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Economics of flotation plant against different size reduction alternatives and flotation grades

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Abstract: This paper quantitatively shows the effect of run-of-mine (ROM) feed grade on flotation plant capacity, and also the combined effects of different feed grades and the size reduction alternative combinations on the project economics. Project economics are defined as CAPEX and OPEX The project profitability was estimated based on a "Cash Flow Model" along the life of the mine, which is ten years. The parameter for tracking project return or profitability is called NPV and IRR (internal rate of return), respectively. These parameters are standard parameters for control of project return in all engineering studies. In the scope of the study, there are a series of case studies including three different comminution alternatives in combination with three different ROM feed grade alternatives. Therefore, the nine case studies were compared based on economics which resulted from different equipment combinations and as well as the different types/amounts of process consumables. Among all the cases, Case 1 (Conventional circuit with 0.1% feed grade) gave the lowest CAPEX whereas Case 9 (High Pressure Grinding Rolls_HPGR circuit with 0.3% feed grade) gave the highest CAPEX. OPEX wise, Case 7 (HPGR circuit with 0.1% feed grade) produced the lowest whereas Case 6 (Semi-Autogenous Ball mill Crusher_SABC circuit with 0.3% feed grade) gave the highest value of OPEX. The NPV of the HPGR circuit with 0.3% feed grade case was found as maximum, which showed the quantitative effect of feed grade and equipment combination on flotation plant economics.

Keywords: comminution, flotation, trade-off, experimental indices, CAPEX/OPEX/NPV

1. Introduction

There are different paths for the comminution of certain sizes ore down to a target size. In this study, three different circuit alternatives and three different ROM feed grades are evaluated against the same design criteria. Another saying the economics required for doing different alternatives are evaluated. Different alternatives result in variate cost options. Other than qualitative decisions, the decision maker (design engineer) should decide based on economics. The equipment list of the comminution alternatives is given in Table 1.

The circuit configurations are shown below in Fig. 1. MPES' software COM_TRD_Sim (Tuzcu, 2019 and Tuzcu, 2020) was used to compare different comminution alternatives.

During the study schedule data, several experimental indices are processed to compare the economics for exactly doing the same job (for example crushing/grinding from 600 mm down to 200 µm for all alternatives).

The flotation circuit consists of rougher, scavenger, and three-stage cleaning circuits. The flowsheet is shown in Fig. 2. The evaluation of the different size reduction alternatives and different feed grades for each alternative was performed. For this purpose, three different size reduction alternatives and 3 different head grades were determined. The total nine cases are given in Table 2. The hourly capacity requirement was determined first. The equipment was sized using design and operating parameters. An Excel Macro was coded and run for mass balancing of the flotation circuit to estimate the mass and material flows in each stream shown in Fig. 2. Flotation cell numbers and sizes were determined using

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the flow rates, retention times, and scale-up factors. After sizing the equipment, the amount of consumables was estimated.

Table 1. Size reduction alternatives

Alternative 1	**Conventional**
Equipment 1	Jaw/Gyratory Crusher
Equipment 2	Secondary Crusher
Equipment 3	Tertiary Crusher
Equipment 4	Rod Mill
Equipment 5	Ball Mill
Alternative 2	**SABC**
Equipment 1	Jaw/Gyratory Crusher
Equipment 2	SAG Mill
Equipment 3	Pebble Crusher
Equipment 4	Ball Mill
Alternative 3	**HPGR**
Equipment 1	Jaw/Gyratory Crusher
Equipment 2	Secondary Crusher
Equipment 3	HPGR
Equipment 4	Ball Mill

