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Maintenance cost influence in a comminution layout design

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Abstract

Maintenance has a relevant weight in operational costs of a comminution process. This cost is mainly due to wear, always present in a comminution process. This study was applied to dry grinding process, habitual in the ceramic structural industry. The influence of power consumption and efficiency of comminution in process design were investigated. A genetic algorithm has been used to optimize machine selection and a discrete time simulation model has been developed to evaluate the comminution process. The underestimated impact of crusher maintenance has been proved. Solutions to maintain the efficiency of comminution process due to wear have been proposed.

Keywords: comminution equipment; wear; genetic algorithm; discrete simulation

1. Introduction

Actually, there is an increasing demand to optimize performance and profit of comminution circuits [1]. There are several industries where these processes exist: mining, pharmaceutical industry, food industry, chemical industry and recycling among others. In this paper, we'll study the structural ceramic industry dedicated to the manufacturing of bricks, tiles and refractories [2]. The first process needed is the clay's preparation and it's done mainly by comminution. The usual machines used during this preparation are: Crushers, Box Feeders, Hammer Mills and Conveyor Belts; the whole process is done in 5 stages (Fig. 1)

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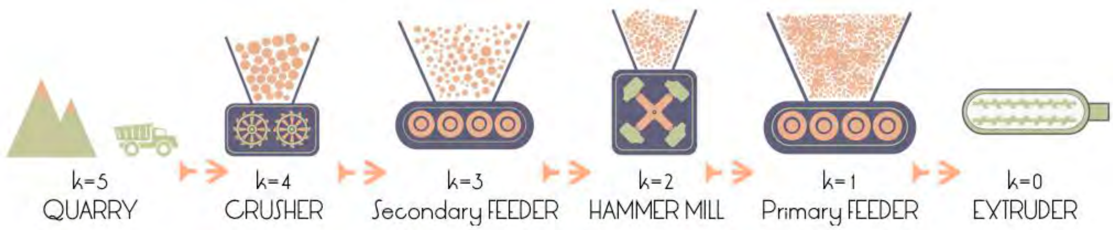

Fig. 1 Basic stages of a dry comminution process

During the grinding process, untreated clay direct from the quarry is milled, and raw material with the grain-size distribution and texture necessary for later shaping is obtained. This work is focused on the dry method (Dry Comminution Process, DCP); the humidity of the material from the quarry conditions the type of process used.

Crushers and Hammer Mills reduce the particle size by a combination of crushing, compression and impact, from one average particle size to a smaller one. In these processes, wear is always present. The majority of the operating costs of commercial crushing are caused by power consumption and the wear part maintenance [3] In a DCP, wear could cause difficulties to operate plants continuously because lengthy and unplanned shut-downs interrupt the overall process, thus it's always preferred to replace all deteriorated parts during the planned maintenance shutdowns. Machinery manufacturers provide, according to their experience and knowledge, the service life-cycle of spare parts to plan these stops. Both the hammer mills and the crusher are designed with wear in mind, providing them with high resistance and easily replaceable parts.

We will start from a previous work where the optimization of the selection of a dry comminution process has been done [4]. We want to study what is the influence of wear parts costs in both the design of the process and operational performance. Works on these issues can be found in [5] and [6]. Although the continuous supply of spare parts is a basic component of the business for suppliers of machinery, there is a lack of studies focused in the optimization of this process, and even more in the case of wear parts costs in the structural ceramic industry.

Nomenclature

Ø	granulometry, the diameter below which 80% of the material passes, mm
P	production, t/h
PS_0	required production in the extruder, t/h
HM	hammer mill
v	linear velocity, km/h
g	gap, mm
ρ	density, t/m^3
η	performance, %
L	shaft length, mm
W	comminution specific energy, kJ/kg
SL	service level, real production divided demanded production, %

2. Methodology

To design a comminution layout, it is necessary to select the machine model for each stage, machines' number, hopper size and control parameters of the process. The high combinatorial, even limiting the number of choices, turns this task into an NP-Hard problem. In order to select the optimal one from the solution set, the design experts mainly judge with his subjective experience between a huge combination of feasible solutions. Not all of them are really feasibly so the solutions tend to be over dimensioned if the designer is focused on reliability or could produce a drop in production if the focus is on the installation cost. There is a need to simulate each solution to validate its performance, but the computational time is too high to evaluate all of them.

