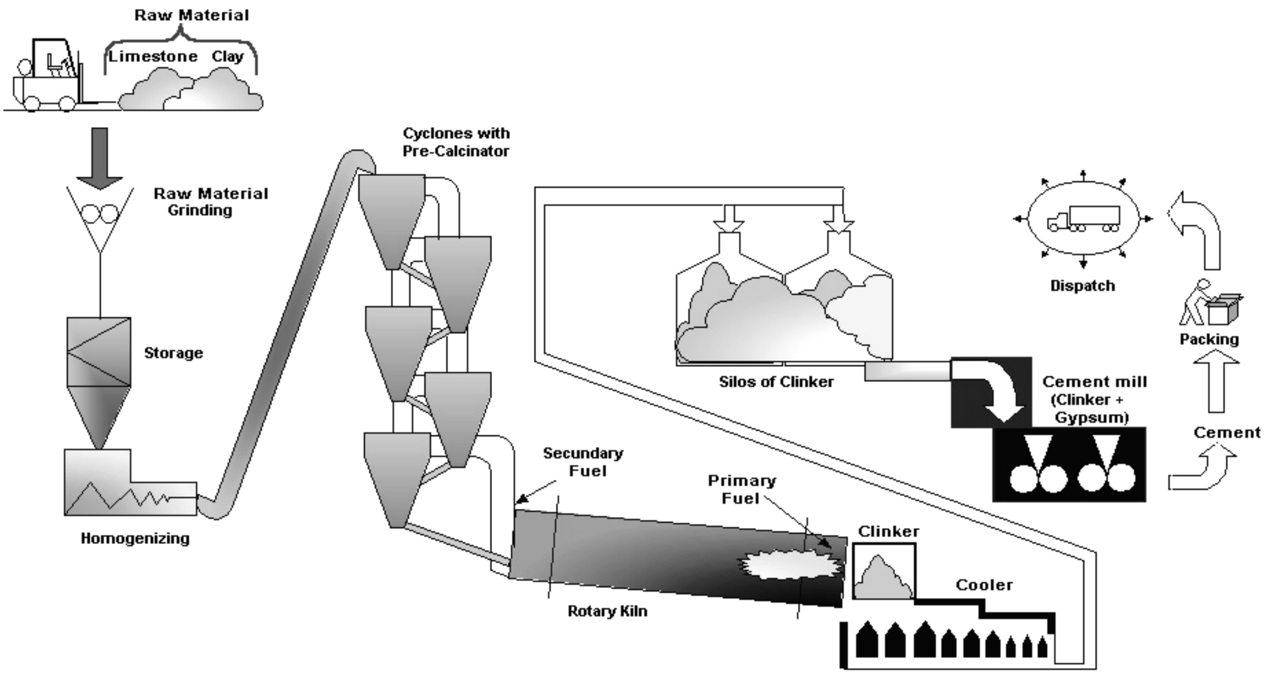

Figure 1. Process steps of the Portland Cement manufacture.

This work presents a formulation for the mixture optimization of some residual wastes employed as alternatives fuels such as: mineral coal, petroleum coke and used tires along with raw materials included in the cement process production This mixture is intended for use in a rotary kiln of clinker production, dry via, with a four stages pre-heater. However, the problem involving mixture of these components is complex. The optimization procedure takes into account process restrictions such as specific heat consumption, cement quality and environmental impact. In this case, the optimization of mixture in cement kilns is a problem with nonlinear cost function with linear constraints.

This paper presents the contribution of a comparative study of several optimization techniques for mixture optimization in cement kilns. Two classes of optimization techniques namely (i) classical (sequential quadratic programming), and (ii) meta-heuristics based on random search (genetic algorithm and differential evolution) are evaluated.

This paper is divided in five parts. First, the residues used for the cement industries is described in details; second, the description of optimization problem is presented; three, the optimization techniques are presented; four, the results of optimization is discussed; and five, the conclusion and future works is presented.

2. Residues used for the cement industries

The ASTM (American Society of Testing Materials) standards specify tests and procedures to assure the uniformity of the cement produced in the whole world. Before the product can be denominated "Portland Cement", it is necessary to proof that its chemical composition is kept within the specifications, in addition to its submission to rigidity and granularity tests. In that way the quality of the cement is proven, independently of the materials and fuels used in its production.