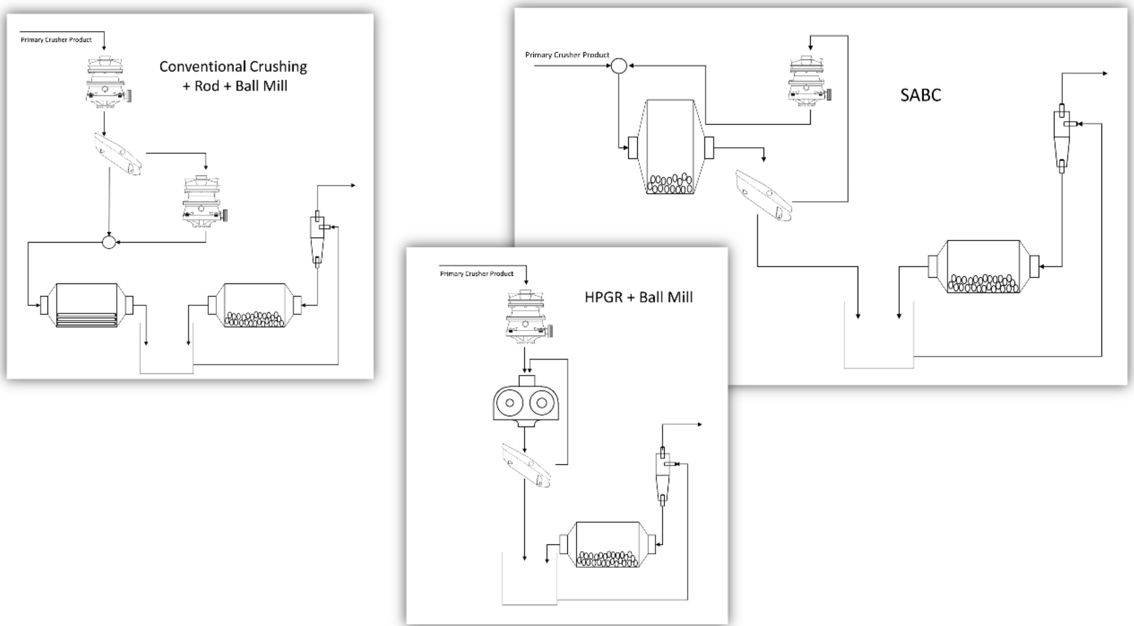

Fig. 1. Circuit configurations of size reduction alternatives

Flotation circuit design is dependent on many factors. These factors can be metal price, feed grade, and ore kinetic and rate parameters. (Krawskawski, 1989). The change in the flowrate, grade, or particle size distribution affects the performance of the industrial flotation plant (Wills, 2013). These parameters directly affect the size and number of cells in the flotation circuit. Determination of the capacity is a vital part of an optimum flotation design as this directly affect the project's economic indicators. Other than qualitative decisions, the decision maker (design engineer) should decide based on economics (CAPEX and OPEX). The first attempt to optimize flotation circuit configuration and operation conditions were made by Mehrotra and Kapur (1974). Several researchers (Schena et al., 1996; Abu-Ali and Abdel Sabour, 2003; Cisternas et al., 2004) worked to optimize flotation circuit design in terms of not only technical but also economics. In addition to these, Jamett et al. (2015) pointed out that the changes in ore grade and metal prices affect the design of the circuit and so on the project financials.

