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Improved Energy Efficiency in Grinding and Classification in a Magnetite Concentration Plant

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ABSTRACT

Ore grinding is one of the stages of mineral processing that is intensive in the use of energy. It utilizes heavy equipment of relatively large dimensions to accomplish the task of breaking ore particles either by impact or attrition using steel balls as grinding media. Therefore, grinding corresponds to one of the main areas of attention that is looked at when it comes to improving energy efficiency.

This research study is focused on reducing the specific energy consumption by 10% or more in a magnetite concentration plant. Two different alternatives were identified and studied: (i) modifying the operation strategy of classification, and (ii) changing the circuit configuration by incorporating a new screen.

The two alternatives were evaluated using the JKSimMet simulation software to quantify specific energy consumption. Out of a total of six scenarios studied only these two proved to be favorable from a technical/economic standpoint and in compliance with the existing operational restrictions. These two alternatives are (1) an increase in apex/vortex ratio of the hydrocyclones and (2) a pre-classification of the ball mill feed to avoid overproduction of fine material. On one hand, it was possible to improve the energy efficiency by 1.6 to 3.4% when increasing the apex/vortex ratio of the hydrocyclones, equivalent to annual savings of 262 to 548 kUSD/year. On the other hand, the configurational change allowed for increasing energy efficiency by 1.9 to 3.4%, equivalent to annual savings of 78 to 135 kUSD/year, with an associated return on investment within four years.

INTRODUCTION

One of the most common ways to transport and market iron concentrates is in the form of pellets, which are agglomerated of fine particles in the form of either spheres or nodules. The production process of iron pellets from magnetite ore begins with grinding and classification of the iron ore, where the particle size of the iron ore is reduced until the desired mineral liberation is achieved. The next stage of magnetic separation aims at producing a high-grade iron concentrate, which commonly ranges between 65 and 67% Fe. This concentrate is then filtered and subsequently submitted to a process called balling, where the mineral is agglomerated, and the pellets are formed. Finally, these pellets are sent to a thermal hardening stage, where the mechanical properties are improved to obtain a final product of high mechanical resistance and hardness, which meets the quality required to be commercialized.

Within all the stages involved in the production process of iron pellets, grinding is the one that consumes the largest amount of energy, being responsible for almost 50% of the total energy consumption in the plant. This is the reason why this paper focusses only on grinding and classification.

The objective of this study is to identify and to quantify alternatives that allow for increased energy efficiency of the grinding circuit in a pellet plant, by reducing the specific energy consumption using the metallurgical simulation software JKSimMet as the main tool.

METHODOLOGY

For this study, a plant with a processing rate of 2.1 Mt/y of iron was considered, for the production of BF pellets with an iron grade of 65%. The ore is treated in the comminution stage in several parallel grinding lines, each one composed of a ball mill and hydrocyclone. For simulation purposes only one milling line was considered. The simulation results obtained could the later be extrapolated to the other identical lines.

An operational analysis of the comminution circuit was carried out first, in order to identify opportunities for improvement, which together with a critical review of the literature, allowed for suggesting various alternatives for improved energy efficiency. These alternatives were separated into two categories: (i) plant operation and (ii) plant configuration. Changes in the plant operation refer to the modification of existing operational strategies. Changes in configuration in this case correspond to those changes that require additional equipment and hence capital investment.

The alternatives were evaluated using the JKSimMet simulation software. The objective of the simulations was to quantify the impact of each alternative on the energy efficiency of the grinding and classification circuit, with respect to the base case configuration and operation. This was done by comparing the specific energy consumption expressed in kWh/t for each alternative with the initial base case scenario detailed in Figure 1.

