Modelling, simulation and optimization of the comminution and flotation circuits of platinum for sustainable mineral processing

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Abstract: The quantum of minerals extracted from ore is critical for the success of mineral processing, hence the necessity to optimize the process flows in order to recover as much minerals as possible. The aim of this research was to identify bottlenecks and recovery-hampering factors within the comminution and flotation circuits of the concentrator plant at a platinum processing company in Zimbabwe. Modelling and simulation of the circuits were carried using Arena and Limn simulation software to optimize the process flows for improved throughput, maximum mineral recovery and enhanced efficiency and productivity. Alternative configurations of the layout of equipment were experimented on and compared with the original setup. The recommended reconfiguration of the circuits achieved increases of 2.97% in mineral recovery and 4 grams/ton in productivity resulting in a maximized output for the sustainable processing of platinum ore.

Keywords: comminution; modelling; flotation; platinum processing; optimization; simulation; sustainability.

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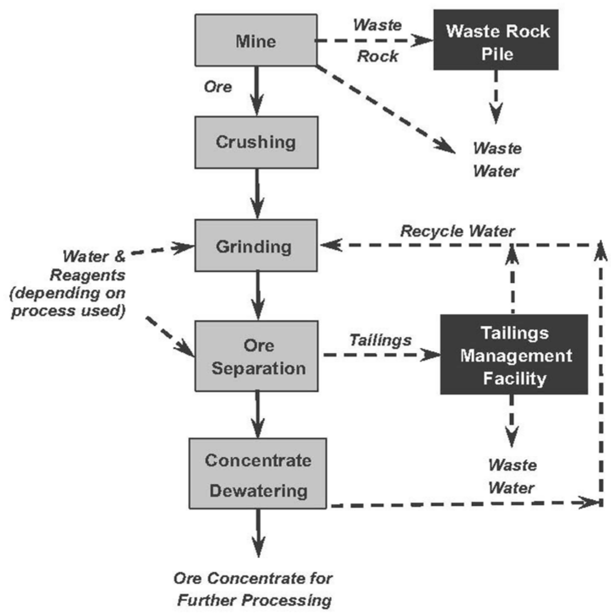
1 Introduction

The processing of platinum ore involves complex and multipart processes that are aimed at achieving extraction of value in an efficient and sustainable manner (Steyn and Brooks, 2017). Throughout the value chain, the processes were designed to be cost efficient through the use of leading technological advancements and world best practices in the engineering and metallurgical aspects of mineral processing (Carrasco et al., 2017). To further achieve the efficiency and productivity to maximize mineral extraction from Platinum Group Metal (PGM) ores, there was need to simplify the multifarious nature of the process flows, materials handling and operations of the mines and processing plant (Jena et al., 2016). The case study was carried out at a platinum mining and processing company in Zimbabwe.

Observations made during the work study revealed that the company exported their ore in concentrate form for further processing and refining in South Africa because of insufficient resources for beneficiation. Invariably, there was loss of revenue to the company and the government, hence the insistence by the Government of Zimbabwe on beneficiation and value addition (Government of Zimbabwe, 2013). At the time of carrying out the research, the case study company was not only in the process of installing additional smelters but was also in the process of establishing a Base Metal Refinery (BMR) to further refine the platinum matte before exporting it to South Africa for the Precious Metal Refinery (PMR). The bulk of the work in platinum mining and processing lay in the comminution and flotation circuits of the concentrator plant which had the most capital and technology intensive equipment and operations as shown in the value chain for platinum processing in Figure 1.

Figure 1 Value chain in platinum processing and production



The mined ore, at 600 mm boulders were crushed and milled through various stages to 75 μm which was further separated through the flotation cells to the concentrate matte. It was evident from the study that the bulk of the ore ended up as waste, either in the form of tailings after flotation or slag after smelting. While the tailings were fast filling up the dams and mounts of slag were building up on a daily basis, issues of sustainable operations had to be taken into account. This required that while processing of the ore was being carried out, the company also needed innovative ways to deal with the waste through optimization of operations. In addition, such a low mineral concentration at the beginning required efficient methods to produce the required productivity that justified the operations. The introduction of additional smelters and the BMR meant that upstream processes in comminution and flotation needed to be efficient to cope with the demands coming from downstream, as well as the need to ensure that the exported matte was in as much refined form as possible in order to realize better revenue.