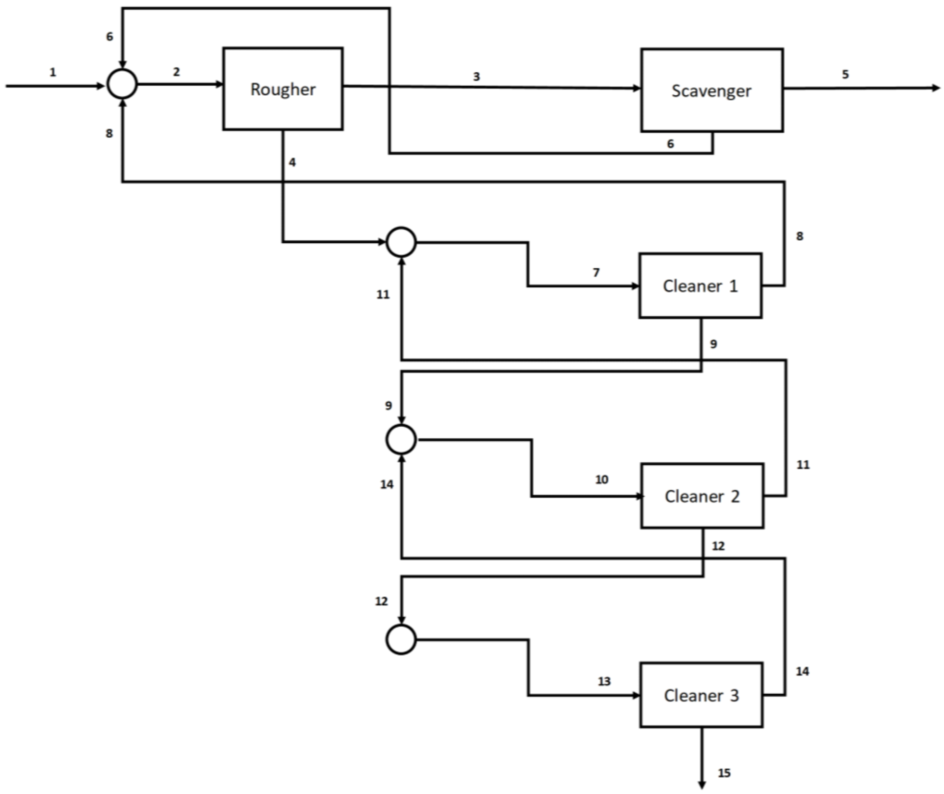

Fig. 2. Flotation circuit flowsheet

Table 2. Cases in the scope of the study

Cases	Explanation
Case 1	Conventional Circuit with 0.1% Feed Grade
Case 2	Conventional Circuit with 0.2% Feed Grade
Case 3	Conventional Circuit with 0.3% Feed Grade
Case 4	SABC Circuit with 0.1% Feed Grade
Case 5	SABC Circuit with 0.2% Feed Grade
Case 6	SABC Circuit with 0.3% Feed Grade
Case 7	HPGR Circuit with 0.1% Feed Grade
Case 8	HPGR Circuit with 0.2% Feed Grade
Case 9	HPGR Circuit with 0.3% Feed Grade

There are different paths for the comminution of certain size ore down to target sizes, such as primary crushing-SAG milling-pebble crushing-ball milling or 3-stage conventional crushing-rod milling-ball milling. Different comminution alternatives result in variate cost options. Morrel (2009) conducted a study on three different communition circuit alternatives to obtain the same final product. According to his result, the overall specific energy requirement of the communition circuit is highest in the SABC alternative compared with HPGR+ball milling and conventional crushing+ ball milling circuit. The use of energy and consumables is an excessive amount in the communition circuit, especially in the low-grade ore (Abouzeid and Fuerstenau, 2009). The overall project economics is strongly dependent on the grinding circuit alternatives in flotation plant design. Méndez et al. (2009)

study shows that the economic performance of the project is affected by grinding circuits. Morell (2008) also showed the energy requirement for different size reduction paths in the SMC testing procedure. The test standard outputs are M_{ic}, M_{ia}, and M_{ih} which represent the specific energy requirement of the ore for crushers, tumbling mills, and HPGR, respectively (Morrell, 2004; 2009). While M_{ia} defines the coarse grinding in tumbling mills, M_{ib} defines the fine part of it, and it is determined by the conventional Bond ball mill work index test (Morrell, 2008). There is also a novel software tool named COM_TRD_SIM developed by the author of this paper (Tuzcu, 2019; 2020) to find out OPEX, CAPEX, and the equipment size of the size reduction path.

This paper aimed to analyze the effect of different size reduction alternatives together with different feed grades on the project economics.

2. Materials and methods

2.1. Design criteria generation

Each design work requires a certain set of parameters that define the working principles of the equipment and as well as the whole system. This is called design criteria or the base on which the design rises. The design criteria define the number of effective working hours per year for each part (crushing, grinding, flotation, dewatering) of the plant, the hardness of the ore, flotation half times, and so on.