Not all the residues should be used as supplemental fuel. A cement industry production line cannot burn dangerous residues that are highly corrosive, reagents or toxic as, for instance, residues that contain chlorine in their composition. These products should be avoided because they can damage equipments (piping and valves) and generate, most of the time, an acid gas denominated chloride hydrogen (HCl).

Other constraints should be included on the amount of metals incorporated to the clinker. Concentrations of certain metals above 0,1% can also affect cement cohesion and should be strictly controlled.

Some examples of residues used in cement industries can be mentioned: the refine waste of lubricant oil, volatile ashes, carbon mill, tyres, tires scrapings, solvents, paints waste, among others (Santi, 1997).

2.1. Alternative fuels in clinker kilns

A mixture of industrials residues can be used as alternatives fuels in clinker kilns, resulting in economical and environmental advantages, while keeping the quality standards of the final product. In order to use these alternative fuels, an analysis must be performed on the proportions of each residue type to be used. The analysis of the residue components will provide the optimum percentage of each residue type in the mixture.

The pollutants present in the residue, basically inorganic materials and heavy metals, combine with the silicates formed in the clinker kilns of the cement factories. The recycling process, in the form of co-processing in these kilns, assures that secondary residue will not be formed. However, these pollutants should be studied with criteria, to investigate the influence that the heavy metals incorporated by these pollutants might have on the characteristics and properties of Portland cement (Trezza and Scian, 2000).

2.2 Chemical composition of fuels used for feeding clinker kilns.

In order to establish the basic parameters for the feeding of fuels in rotary clinker kilns, some essential parameters for the formulation of an optimization model must be obtained. For this purpose, initial data were gathered, related to the chemical composition of commonly used fuels (coal) and of alternative fuels (petroleum coke, and used tires). The ashes chemical composition was also obtained, especially for the ashes components that are also part of the raw materials used for the clinker production. The chemical composition information, together with the calorific power (Lower Heating Value, LHV) of each one of these fuels and residues, is presented in Tab. 1.

Table 1. Chemical composition in mass (%) of main fuels used as primary and alternative fuels in clinker kilns

Component	Coal [(a)] (%)	Petroleum coke [(b)] (%)	Tires uses [(c)] (%)
C	63.9	8 – 100	72.15
H	3.6	3.5	6.74
S	4.6	0.5 - 7.0	1.23
O	0.9		9.67
N	1.8	1.5	0.36
Cl	-		0.149
Ash	24.9	1 – 4	8.74
CaO	1.03		10.64*
SiO_2	9.32		22.0*
Al_2O_3	5.08		9.09*
Fe_2O_3	7.21		1.45*
MgO	0.44		1.35*
Cr	0.008	1 – 23**	0.0097
Ni	0.008	30 – 420**	
Pb	0.027	1 – 10**	0.0065
TI	0.0004	1 – 80**	0.00001
Hg	-	0.1 – 10**	
As	0.00017	0.1 – 10**	
V	0.0648	130 – 2300**	
LHV [kJ/kg]	25.392	32.447 – 36.425	32.100

Sources: [(a)] :(Carvalho, et al., 1997), [(b)] :(ABCP, 1984); [(c)] :(Trezza and Scian, 2000); * Component of ash; ** ppm.

3. Description of optimization problem

The modeling will employ optimization algorithms aiming to assure a better kiln operation stability, a reduction in the energy consumption and an environment impact minimization. The modeling will contemplate two aspects as described below:

a) the effects that the alternative fuels employment can cause:

- at the clinker quality through the raw material and fuels chemical composition;
- at the environment through the raw material and fuels CO_2 and SO_2 emissions;
- at the human health through the heavy metals emissions comprised in the raw materials and fuels;
- at the manufacture cost taking into account the raw materials and fuels cost, obtaining as a result raw materials and fuels optimum composition for the clinker manufacture.

b) the cost and energy consumption required to the clinker grinding for the Portalnd cement manufature (Tokyay, 1999). The grinding product must be limited through its fineness in order to create better conditions to the hardening process

(Duda, 1977). The equation which represents the grinding electric energy required must be express in function of the specific surface and mixture control modulus.

In order to carry out the modeling as it described above, it is necessary to know the inlet parameters data such as raw materials, fuels, raw materials cost, etc. These parameters must be managed according to the objective function previous defined, which will have as a result the cost and environment minimization among others. The structure necessary to model the problem may be summarizing as shown Fig. 3.