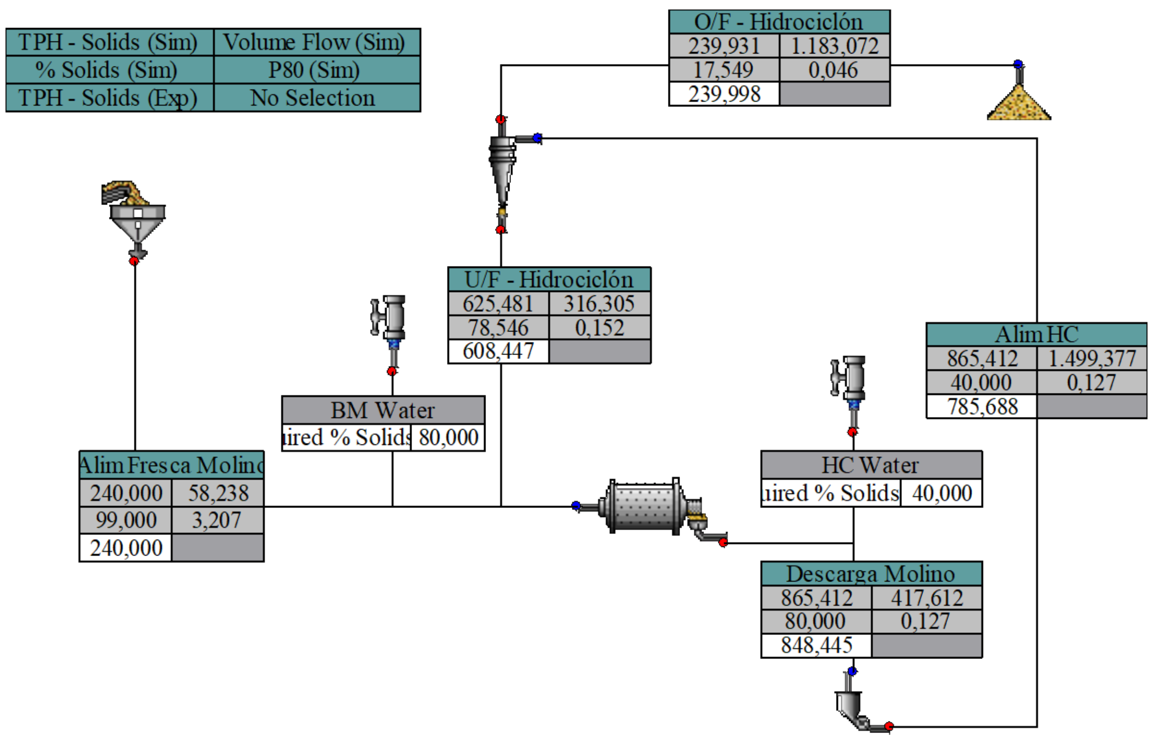

Figure 1 Flowsheet of the base case scenario

This base case scenario considers a fresh feed with a rate of 240 tph, which corresponds to the average throughput of one single grinding line on yearly basis. The ball mill slurry discharge with 40% solids enters the hydrocyclones clusters that produces an overflow with a P80 of 46 μm and a circulating load of 260% that returns to the ball mill. Table 1 below shows the design parameters and the simulation models used for the main equipment.

Table 1 Base case design parameters and simulation models

Ball mill		**Hydrocyclones**	
Simulation model	Perfect mixing	Simulation model	Nageswararao
%Solids ball mill	80%wt	Units in parallel	5
%Critical speed fraction	70.5%	Operating pressure	186 [kPa]
Internal diameter	4.83 [m]	%Solids in feed	40%wt
Internal length	11.4 [m]	Cylindrical diameter	0.66 [m]
Mill filling	31%	Inlet diameter	0.25 [m]
Ball size	39 [mm]	Vortex diameter	0.248 [m]
Work Index	11.7 [kWh/t]	Apex diameter	0.140 [m]
F80	3207 [mm]	Cylindrical length	0.580 [m]

The studied alternatives are the following:

Operational change	Configurational change
1. Maximize the dilution of the hydrocyclone overflow. 2. Maximize the solids content in the discharge of the hydrocyclone.	1. Installation of a screen prior ball milling to classify the fresh feed, sending the undersize to the discharge pump sump. 2. Installation of a screen in the underflow of the hydrocyclone to reclassify the coarse particle that is recirculated to the ball mill. 3. Installation of a screen in the overflow of the hydrocyclone to reclassify the fines.