The design criteria used in three different size reduction alternatives and three different feed grades examined within the scope of the study are given in Table 3. As mentioned above the criteria below include the information about the individual equipment and the whole system. The amount of work to be done and availabilities was determined, and the experimental indices were gathered from the laboratory experiments and literature. Such as SMC (Morrell, 2009) indices, flotation retention time, reagent consumptions, etc.

2.2. Modeling different size reduction alternatives

In this regard, three different circuit alternatives are evaluated against the same design criteria. Another said the capital cost and consumables required for doing the same job with different alternatives are evaluated. The alternatives are explained below:

After sizing the equipment, the amounts of consumption per annum were calculated. An index determined the specific energy and power value which determines the amount of consumables (liner/lifter, ball/rod, energy, etc.).

2.2.1. Alternative 1: Conventional 3 stage crushing + rod +ball milling

The first alternative is mostly used configuration for comminution alternatives before the invention of SAG Mill and HPGR. Because the use of rod mills has declined with the implementation of these equipments in grinding circuits. In this alternative, the ore is crushed by 3-stage crushing to downsize to a suitable range for rod mill feed. Rod mill product is sent to the ball mill working closed circuit with hydrocyclones.

2.2.2. Alternative 2: Primary crushed SABC

Because of the demand for high capacity and decreasing feed grade, the combination of SAG mill and ball mill has become preferred. Since the oversize material recycling decreased the SAG mill capacity, the pebble crushing is included in the basic SAG/Ball mill flowsheet and the SABC configuration has evolved. The oversize of the SAG Mill discharged is sent to the pebble crusher. Crushed pebbles are sent back to the SAG Mill and the undersize of the trommel screen send to the ball mill working closed circuit with hydrocyclones.

2.2.3. Alternative 3: HPGR/ball milling circuit

HPGR was introduced in 1977 by Schönert and it is known to be an energy-efficient alternative compared to conventional crushers and mills (Fuerstenau et al., 1991). In addition to being an energy-efficient alternative, there is no need for grinding media to size reduction and required less wear surface, so it offers less operating cost. The primary crushed ore is sent to the secondary crusher. The secondary crusher product is fed to the HPGR working in a closed circuit with the screen. While screen overflow recycles to the HPGR, the underflow of the screen is sent to the ball mill.

Table 3. Design criteria

Design Criteria		
Parameters	**Unit**	**Value**
General		
Specific Density	Mg/m^3	2.3
Head Cu Grade	%	0.1 / 0.2 / 0.3
Annual Design Throughput	Mg/year	2,500,000
Number of Working Day	day/year	300
Number of Shift	shift/day	3
Shift Availability	%	90
P80_Primary Crusher	mm	200
Secondary Crusher Size Reduction Ratio	mm	3
Tertiary Crusher Size Reduction Ratio	mm	3
HPGR Product P80 Size	mm	4.95
Rod Mill Product P80 Size	mm	1.5
Final Product P80 Size	µm	200
Ball Mill (L/D)		1.5
SAG Mill (L/D)		0.44
Bond		0
BWi	kWh/Mg	15.08
Ai	g/Mg	0.34
Gbp	g/rev.	1.21
Screen Aperture	µm	106
F80	µm	2,617.3
P80	µm	86.15
SMC		0
Mia	kWh/Mg	14.5
Mic	kWh/Mg	11.0
Mih	kWh/Mg	10.3
Flotation		
Rougher Residence Time	min	10
Scavenger Residence Time	min	5
Cleaner 1 Residence Time	min	7
Cleaner 2 Residence Time	min	5
Cleaner 3 Residence Time	min	3
Solid %	%	35
Rougher Recovery	%	50
Scavenger Recovery	%	65
Cleaner 1 Recovery	%	80
Cleaner 2 Recovery	%	82
Cleaner 3 Recovery	%	85
Flotation Reagent		
Frother	g/Mg	40
Promoter	g/Mg	20
Depressant	g/Mg	2000
Lime	kg/Mg	1726
Copper price	US$/Mg	10,000

2.3. Different feed grade for flotation circuit

In this study, three different feed grades were examined, 0.1, 0.2, and 0.3% respectively against the same throughput and stage recoveries.