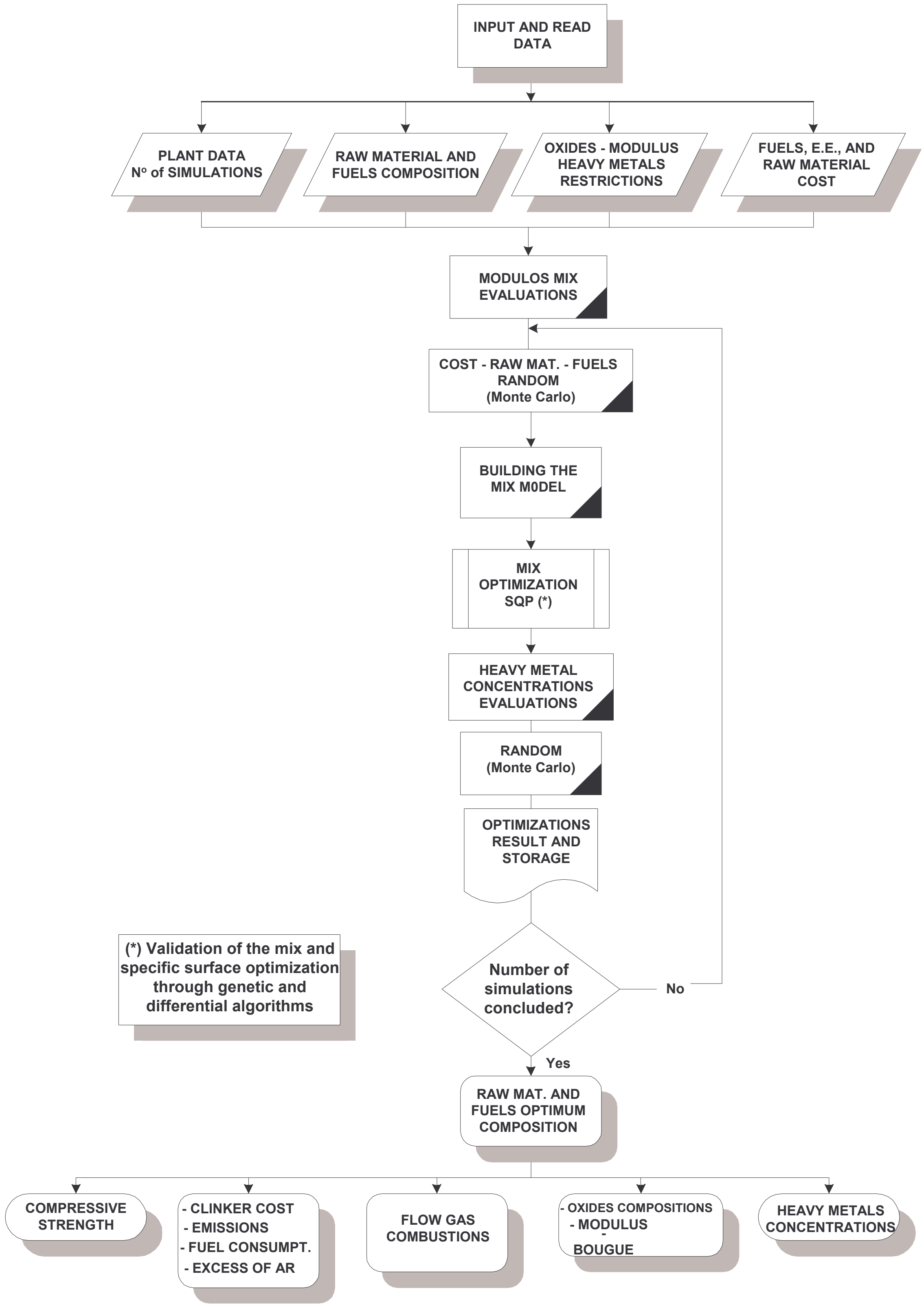

Figure 3. Flowchart when the industrial wastes co-processing is employed.

3.1 Modelling Building the Raw Materials and Fuels Mixture

The goal of this item is to obtain the raw materials and fuels (Blend) optimum composition necessary to manufacture the clinker employing the optimization algorithms.

The optimization of raw materials should consider rotary kilns operation stability, the quality of the clinker produced, the composition minimum cost, and the electricity consumption. The general optimization problem can be stated as a nonlinear programming problem for the minimization of an objective function with restrictions. The objective function is given by:

$$C = \sum_{i=1}^{n} p_i x_i + pA \exp(BS) \tag{1}$$

where the objective function models the clinker production cost C (US$/ton), taking into consideration raw material costs as well as the energy consumption requested for grinding.