Once the base case scenario and its alternatives were well defined, the simulations were carried out. To quantify the impact on energy efficiency of each case and to make them comparable with each other, each scenario had to satisfy the following operational restrictions:

1. Carry out the same grinding task as the base case. That is, to start with an F80 of 3207 microns to obtain a P80 at the overflow of the hydrocyclone of 46 microns.
2. Keep the total water consumption of the circuit constant. That is, to keep the solids percent in the overflow constant at 18% which is equivalent to maintaining a constant water flow rate for a narrow range of feed tonnages. This restriction does not apply to the hydrocyclone overflow.
3. Do not exceed 84% solids in the underflow of the hydrocyclone, in order to avoid the undesirable condition of roping.
4. The power consumed by the ball mill should not be greater than 4026 kW, which corresponds to 90% of the power installed.

The evaluation criteria used to characterize these alternatives is based on *quantifying the increase that each alternative allows for, expressed as ton/hour, in the treatment capacity of the grinding circuit compared to the base case scenario*. Such increase in treatment capacity is directly associated with a reduction in specific energy consumption SE, calculated as the ratio between the power demanded by the ball mill, in units of kW, and the throughput, tph. Those alternatives that generate an increase in the treatment capacity were, consequently, the ones that allowed to reduce the SE and to improve the energy efficiency of the circuit.

The alternatives that proved to generate a positive impact on the energy efficiency of the circuit and that comply with current operational restrictions were subjected to a preliminary economic evaluation to quantify the energy costs savings obtained by the reduction of SE kWh/t. This economic benefit only reflects the impact of energy savings and does not consider additional benefits related to an increase in throughput.

DISCUSSION OF RESULTS

Out of all suggested alternatives, only two complied with the operational restrictions and presented a positive impact on the energy efficiency of the circuit, corresponding to: 1) the operational change of using a higher apex/vortex ratio, and 2) the configurational change comprising the implementation of a screen in the power supply to the ball mill. The results obtained in the simulations with JKSimMet for each one of the alternatives mentioned above are presented below.

Operational change

To evaluate this alternative, a total of six scenarios were simulated, varying the apex/vortex ratio to both higher and lower values with respect to the base case, corresponding to 0.56. Table 2 and Figure 2 below show the results obtained in the simulations.

Table 2 Impact of different Apex/Vortex ratios on other operational parameters

Variables	Base case	Case 1	Case 2	Case 3	Case 4	Case 5
Apex/vortex ratio	**0.56**	0.45	0.50	0.55	0.60	0.65
Throughput [tph]	**240**	225	232	237	244	248.5
Circulating load [%]	**261%**	198%	225%	250%	283%	313%
%-400# mill discharge	**29%**	32.8%	31%	29.8%	28.2%	27.2%
%-400# hydrocyclone U/F	**32%**	26.1%	28.5%	30.9%	33.5%	35.9%
Water flow to pump sump [m^3/h]	**1499**	1308	1394	1464	1565	1646
SE [kWh/t]	**16.0**	17.1	16.5	16.2	15.7	15.4