When there is a single concentrate and tailing stream in the system, it is called two product system. To calculate the recovery of the metal or mineral in this system, there is a formula known as two product formula (Wills, 2013) as seen in Eq. 1:

$$R = \frac{C\,x\,c}{F\,x\,f} x100 \tag{1}$$

Eq. 1 can also be written in the form of mineral assay grade in each stream:

$$R = \frac{c}{f} x \frac{f-t}{c-t} \mathrm{x}100 \tag{2}$$

where F is total weight of the feed, C is total weight of the concentrate, f is mineral assays of the feed, c is mineral assays of the concentrate, t is mineral assays of the tailing.

2.4. Different alternatives

There are 9 different cases belonging to 3 different grades with 3 different size reduction alternatives. The cases are given in Table 4.

Table 4. Different cases in the scope of the study

Cases	Explanation
Case 1	Conventional Circuit with 0.1% Feed Grade
Case 2	Conventional Circuit with 0.2% Feed Grade
Case 3	Conventional Circuit with 0.3% Feed Grade
Case 4	SABC Circuit with 0.1% Feed Grade
Case 5	SABC Circuit with 0.2% Feed Grade
Case 6	SABC Circuit with 0.3% Feed Grade
Case 7	HPGR Circuit with 01% Feed Grade
Case 8	HPGR Circuit with 0.2% Feed Grade
Case 9	HPGR Circuit with 0.3% Feed Grade

3. Results

3.1. Flotation mass balance for all cases

Flow rates of each stream were calculated for three different feed grades. The mass balance was performed using known feed and process operating conditions based on the laboratory experiment/literature knowledge or design engineer specifies, and model equations. This type of balance depends only on the input parameters and is not dependent on measured data from any streams. And, they are called model-based balances and are often referred to as simulation or design balances and allow to design engineers to evaluate various process alternatives (Fuerstenau et al., 2003). In this case, three different feed grades with the same feed rate were evaluated.

Since there is no existing plant data, model parameters are estimated manually or selected from previous similar studies. The model parameters used in this study are given below.

The overall circuit recovery was calculated as 80.9%. Based on the given design criteria and recovery of the stages, the mass balance result for three cases is given in Table 6.

According to the obtained results from mass balances, under the same operational conditions, while feed grades increased from 0.1% to 0.2%, and 0.3% the final concentrate grades increased from 8.95%, 16.45%, and 22.82%, respectively. At the same time, the amount of final concentrates increased from 3.6 Mg/h to 4.3 Mg/h with the increased feed grades from 0.1 to 0.3%. This case study quantitatively shows the effect of the variable feed grade on the final concentrate amount and grades, and hence on the capacity and cost.

Table 5. Model input parameter for mass balance

Stages	Valuable Recovery (%)	Tails Recovery (%)
Rougher	50.00	15.00
Scavenger	65.00	25.00
Cleaner 1	80.00	20.00
Cleaner 2	82.00	30.00
Cleaner 3	85.00	40.00