Given that it's not possible to evaluate all the potential options, a genetic algorithm, GA, is designed. The objective is to find an optimal equipment set that minimizes the installation cost, achieve a constant production in the extruder, PS_0 [t/h]. In order to evaluate the solutions proposed by the algorithm, a discrete simulator is also developed and programmed in Matlab.

In previous work [7], the algorithm was implemented in the ceramic industry to prove the performance and to find an optimal solution to different cases that might appear during the design process. These cases are a combination of productions (50-100-200 t/h) granulometry changes (125.5/1 and 81.2/10) and service levels (100%) applied to a basic dry comminution process. Taking these requirements into account, the available commercial models are selected and Table 1 summarizes the main characteristics of the machines for the different stages.

Table 1. Feasible equipment and parameters to ceramic industry.

	No. models	No. machine models	No. hopper models	Q [m^3/h]	Capacity [m^3]	Cost [€]
Hammer Mills (k=2)	25	5	5	22 - 63	1.4 – 4.67	76100 - 15075
Crusher (k=4)	25	5	5	29 - 114	0.41 – 28.73	42460 - 122420
Feeders (k=1&3)	25	5	5	10/40 – 90/120	1.34 – 67.08	32000 - 61140

The installation cost of the best solution is presented in Table 4 column Investment, that is the total amount of equipment cost, being SL equal to 100%. That means that the production and granulometry that the extruder receives it's always the required. It's relevant the elevated price of these installations, that's why the amortization period is usually 10 years. In this type of installations, the equipment has extraordinary wear, which supposes a high cost of spare parts. For this reason, it is interesting to know what this cost is, and to determine its influence on installation design, if it is considered in the design stages.

2.1. A first approximation

As a first consideration, we have repeated the test including the maintenance costs. Nevertheless, it's not usual that DCP operator demands spare parts of the crusher even though the spare parts of the Hammer Mill (HM) are supplied continuously. Thus, the cost of acquisition of HMs spare parts has been included but not the crusher maintenance cost.

Tables 2 and 3 show both the costs and the life-cycle of the different elements; data extracted from the history of a consolidated company in the sector. Life-cycle maintenance is based in the Mean Time Between Failures (MTBM), where machines are considered without degradation. Each HM model has a different number of hammers and the size also varies. Additionally, the dimensions of the screens and the number and shape of the liners varies according to model. It happens something similar to the crusher. The table reflects the amount of the total costs. Labour cost and production losses are not taken into account because changes are planned in advance. Five models of equipment are taken from Table 1.

Table 2. Spares & parts wear in a Hammer Mill.

	HM-1	HM-2	HM-3	HM-4	HM-5	life-cycle [h]
Hammers	€ 492	€ 656	€ 975	€ 1170	€ 1365	362
Screens	€ 440	€ 700	€ 960	€ 1220	€ 1480	1180
Hammer holders	€ 713	€ 951	€ 1414	€ 1697	€ 1979	1900
Wear parts	€ 1800	€ 1900	€ 2000	€ 2100	€ 2200	6895

Table 3. Spares & parts wear in a Crusher.

	CR-1	CR-2	CR-3	CR-4	CR-5	life-cycle [h]
Knives	€ 720	€ 960	€ 1120	€ 1200	€ 1440	Unknown
Shafts	€ 3780	€ 7051	€ 8197	€ 11759	€ 14064	Unknown

The results of the algorithm, see Table 4, are the sum of the investment cost and the consumption of spare materials throughout the 10 years' payback of the machinery. Although the expense is relevant, it seems that it does not influence the type of solution provided by the algorithm, and remains constant.

Table 4. Investment plus wear parts cost during 10 years' period.