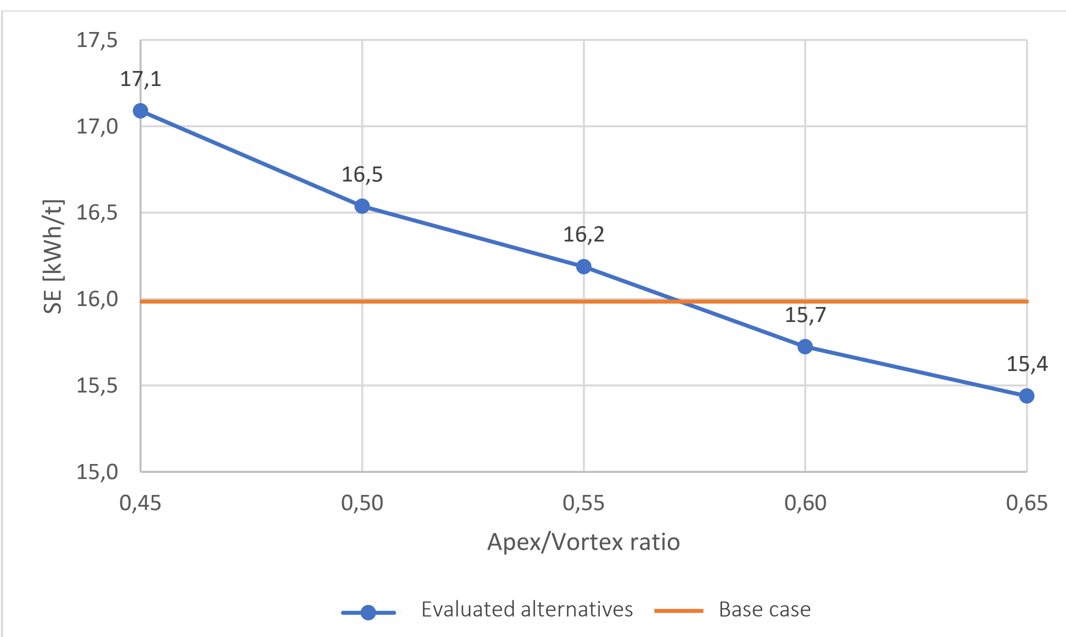

Figure 2 Effect of the variation in the apex/vortex ratio on the SE kWh/t

The results presented above show that a reduction in the opening of the apex from 161 mm (case 5) to 112 mm (case 1), produces a considerable reduction in the fines recirculation from 35.9% to 26.1% to the ball mill. However, this positive effect of a reduced apex/vortex ratio is outweighed by the negative effect of reducing the circulating load, leading to an increase in the content of fines inside the ball mill from 27.2 to 32.8%. From this point of view, the best alternatives would be those with higher apex/vortex ratios, in fact in the Figure 2 it is possible to observe that increasing the apex/vortex ratio favours the energy efficiency of the ball mill. The specific energy consumption is reduced from 17.1 to 15.4 kWh/t when increasing the ratio from 0.45 to 0.65. The apex/vortex ratios of 0.6 and 0.65, were the cases that showed most favourable results compared to the base case scenario, presenting an increase in energy efficiency of 1.6% for the ratio of 0.6 and 3.4% for the ratio of 0.65. The latter translates into operating costs savings of 65 to 137 thousand USD per year.

Configurational change

Often, fresh feed contains a significant percentage of fine particles that already meets the desired grind size. In this case, it would be advisable to submit the material to a classification stage prior entering the ball mill to avoid overproduction of fine particles. Therefore, the implementation of a screen prior to the ball mill was proposed, to minimize the content of fines (Figure 3). It is important to mention that a certain presence of fines is desirable in the mill feed, however overproduction of fines should always be avoided.