Table 6. Mass balance results for three different feed grade

	Feed Grade: 0.10%				Feed Grade: 0.20%				Feed Grade: 0.30%			
Stream Name	Solid Mg/h	Grade %	Water m³/h	Total m³/h	Solid Mg/h	Grade %	Water m³/h	Total m³/h	Solid Mg/h	Grade %	Water m³/h	Total m³/h
Fresh Feed	400	0.10	743	174	400	0.20	743	174	400	0.30	743	174
Rougher Feed	622	0.14	1156	271	623	0.27	1156	271	623	0.41	1156	271
Rougher Tailing	529	0.08	982	230	529	0.16	982	230	528	0.24	981	230
Rougher Concentrate	94	0.45	174	41	94	0.90	175	41	94	1.35	175	41
Scavenger Feed	529	0.08	982	230	529	0.16	982	230	528	0.24	981	230
Final Tailing	396	0.02	736	172	396	0.04	736	172	396	0.06	735	172
Scavenger Concentrate	132	0.26	246	58	132	0.53	246	58	133	0.79	246	58
Cleaner 1 Feed	113	0.45	210	49	113	0.90	210	49	114	1.34	211	49
Cleaner 1 Tailing	90	0.11	167	39	90	0.23	167	39	90	0.34	167	39
Cleaner 1 Concentrate	23	1.78	43	10	23	3.50	43	10	24	5.16	44	10
Cleaner 2 Feed	28	1.66	52	12	28	3.28	53	12	29	4.84	53	12
Cleaner 2 Tailing	19	0.43	36	8	19	0.86	36	8	19	1.29	36	8
Cleaner 2 Concentrate	9	4.42	16	4	9	8.48	17	4	9	12.21	17	4
Cleaner 3 Feed	9	4.42	16	4	9	8.48	17	4	9	12.21	17	4
Cleaner 3 Tailing	5	1.14	9	2	5	2.26	9	2	5	3.36	9	2
Final Concentrate	4	8.95	7	2	4	16.45	7	2	4	22.82	8	2

3.2. Main equipment list for all cases

The main equipment list and their sizes are presented in Table 7.

3.3. Power load list for all cases

The SMC (Morrell, 2009) index was used for three different size reduction alternatives examined within the scope of the study. The primary crusher product P80 size was assumed to be 200 mm and the specific energy required to reduce the ore to the target 200 μm size was calculated for crushers, rod, ball, sag mills, and HPGR. The flotation cells' agitator power requirement was calculated based on the volume and number of the selected cells. After the hourly requirement was determined annual consumption was calculated with the annual working hour and load factor. The results for the nine cases are given in Table 8.

Table 7. Main equipment list of cases

		Size (Dimensions, Volume, and Number of Cells)								
#	Equipment Name	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
1	Secondary Crusher									
2	Tertiary Crusher									
3	Pebble Crusher									
4	Rod Mill, D x L (m)	4.0 x 5.8	4.0 x 5.8	4.0 x 5.8						
5	SAG Mill, D x L (m)				7.3 x 3.2	7.3 x 3.2	7.3 x 3.2			
6	HPGR, D x L (m)							1.7 x 1.2	1.7 x 1.2	1.7 x 1.2
7	Ball Mill, D x L	4.8 x 7.2	4.8 x 7.2	4.8 x 7.2	4.5 x 6.7	4.5 x 6.7	4.5 x 6.7	5.3 x 8.0	5.3 x 8.0	5.3 x 8.0
8	Rougher Cells, V x # (m^3)	25 x 11	25 x 11	25 x 11	25 x 11	25 x 11	25 x 11	25 x 11	25 x 11	25 x 11
9	Scavenger Cells, V x # (m^3)	15 x 8	15 x 8	15 x 8	15 x 8	15 x 8	15 x 8	15 x 8	15 x 8	15 x 8
10	Cleaner 1 Cells, V x # (m^3)	5 x 7	5 x 7	5 x 7	5 x 7	5 x 7	5 x 7	5 x 7	5 x 7	5 x 7
11	Cleaner 2 Cells, V x # (m^3)	1 x 7	1 x 7	1 x 7	1 x 7	1 x 7	1 x 7	1 x 7	1 x 7	1 x 7
12	Cleaner 3 Cells, V x # (m^3)	0.8 x 1	1 x 2	1.2 x 2	0.8 x 1	1 x 2	1.2 x 2	0.8 x 1	1 x 2	1.2 x 2