PS_0 [t/h]	$Ø_{in}/Ø_{out}$	Investment Cost [€]	% Inv Cost/ Total Cost	Maintenance Cost [€]	% Main Cost/ Total Cost	Total Cost [€]
50	125.5/1	244933	63%	146850	37%	391783
50	81.2/10	244470	62%	147800	38%	392270
100	125.5/1	375450	56%	293980	44%	669430
100	81.2/10	374455	56%	296420	44%	670875
200	125.5/1	797689	58%	588260	42%	1385949
200	81.2/10	795697	57%	596243	43%	1391940

Production rate continues to be the most significant factor. There are some options to justify this result: firstly, the wear is directly proportional to operation hours and in this comminution design it is proportional to the production. Secondly, it must be taken into account that the wear performance of the equipment has not been considered.

2.2. Wear influence in comminution performance

A hammer mill is essentially a horizontal rotating shaft that spins at high speed on which hammers are mounted. The hammers are free to swing on the ends of the cross. The material is impacted by the hammers and thrown against the walls protected by liners. The machine 's product is the material whose size is less than the holes in the screen. Production is related to machine dimensions, hammers impact velocity, holes size and its distribution in the screen, wear, material characteristic among others. However, it is beyond the scope of this paper to precisely identify the relationship between all these parameters. Hammer mill behaviour can be found in [8] and study focus in increase hammer wear resistance in [9] [10]

Hammers and hammers support wear doesn't affect directly the production but if they are not replaced in time, serious imbalances and vibrations may occur and they may even break, generating catastrophic damage inside the machine, leading to crushing process dysfunction. The screen limits the maximum material diameter, when they are worn put the granulometry became bigger, causing the low quality of the output material and a high degree of rejection of it in the quality control process. Wear parts or liners protect the integrity of the machine to increase its service life. There is a relationship between the quantity of fines generated in the mill and the mill wears [11], but we are going to assume continuous wear over time.

Furthermore, the crushers triturate the material making it break through between two shafts that spin counter wise at different speed. This shaft moves heavy plates where high resistance knives are mounted. Although it is still difficult to calculate accurately their behaviour it is possible to estimate its production in a simple and reliable way. According to Fig 2 the production can be expressed in Eq. (1).

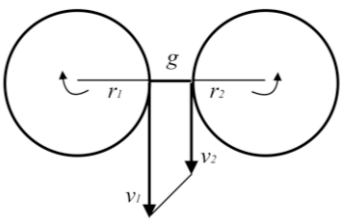

Fig. 2. Crusher velocity scheme.

$$P = g * \left[v_1 - \left(v_1 - \frac{v_1 - v_2}{2}\right)\right] * \eta * L * \rho \quad (1)$$

The rotor speed remains constant but as the plates wear out, the linear speeds decrease. However, the production increases at the expense of an increase in the particle size distribution, as can be seen in
Table 5.

Table 5. Production variations due to wear

g [mm]	v_1 [km/h]	v_2 [km/h]	P [t/h]
48	2.123	1.327	129.2
49	2.121	1.325	131.7
50	2.118	1.324	134.2
51	2.115	1.322	136.7
52	2.113	1.320	139.2
53	2.110	1.319	141.7
54	2.107	1.317	144.2

2.3. Energy consumption

Energy consumption of conveyors is proportional to production and is also related to the slope needed to reach the next stage. At the feeders, the amount of clay inside the hoppers is the more significant parameter.

In the comminution stages Kick's law, expressed as equation (2), has been used to calculate the energy consumption. Kick's theory is based on the ratio between the required energy and removal volume. This law fits quite well with the historical data collected by the company. The *c* value for the crusher is 0.331 and 1.174 for HM.

$$W = c * ln\left(\frac{\text{Ø}_{in}}{\text{Ø}_{out}}\right) \quad (2)$$

At the crusher, energy consumption decreases because it shreds less, and the size reduction in the crusher gradually decreases. Moreover, production is even better with lower energy conmsuption as we can see in
Table 5. The crusher, seemingly, works better because of power consumption decreases and production increases. That's why it's not strange that users don't pay attention to crusher wear. The granulometry slowly gets worsen, but it's very difficult to measure this value because it is not decisive in final brick quality.

However, HMs have to crush an increasing particle size so that its energy consumption increases progressively. We have evaluated how best solutions obtained by the GA behave over time. It has been assumed a decrease in the diameter of the shredders of 1mm every 1000 hours and simulated behaviour of the plant during 10000 hours.