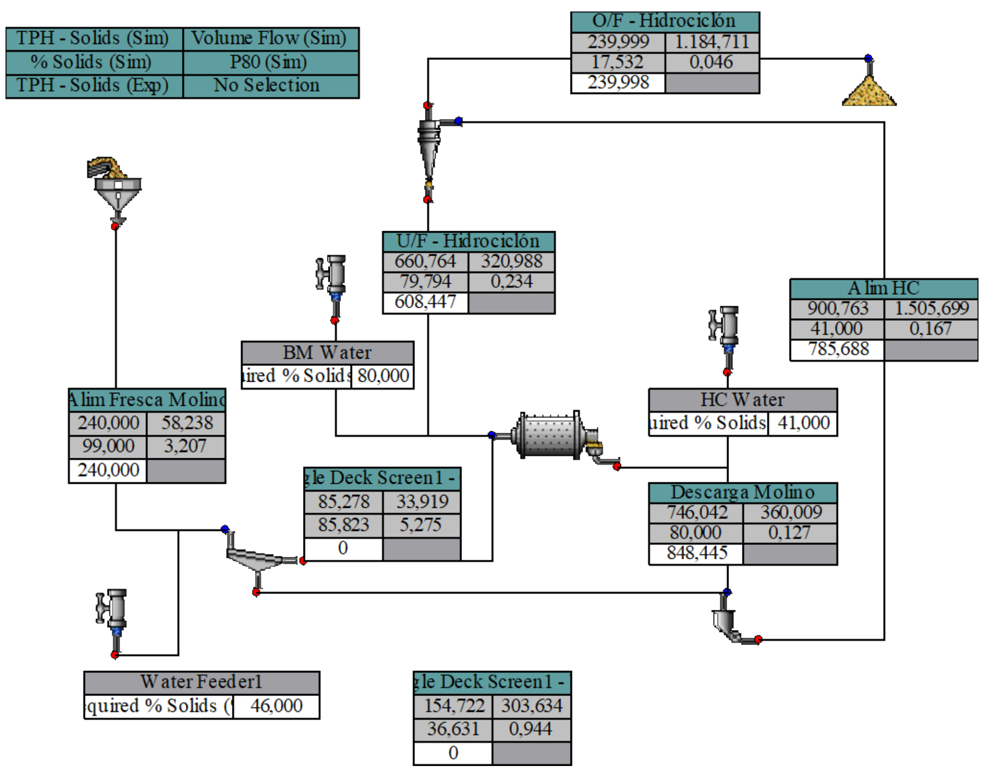

Figure 3 Configurational change case scenario

To evaluate the impact of this alternative on the energy efficiency of the circuit, a total of 7 cases were simulated varying the screen size for the ball mill feed, using the screen model "Single Component Efficiency Curve". The screen sizes selected for the simulations ranged from 0.053 to 12.5 mm. The finest screen size was selected based on the existing high-frequency screens (Muketekelwa, 2017). The coarsest size corresponds to the maximum particle size contained in the fresh feed. The objective of this last analysis was to compare direct circuit configuration as is currently used (base case), with a reverse circuit configuration that uses a screen size equivalent to the maximum particle size in the feed. Table 3 indicates the results obtained from the simulations carried out in JKSimMet.

Table 3 Configuration change evaluation results

Variables	Base case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Mesh size [mm]	**-**	0.053	0.074	0.105	0.212	0.5	2	12.5
Throughput [tph]	**240**	251	251	248	247	245	240	233
P80 [μm]	**46**	46	46	46	46	46	46	46
Circulating load [%]	**261%**	263%	262%	261%	263%	267%	275%	288%
%-400# Ball mill feed	**13%**	9.8%	9.9%	10.0%	10.1%	10.2%	10.5%	10.7%
%-400# Ball mill discharge	**29.2%**	26.3%	26.6%	27.0%	27.4%	27.9%	29.0%	30.7%
SE [kWh/t]	**16.0**	15.3	15.3	15.4	15.5	15.7	16.0	16.5

It can be observed that implementing a screen in the feed to the ball mill reduces the content of fines from 29 to 26%. However, when observing case 7, where the opening of the screen size is 12.5 mm, equivalent to the maximum particle size in the feed, the content of fines inside the mill is greater than that of the base case scenario. This is because the fresh plant feed reports almost entirely to the screen undersize, which goes straight to ball mill discharge sump, hence simulating a reverse circuit. This causes a reduction in the flow rate of material through the mill, contaminated it with a higher content of fines, equivalent to 30.7%. Additionally, an increase in the treatment capacity of the ball mill is observed for all intermediate cases (those with screen sizes between direct and reverse circuits). This increase in grinding capacity depends on the screen size, where it is evident that those cases where the screen size was finer, achieve a higher throughput than the cases with coarser screen sizes.

Figure 4 indicates visually the effect of the screen size on the SE, kWh/t, where it is confirmed that smaller screen sizes favor the energy efficiency of the circuit, since they significantly reduce the SE. When comparing the latter with the base case scenario (orange line in Figure 4), it is observed that this type of configuration presents a benefit in the energy efficiency of the circuit only for screen sizes smaller than 2 mm; above this size it is not recommended to implement this configuration.