Table 8. Power load list for all cases

#	Equipment Name	Annual Consumption, GWh/year								
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
1	Secondary Crusher	2.42	2.42	2.42				1.45	1.45	1.45
2	Tertiary Crusher	2.75	2.75	2.75						
3	Pebble Crusher				1.45	1.45	1.45			
4	Rod Mill	7.97	7.97	7.97						
5	SAG Mill				16.26	16.26	16.26			
6	HPGR							6.01	6.01	6.01
7	Ball Mill	14.38	14.38	14.38	11.01	11.01	11.01	20.54	20.54	20.54
8	Rougher Cells	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24
9	Scavenger Cells	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
10	Cleaner 1 Cells	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
11	Cleaner 2 Cells	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
12	Cleaner 3 Cells	0.03	0.06	0.06	0.03	0.06	0.06	0.03	0.06	0.06
	Total	31.92	31.95	31.95	33.10	33.13	33.13	32.38	32.41	32.41

Table 9. Energy costs for all cases

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Total Cost, MUS$/year	4.79	4.79	4.79	4.97	4.97	4.97	4.86	4.86	4.86
Total Cost, US$/Mg-ore	1.91	1.92	1.92	1.99	1.99	1.99	1.94	1.94	1.94

3.4. Consumables, wear parts, and reagent list for all cases

After sizing the equipment, the amounts of consumption per annum were calculated. During the study, the ore-specific crushing/grinding indices, the ore-specific gravity, the design engineer defined availability and the amount of annual ore to be processed were used to calculate annual lifter, and ball/rod consumptions. The experience-based empirical models were used for lifter consumption calculation (Tuzcu, 2019; 2020).

$$Wear\ Model = \frac{\#liner\ pair}{5000\ hours} = 5\ x\ a\ x\ e^{b(C_1 x\ A_i{}^2 + C_2\ x\ A_i + C_3)} \tag{3}$$

where a, b are model constants, A_i is Bond abrasion index and C_1, C_2, C_3 are constants used for crusher wear model equation.

$$M_{lifter\ consumption} = C_4\ x\ P\ x\ t - C_5 \tag{4}$$

where $M_{lifter\ consumption}$ is lifter consumption amount (tons), P is mill power drawn (kW), t is time (hours) and C_4, C_5 are constants used for SAG lifter consumption

These models have been developed based on observation and experience over the years. Different types of reagents are used in flotation to recover valuable mineral particles and remove tailings including frothers, promoters, and depressants. To collect the valuable mineral particles in the froth zone with the promoter, the bubbles must not break until they are skimmed off. For this purpose, frothers aid in froth formation with sustaining desired froth stability. The depressants are often used to increase the efficiency of flotation by preventing the formation of froth by one mineral and allowing the desired mineral to be attached to the froth. The consumptions of consumables, wear parts, and reagents for all cases are given in Table 10.

Table 10. Consumables, wear parts, and reagent consumptions for all cases

	Consumables, Wear Parts, and Reagents						
Cases	**Ball and Rod (Mg/year)**	**Crushers Liner (set/year)**	**Mills Liner (set/year)**	**Lime (Mg/year)**	**Frother (Mg/year)**	**Promoter (Mg/year)**	**Depressant (Mg/year)**
Case 1	2,583.3	30	14	4,315.0	337.1	168.6	8,066.3
Case 2	2,583.3	30	14	4,315.0	337.4	168.7	8,067.8
Case 3	2,583.3	30	14	4,315.0	337.7	168.8	8,069.3
Case 4	2,987.0	12	12	4,315.0	337.1	168.6	8,066.3
Case 5	2,987.0	12	12	4,315.0	337.4	168.7	8,067.8
Case 6	2,987.0	12	12	4,315.0	337.7	337.7	8,069.3
Case 7	2,250.0	12	6	4,315.0	337.1	168.6	8,066.3
Case 8	2,250.0	12	6	4,315.0	337.7	168.7	8,067.8
Case 9	2,250.0	12	6	4,315.0	337.7	168.8	8,069.3

Table 11. Consumables, wear parts, and reagents cost for all cases

Cases	**Total (MUS$/year)**	**Total (US$/Mg-ore)**
Case 1	10.75	4.30
Case 2	10.75	4.30
Case 3	10.75	4.30
Case 4	11.12	4.45
Case 5	11.12	4.45
Case 6	11.12	4.45
Case 7	8.90	3.56
Case 8	8.90	3.56
Case 9	8.90	3.56

3.5. CAPEX for all cases

The CAPEX of the nine cases is shown in Table 12.