The first term (summation of linear terms) represents materials cost which comprises raw materials and fuels (primary and alternative) used in the clinker production, so that p_i are the costs for raw materials i=1,2,…,n which participate into the unburnt blend with the percentages x_1, x_2,….

The second term (nonlinear) represents the unit electricity cost p (US$/kWh) times the grinding energy consumption in kWh/ton. The grinding energy consumption depends on a specified Blaine specific surface area S (cm^2/g), and also on parameters A and B, which depend on the clinker composition.

The data for the objective function of the raw mixture optimization problem Eq. (1) was taken from Tab. 1, where the chemical composition of the primary fuel is x_5 (coal), and the compositions of the secondary fuels are x_6 (petroleum coke) and x_7 (used tires). Based on an elementary chemical analysis of the raw materials, the percentile values of the several oxides present in limestone (x_1), clay (x_2), sand (x_3), and iron ore (x_4), are shown in Tab. 2.

As far as costs are concerned, the cost of mineral coal is US$35.0/ton, the cost of petroleum coke is US$40.0/ton and scrap tires are considered as revenue for the cement industry, with an income of US$50.0/ton. The other costs considered are: limestone US$0.93/ton, clay US$0.57/ton, sand US$1.54/ton and iron ore US$0.77/ton. The price of the electric power supplied by the concessionary represents a cost of US$31.0/MWh.

Table 2. Chemical composition of raw materials, in mass (%).

	Raw Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O
1	Limestone	50.66	5.04	1.19	0.67	0.78	0.1	0.1
2	Clay	1.23	61.62	16.59	9.01	-	0.3	0.3
3	Sand	1.13	93.00	2.87	1.20	0.10	0.5	0.5
4	Iron ore	0.71	7.60	1.13	82.97	-	-	-

Operational and environmental restrictions are present, as explained below. The nonlinear optimization problem of cost minimization considering the above data and the restriction equations is given by:

$$\begin{aligned} &Min\;\; f(x) = 0.93\,x_1 + 0.54\,x_2 + 1.54\,x_3 + 0.77\,x_4 + 35\,x_5 + 40\,x_6 - 50\,x_7 + \\ &\quad 0.031^*\{(5.76(MS) - 5.82)\; \exp[-0.2\,(MS) + 0.98]\} \end{aligned} \tag{2}$$

Where

$$MS = \frac{5.04\,x_1 + 61.62\,x_2 + 93\,x_3 + 7.6\,x_4 + 9.32\,x_5 + 1.93\,x_7}{1.86\,x_1 + 25.6\,x_2 + 4.07\,x_3 + 84.1\,x_4 + 12.29\,x_5 + 0.92\,x_7} \tag{3}$$