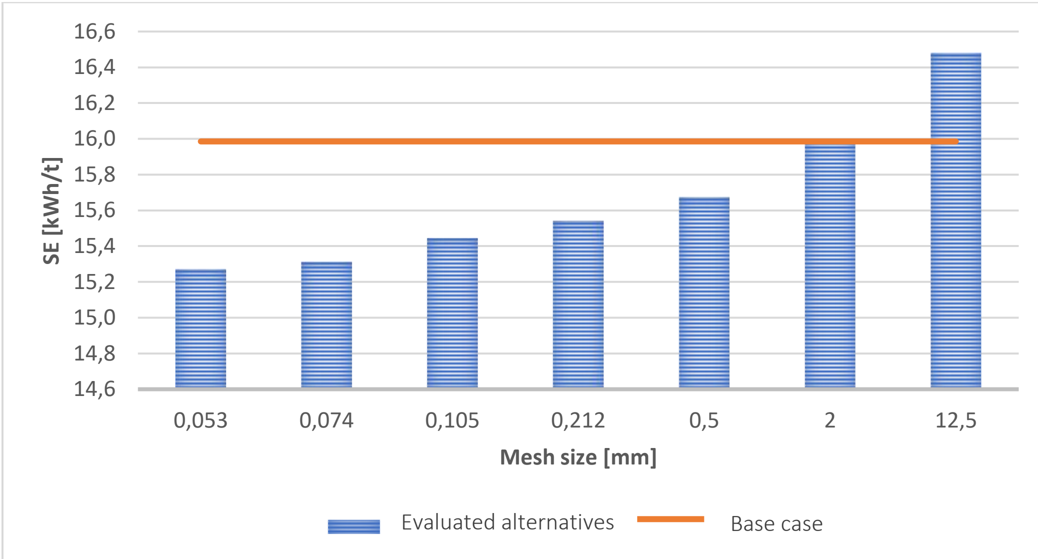

Figure 4 Effect of variations in the opening of the screen mesh, mm, on the SE, kWh/t.

Out of the five case studies that presented favorable results in terms of energy efficiency, only the cases with screen of 0.105, 0.212 and 0.5 mm, proved to be technically feasible. Very fine screens require too much surface area that does not fit within the existing plant lay-out. Therefore, an economic evaluation was carried out only for the three cases that proved to be feasible (Table 4).

Table 4 Results of economic evaluation of the configurational change

Screen size [mm]	0,105	0,212	0,5
Annual energy consumption savings [MWh]	1137	933	652
Annual energy cost savings [USD]	$135,472	$111,168	$77,749
Screen CAPEX [USD]	-$831,363	-$554,242	-$277,121
Net loss first year [USD]	**-$695,891**	**-$443,074**	**-$199,372**
Estimated gain/loss by year 4 [USD]	**-$154,003**	**-$109,570**	**$111,624**

Although implementing this type of configuration allows for an obvious reduction in operational costs associated to a decrease in energy consumption, when considering the investment costs associated with the implementation of new equipment, it can be seen that implementation of this alternatives gives a positive payback around 4 or 5 years' time, which is an excessive payback considering an increase of only +5 tph, so the investment associated with this configurational change is not justified.

It should be noted that the previous one corresponds to a preliminary economic evaluation, which only considers a balance between the economic benefit generated by the reduction in energy consumption and the investment costs for the acquisition of new equipment (screens); therefore, maintenance costs regarding the screening and classification operation were not considered.

CONCLUSIONS & RECOMMENDATIONS

In the search for increasing the energy efficiency of the grinding and classification circuits of grinding and classification circuit of an iron ore pellet plant, the following was concluded:

- The operational change involving the modification of the apex / vortex ratios, showed that larger openings of the apex with respect to the vortex generate an increase in the treatment capacity [tph], and a reduction in the SE [kWh/t] of the grinding circuit. As a result of this, it is recommended to increase the apex/vortex ratio from the current 0.56 to a ratio of 0.6 or 0.65, obtaining an increase of 1.6 and 3.4% in efficiency energy of the circuit, respectively. This operational change, that does not require additional investment costs, generates annual energy savings of 2204 to 4598 MWh. This would produce a net economic benefit of 263 to 548 thousand USD per year, approximately.

- The configurational change, that focusses on minimizing the content of fines inside the ball mill by implementing a screen in the feed to the ball mill, and where the screen underflow will report directly to the ball mill product sump, achieved an increase in energy efficiency between 1.9 and 4.5%. These results were obtained for screen sizes ranging from 0.053 to 0.5 mm. The finer screens presented a more significant increase in energy efficiency than the coarser screens; however, the cases evaluated at screen sizes of 0.053 and 0.074 mm were not feasible, because of the large surface area that they would require. Coarser screens (0.105, 0.212 and 0.5 mm) are technically feasible and generate annual savings of 311 to 542 thousand USD, obtaining a return on investment costs within 4-5 years, considered too long to justify the implementation of the configuration change.

As a general recommendation, the operational and configurational alternatives proposed in this study should be further evaluated using different tools. These can be other metallurgical modeling software or by performing experiments at laboratory and pilot-scale, to assure more precise technical and economic information of the benefits that will be generated.

Additionally, it is recommended to carry out a more in-depth economic evaluation of the proposed changes, both operational and configurational, considering the additional maintenance costs associated with the new equipment and the profits generated by higher tonnage processed.

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