For example, Fig. 3 displays the results for PS_0=50 t/h and a granulometry change from Ø_{in}=81.2 mm to Ø_{out}=10 mm. Similar results have been found with different values of production (50, 100 and 200 t/h) and size reduction (Ø_{in}=81.2/Ø_{out}=10mm and Ø_{in}=125.2/Ø_{out}=1mm). It is represented separately power consumed by HMs and Crushers and total power consumed by installation, including mills, crusher, conveyors and feeders.

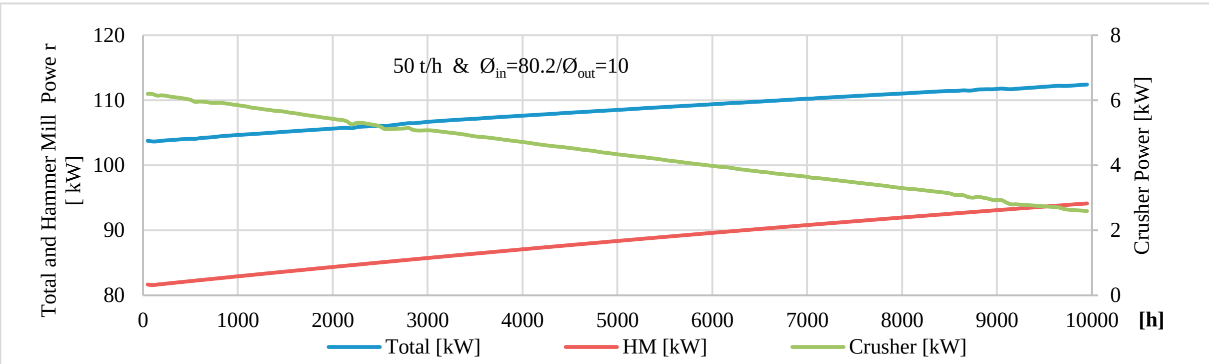

Fig. 3. Power consumption with wears in the crusher.

Problems are observed in the service level (SL) of the facilities when PS_0=100 t/h and above, as can be seen in Fig. 4. A production line that was originally perfectly balanced has small imbalances produced by the excessive production in the crusher.

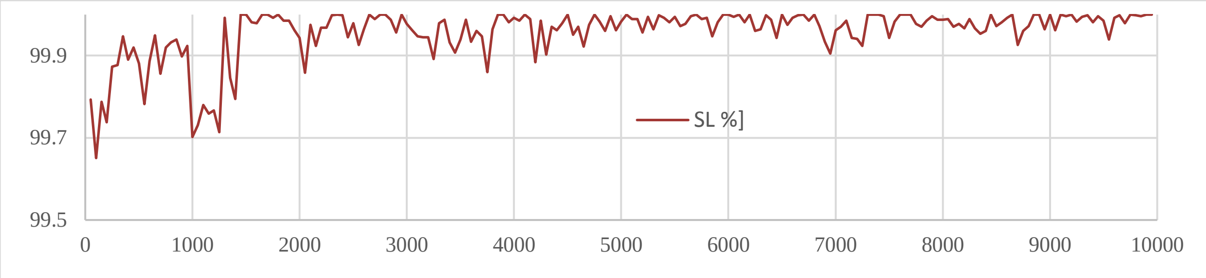

Fig. 4. Service Level for PS_0=100 t/h.

2.4. Power Limit

In the simulation model we have assumed that available power is unlimited, but checking results, it showed that this hypothesis is not correct. Thus, machines are designed with a slightly oversized engine and we have proceeded to evaluate the solutions accepting a maximum oversize of 5%. Fig. 5 displays power consumption and SL for PS_0=200t/h & $Ø_{in}$=125.5/$Ø_{out}$=1mm during 10000h working time; behaviour registered for the other 5 cases analysed is similar. Power of the mill goes up slowly until it reaches its maximum, because it doesn't have enough power, and production and SL begin to decrease, as can be seen in Fig. 5. Therefore, solutions are no longer valid for extended periods of time.