subject to following constraints, gi(x),

$$50.60x_1 + 1.23x_2 + 1.13x_3 + 0.71x_4 + 1.03x_5 + 0.93x_7 \geq 62 \tag{4}$$

$$50.60x_1 + 1.23x_2 + 1.13x_3 + 0.71x_4 + 1.03x_5 + 0.93x_7 \leq 67 \tag{5}$$

$$5.04x_1 + 61.62x_2 + 93x_3 + 7.6x_4 + 9.32x_5 + 1.93x_7 \geq 19 \tag{6}$$

$$5.04x_1 + 61.62x_2 + 93x_3 + 7.6x_4 + 9.32x_5 + 1.93x_7 \leq 25 \tag{7}$$

$$1.19x_1 + 16.59x_2 + 2.87x_3 + 1.13x_4 + 5.08x_5 + 0.79x_7 \geq 2 \tag{8}$$

$$1.19x_1 + 16.59x_2 + 2.87x_3 + 1.13x_4 + 5.08x_5 + 0.79x_7 \le 9 \tag{9}$$
$$0.67x_1 + 9.01x_2 + 1.2x_3 + 82.97x_4 + 7.21x_5 + 0.13x_7 \ge 1 \tag{10}$$
$$0.67x_1 + 9.01x_2 + 1.2x_3 + 82.97x_4 + 7.21x_5 + 0.13x_7 \le 5 \tag{11}$$
$$0.78x_1 + 0.10x_3 + 0.44x_5 + 0.12x_7 \le 6.5 \tag{12}$$
$$0.762x_1 + 2.74x_2 + 83.64x_3 - 185.83x_4 - 18.96x_5 - 0.186x_7 \ge 0 \tag{13}$$
$$-0.018x_1 + 7.5x_2 - 82.011x_3 + 219.47x_4 + 23.88x_5 + 0.554x_7 \ge 0 \tag{14}$$
$$0.319x_1 + 4.877x_2 + 1.31x_3 - 106.73x_4 - 4.29x_5 + 0.621x_7 \ge 0 \tag{15}$$
$$0.619x_1 + 7.737x_2 + 0.37x_3 + 222.88x_4 + 14.387x_5 - 0.439x_7 \ge 0 \tag{16}$$
$$38.24x_1 - 155.67x_2 - 173.6x_3 - 164.34x_4 - 37.86x_5 - 4.2x_7 \ge 0 \tag{17}$$
$$-35.48x_1 + 190.65x_2 + 212.43x_3 + 201.0x_4 + 46.51x_5 + 5.34x_7 \ge 0 \tag{18}$$
$$25392x_5 + 34436x_6 + 32100x_7 = 3600 \tag{19}$$
$$0.046x_5 + 0.07x_6 + 0.0123x_7 \le 0.05 \tag{20}$$
$$0.1X_1 + 0.3X_2 + 0.5X_3 \ge 0.20 \tag{21}$$
$$0.1X_1 + 0.3X_2 + 0.5X_3 \le 2.07 \tag{22}$$
$$0.1X_1 + 0.3X_2 + 0.5X_3 \ge 0.03 \tag{23}$$
$$0.1X_1 + 0.3X_2 + 0.5X_3 \le 0.33 \tag{24}$$
$$0.3X_1 + 5X_2 + X_3 \ge 0.31 \tag{25}$$
$$0.3X_1 + 5X_2 + X_3 \le 1.76 \tag{26}$$
$$A_1X_6 + B_1X_7 \le 0.10 \tag{27}$$
$$A_2X_6 + B_2X_7 \le 0.35 \tag{28}$$
$$A_3X_6 \le 0.05 \tag{29}$$
$$A_4X_6 + B_4X_7 \le 0.10 \tag{30}$$

Equations (4) to Eq. (12) represent the operational order restrictions, where the content of CaO SiO_2, Al_2O_3, Fe_2O_3 must be between 62 and 67% (Eq. (4) and Eq. (5)), 19 and 25% (Eq. (6) and Eq. (7)), 2 and 9% (Eq. (8) and Eq. (9)), 1 and 5% (Eq. (10) and Eq. (11)), respectively. The maximum content of magnesium is limited in 6.5% (Eq. (12)). Eq. (13) to Eq. (18) represent the numerical values of Eq. (1) to Eq. (3), for the modules restrictions of the mixture, and they refer to clinker quality. The total feeding of fuels must satisfy the specific heat consumption, presented in restriction Eq. (19). The restriction for the sulphur is presented in Eq. (20). The restrictions Eq. (21) and Eq. (22) represent the acid oxide in the raw material. The restrictions of Eq. (23) to Eq. (26) refer to the alkalis content in the raw material. The more volatile and dangerous heavy metals are controlled by the restrictions of Eq. (27) to Eq. (30) (Carpio et al 2004a).

4. Optimization Techniques

The nonlinear programming problem of Eq. (2) and Eq. (3) is solved using three different approaches: (i) sequential quadratic programming, (ii) Genetic algorithms and (iii) differential evolution. The fundamentals of sequential quadratic programming, differential evolution and genetic algorithm are presented in Carpio et al. (2003), Carpio et al. (2004b) and Carpio et al. (2005) respectively.

5. Results

Numerical results for SQP obtained using the SQP function from the optimization toolbox in the Matlab software, Matlab 6.5 (MathWorks, 2004).

The meta-heuristics (genetic algorithm and differential evolution) were implemented in the Matlab software. For each of the previously described meta-heuristic, a total of 50 experiments were done, using the parameters before mentioned and different initial random seeds. Variables were allowed to span within the range $0 \le X_i \le 2$, i=1,7.

A total of 15,000 cost function evaluations (30 individuals; 500 generations for evolutionary algorithms) was done by each meta-heuristic, every run. Other particular parameters used in the standard optimization methods are fixed empirically were:

- GA: representation of individuals by binary strings, roulette wheel selection with elitism, and crossover and mutation probabilities: 0.80 and 0.10, respectively;
- DE: DE/rand/1/bin with CR=0.8 and fm = 0.4.