Table 12. CAPEX for all cases

CAPEX Items	CAPEX Cost, M US$								
	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**
Equipment	22.95	22.98	22.99	24.49	24.52	24.53	27.49	27.52	27.53
Freight & Install	4.8	4.8	4.8	5.2	5.2	5.2	5.8	5.8	5.8
Electrical & Instrumentation	9.1	9.1	9.1	9.7	9.7	9.7	10.9	10.9	10.9
Piping	7.9	7.9	7.9	8.4	8.4	8.4	9.4	9.4	9.4
Plate Work	2.4	2.4	2.4	2.6	2.6	2.6	2.9	2.9	2.9
Steel Work	5.4	5.4	5.4	5.8	5.8	5.8	6.5	6.5	6.5
Civil	6.6	6.7	6.7	7.1	7.1	7.1	8.0	8.0	8.0
Architectural	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4
TOTAL	**60.40**	**60.48**	**60.51**	**64.45**	**64.53**	**64.56**	**72.35**	**72.43**	**72.46**

3.6. Key economic indicators

The key economic indicators of the nine cases are shown in Table 13.

Table 13. Key economic indicators of all cases

		CASES								
Parameters	**Unit**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Annual Feed	Tg	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Plant Life	year	10	10	10	10	10	10	10	10	10
Annual Revenue	000'$	17,517	39,455	61,381	17,517	39,455	61,381	17,517	39,455	61,381
Annual Energy Cost	M$	4.79	4.79	4.79	4.97	4.97	4.97	4.86	4.86	4.86
Annual Consumables, Wear Parts, and Reagents Cost	M$	10.75	10.75	10.75	11.12	11.12	11.12	8.90	8.90	8.90
After Tax NPV @0	000'$	- 111,496	47,960	207,429	- 121,460	37,996	197,465	-104,355	55,101	214,569
After Tax NPV @5	000'$	- 99,401	23,709	146,840	- 108,018	15,092	138,224	-96,610	26,500	149,632
After Tax NPV @7.5	000'$	- 94,923	14,504	123,956	- 103,033	6,394	115,846	-93,769	15,658	125,110
After Tax NPV @10	000'$	- 91,204	6,745	104,721	- 98,888	- 939	97,037	-91,423	6,525	104,501
IRR	%	-	13%	43%	-	10%	39%	-	12%	38%

*NPV: net present value

**IRR: internal rate of return

**CAPEX: capital expenditures: equipment, mechanical, civil-structural, electrical, etc.

***OPEX: operating expenditures: consumables, chemicals, energy, etc.

4. Conclusions

In this study, the effect of different size reduction alternatives and, feed grades for flotation plants was examined on the project economic indicators. According to the obtained results, with a 0.1% feed grade, the revenue of the projects was less than the OPEX of the project, and the project economic indicators showed negative results. As was expected, the highest revenue was obtained in cases' with a 0.3% feed grade. Hence the IRR could not be calculated. In the IRR calculation, the CAPEX of the project has a major effect. The conventional size reduction circuit had fewer CAPEX requirements. Since then the highest IRR was obtained in case 3 which is the conventional circuit with a 0.3% feed grade. Because of the HPGR/Ball milling circuit lowest OPEX and highest revenue with 0.3% feed grade, the highest after-tax NPV was obtained in Case 9. This result shows that even if the HPGR /Ball milling circuit has the highest CAPEX, thanks to reducing OPEX it provides more profit than other size reduction alternatives during the life of the project. This study yields an important quantitative conclusion that the OPEX of the investment is far more important than the CAPEX for the project NPV. However initial investment (CAPEX) is more effective on project IRR. In the study, the same throughput with different size reduction paths with 3 different copper grades was traded off. It was seen that a higher copper feed grade naturally yields higher metal production, so the more flotation cells on the concentration side. All of the above conclusions were quantified for 9 cases in this study.

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