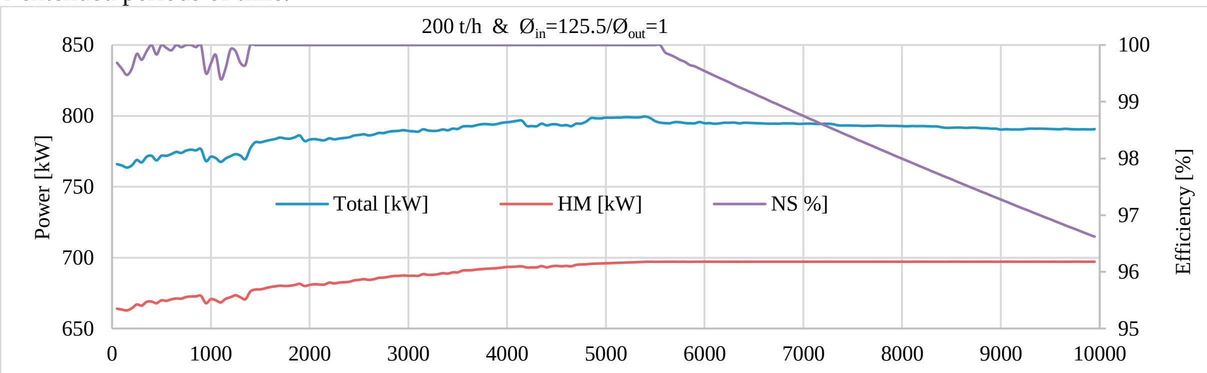

Fig. 5. Results with wear and power limit to PS_0=200 t/h & $Ø_{in}$=125.5/$Ø_{out}$=1,

Fig. 6 shows Service Level over time and how it changes when there isn't maintenance at the crusher. Note that when granulometry decrease is lower ($Ø_{in}$=81.2/$Ø_{out}$=10), HMs reach power limit sooner, so SL falls off earlier because the power required is lower so it's easier to reach the limit.

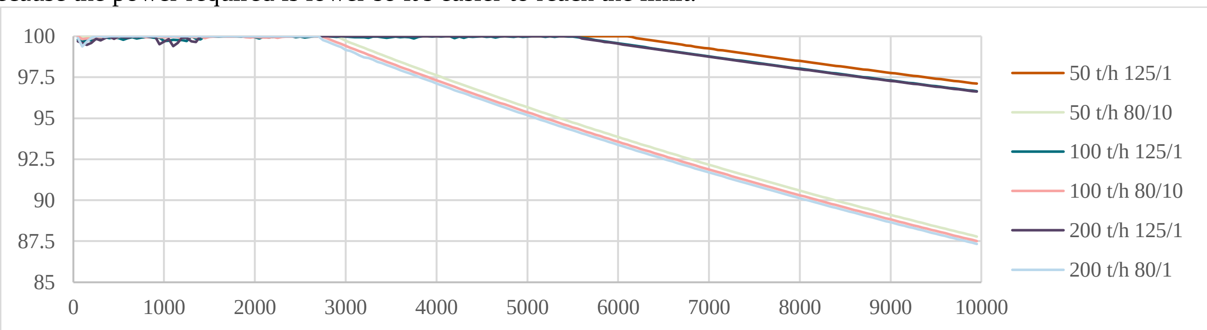

Fig. 6. Service Level [%].

3. Discussion

Based on results, it's necessary to establish preventive maintenance to replace parts in the crushers (knives and shafts). The maintenance time should be enough to ensure that we don't reach the maximum consumption power of the HMs but minimizing total costs. As can be seen in Fig. 6, the maintenance intervals depend exclusively on granulometry decrease and it doesn't depend on required production. Thus, crusher life-cycle is 2800h when $Ø_{in}$=81.2/$Ø_{out}$=10; if $Ø_{in}$=125.5/$Ø_{out}$=1, lifespan is 5500h.

These results have revealed that crusher maintenance is required but, as has been explained, installation operators don't request these spare parts. This lack of knowledge about long term installation operation is one of the reasons that lead to designers to oversize both number and size of equipment in each stage of the process and increase installation costs.

The problem is that even maintenance is carried out in crushers, SL of the solutions is not always 100%, as can be seen in Fig. 6 in life span zone (until 2800h and 5500h), although in any case is lower than 99.5%. In Table 6, equipment and maintenance costs of initial solutions are displayed, and also % of maintenance cost related to equipment investment.