When applying meta-heuristic to the optimization of problem, a key issue is how constraints related to the problem are handled by algorithm. When meta-heuristic are used for constrained optimization problems, it is usual to handle constraints using the concept of penalty functions (that penalize unfeasible solutions). In this case, the decision variables are considered inequalities, gi (x). In this work we minimize a cost function defined in Eq. 5, and thus Eq. 5 is rewritten as:

$$f(x) = \begin{cases} f(x), & \text{when } g_i(x) \leq 0 \\ f(x) + q \cdot \sum_{i=1}^{cn} g_i(x) \end{cases} \tag{32}$$

where *q* is a positive constant (arbitrarily set to 1) and cn is the number of constraints *gi(x)* that were not satisfied.

Table 4 summarizes results obtained by the EAs implemented in this work, and those available in the literature, for the optimization of the objective function C using different optimization methods.

Table 4 shows that the best results were obtained using DE. GA, but they still have to be improved. An important remark is that the DE and GA implemented in this work used the penalty-based method for constraint handling.

Table 5 presents the non linear optimization modeling solutions according to the algorithms proposed. The algorithms show similar responses for the clinker cost, optimum mix composition and for the alternative fuels consumptions.

Table 4. Results for the optimization of the objective function C, (Eq.5), using different optimization methods (10 runs with different seed of random numbers for generation of initial solution of optimization methods in range [0, 2]).

Optimization method	Best	Worst	Average	Standard deviation
SQP	4.761624	4.761624	4.761624	0.000000
GA	5.367260	13.58700	9.131185	13.68720
DE	4.713311	5.319867	4.781955	0.189859

Table 5. Solution for the optimization model

Objective Function C = US$4.712/ton	Oxides compositions in Clinker (%)	Modulus	Specific heat consumption = 3600 (kJ/kg $_{clq*}$)
Compositions (kg/kg $_{Clq*}$) X_1 = 1.2192 X_2 = 0.2263 X_3 = 0.0000 X_4 = 0.0000 X_5 = 0.0000 X_6 = 0.0784 X_7 = 0.0280	CaO = 62.07 SiO_2 = 20.13 Al_2O_3 = 5.22 Fe_2O_3 = 2.86 MgO = 0.95	MS = 2.50 MA = 1.82 MH = 2.20	Consumption of fuels (kg/ton$_{clq*}$) Coke of petroleum = 78.4 Used tires = 28.03 *Clq: Clinker

The results in the above solution correspond to a final clinker composition satisfying all restriction equations, with all parameters within their allowable range. The solution for the optimization model is a function of the specific heat consumption, and of the operational and environmental restrictions. Thus, this result also presents the maximum limits to the use of alternative fuels.

6. Conclusion and Future Works

In cement production, the dosage phase for the raw materials and for the fuels used in rotary kilns allows some room for changes in the composition of these components, looking for cost minimization without loss in cement quality, while satisfying environmental and operational restrictions. Alternative fuels, such as petroleum coke and scrap tires, present a potential to be used in rotary kilns. The optimum substitution rate of other fuels by these alternative fuels is investigated in this work.

A model is presented in this work in which the compositions of the raw materials and of the fuels enter as variables of a nonlinear programming problem. The solution to this optimization problem seeks composition values for these variables which will result in a burned clinker with a minimum lime free, thus avoiding undesired cement expansions.

The optimization procedure looks for the smallest cost in the mixture of fuels, because these fuels represent up to 30% of the production costs. Another component of the cost function is the consumption of electricity in the clinker grinding, which also represents at least 30% of the energy required to produce one ton of cement.

The SQP algorithm presented good results and fast convergence although one cannot guarantee that the results are global optimum. The SQP results were verified as global optimum only when the heuristics methods (DE and GA) were employed.

The heuristics methods are relatively simple, easy to implement and easy to use. The best result was obtained using DE optimization. In this solution, not all forecasted demands are attended, such as that of product 2 to the retailer 1 in the three periods considered. Even so, DE obtained a better solution than those published in previous work. Yet the solutions generated during GA evolution had an increase in the computational time due to the greater number of population generation.

Future work will include the hybridization of the EA's, by using a local search technique, such as branch-and-bound. This approach, combining of the efficient global search of EA's and the effectiveness of deterministic local search, possibly will give good results for real-world problems.

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