Table 6. Total cost of initial solutions.

PS_0 [t/h]	Øin/Øout	Invest. Cost [€]	% Inv_Cost /Total_Cost	HM-Mnt. Cost [€]	% HM_Cost /Total_Cost	CR-Mnt. Cost [€]	% CR_Cost /Total_Cost	Mnt. Cost [€]	% Mnt_Cost /Inv,_Cost	Total Cost [€]
50	125.1/1	244933	57%	146850	34%	36774	9%	183624	75%	428557
50	80.2/10	244470	54%	147800	33%	61519	14%	209319	86%	453789
100	125.1/1	375450	51%	293980	40%	64188	9%	358168	95%	733618
100	80.2/10	374455	48%	296420	38%	108390	14%	404810	108%	779265
200	125.1/1	797689	53%	588260	39%	129150	9%	717410	90%	1515099
200	80.2/10	795697	49%	596243	37%	218080	14%	814323	102%	1610020

We should ask if it is possible to apply the simulation-based optimization approach designed to minimize the cost of equipment and maintenance cost along the 10 years of the amortization period. The problem is that to evaluate each solution is necessary to simulate installation behaviour during more than 10000 hours (2 times the life span of crushers). The computation time takes 1.8h for each solution on average. GA needs to evaluate around 1200 different solutions and the estimated computation time is about 88 days for each problem.

To avoid this problem, we have applied a local search algorithm looking for a solution with 100% SL and low cost. Starting solution is the initial solution, and neighbourhood movements consist of small changes in equipment capacity [m^3]. Table 7 shows the new solutions cost.

If we compare results shown in Tables 6 and 7, installation and spare parts costs have similar values, as its contribution to final costs. The cost increase of new solutions does not exceed 25000€, with a difference in SL of less than 0.5%. Thus, having into account that the amortization periods are long, it is justified to ensure 100% SL from the beginning.

Table 7. Total cost of new solutions.

PS_0 [t/h]	$Ø_{in}$/$Ø_{out}$	Invest. Cost [€]	% Inv_Cost /Total_Cost	HM-Mnt. Cost [€]	% HM_Cost /Total_Cost	CR-Mnt. Cost [€]	% CR_Cost /Total_Cost	Mnt. Cost [€]	% Mnt_Cost /Inv, Cost	Total Cost [€]
50	125.1/1	244933	57%	146850	34%	36774	9%	183624	75%	428557
50	80.2/10	244470	54%	147800	33%	61519	14%	209319	86%	453789
100	125.1/1	390710	52%	294750	39%	72739	10%	367489	94%	758199
100	80.2/10	375850	48%	298430	38%	108870	14%	407300	108%	783150
200	125.1/1	835680	52%	597200	37%	174340	11%	771540	92%	1607220
200	80.2/10	821834	51%	596430	37%	205380	13%	801810	98%	1623644

On the other hand, we would highlight that the spare parts cost contribution to the overall cost is significant, and the value is very similar to equipment cost. HMs maintenance cost is higher than crusher maintenance, but this last cost is not negligible because it constitutes about 10% of the total. An important question to be considered in future is related to HMs lifespan because available values of HMs Life-cycle maintenance have been performed in installations where knives and shafts of crusher are not replaced, and HMs may also have increased wear. For this reason, it's necessary to check if HMs wear reduces when a preventive maintenance plan for crushers is defined.

4. Conclusions

It has been known that wear has a significant economic cost. But unlike most usual cases, the wear on crusher has unexpected consequences on the general behaviour of the plant. However, maintenance is usually centred on hammer mill, not having into account wear on crusher, and we have seen the reason that can explain this behaviour. As a general recommendation, crusher preventive maintenances should be established to avoid service level drop. It would also be good to optimize scheduled maintenance.

For future work, it would be desirable to model hammer mill in more detail by establishing a reliable relationship between granulometry and production and between granulometry and wear.

If we also include in the equation the energy consumption, the optimization of the design of a grinding plant should lead us to find a balance point between the chosen machinery, the maintenance periods and the spare parts cost over the whole life of the plant.

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