Like many countries around the world, Zimbabwe was also affected by the global financial crisis of 2008 which saw quite a number of companies liquidated (Bakrania and Lucas, 2009). In addition, the world experienced one of the worst downturns in platinum prices in 2015 (Johnson Matthey, 2017), which forced the case study company to scale down operations in order to remain in business (Zimplats, 2015). This meant that, although the company was fully automated and capitalized, the various stages of platinum mining and processing had to be optimized in order to achieve the same level of throughput under the circumstances. This research focused on the comminution and flotation circuits of the concentrator through identifying bottlenecks and recovery hampering factors as well as establishing the amount of ore and concentrate that passed through. Through interactive interviews and direct observations, data was collected and used for simulation and experimentation in order to advise the company of which configuration provided the maximum throughput and what implications this had on other aspects of the processing plant such as power consumption and configuration of the concentrator workstations. Faced with the financial crisis that posed the danger of halting operations, the research focussed on maximising available utilities in order to extract as much concentrate matte as possible in a sustainable manner that ensured that the company remained in business.

2 Methodological background and literature review

The amount of minerals extracted and their quality depended on the technologies employed in the processing of ore (Mwanga et al., 2017). In view of the usually very low amounts of valuable minerals that can be extracted, the bulk of which was disposed as waste, the equipment and processes used must be efficient, otherwise the operations would not justify the investment (Carrasco et al., 2017). The appropriate optimization of the processes was also critical in order to recover as much minerals as possible. The comminution of platinum was accomplished through various stages from jaw crushing (primary) through secondary crushing by Semi Autogenous Grinding (SAG) and final crushing by ball mills (Carrasco et al., 2017), similar to the existing configuration at the case study company. Any ore that the SAG mill failed to crush to less than 12 mm was screened and conveyed to a gyrasphere cone crusher after which it was re-conveyed to the SAG mill. Crushed ore below 12 mm was pushed through to the ball mill for further crushing and milling down to 75 μm for the flotation cells.

Similarly, any ore that the ball mill failed to reduce to the required size for the flotation cells was screened and recycled to the SAG mill for further milling, evidently time consuming and inefficient processes. The milled ore from the ball mill was then pushed through to the flotation circuit of the concentrator. Flotation was carried out through a series of tank cells containing tailings or slimes (Jovanovic and Miljanovic, 2015). The flotation feed from the 1 mm linear trash screen was pushed through the stilling box and distributor for separation into 2 flotation lines, pulp which was passed through rougher conditioner tanks with flotation reagents while the overflow from the conditioner tanks was conveyed by gravity to rougher cells. The slime from the conditioner tanks was pumped to the rougher scavenging conditioner tanks and overflows into the rougher scavenging flotation cells and eventually conveyed for thickening as this was mostly waste which was dumped at the tailings dam. These were highly mechanized and fully automated processes.

Due to the series connection of the workstations, it was critical not only to ensure that the processes continued uninterrupted but efficiently as well in order to maximize the throughput. The work study revealed a number of challenges such as production throughput below the designed plant capacity, reductions in tonnage milled compared to previous reporting periods, reductions in platinum output as well as increase in dried concentrate matte queueing for the smelter (Zimplats, 2015). Some of these were a result of the drop in world prices for platinum. However, the demand for granulated matte from South Africa for further refining had not significantly changed and hence the need to maintain or surpass the throughout (Zimplats, 2015). Based on literature and data collected in the concentrator section, a number of alternative configurations for the comminution and flotation circuits were considered, the basis on which the optimization of the plant was accomplished by way of advising management of these alternatives for cost reduction, productivity boosting and optimal processing of platinum for sustainability.

2.1 High pressure grinding rolls

The first alternative considered was for the use of High Pressure Grinding Rolls (HPGR) in the SAG and ball mills as this option was not only energy efficient but did not require constant maintenance as conventional mills, apart from also providing higher throughput (Steyn and Sandrock, 2013). Although the use of HPGR required precision equipment, hence capital intensive, in the long term their incorporation in comminution circuits enabled the milling of the ore to an extent that it may not be necessary to have the gyrasphere cone crusher for recycling ore that would have failed the pass at the SAG mill as they provided consistent and regular size of ore. The biggest challenge of using HPGR would be to invest in such new forms of milling equipment, which can however be compensated by the possible removal of the gyrasphere cone crushers.

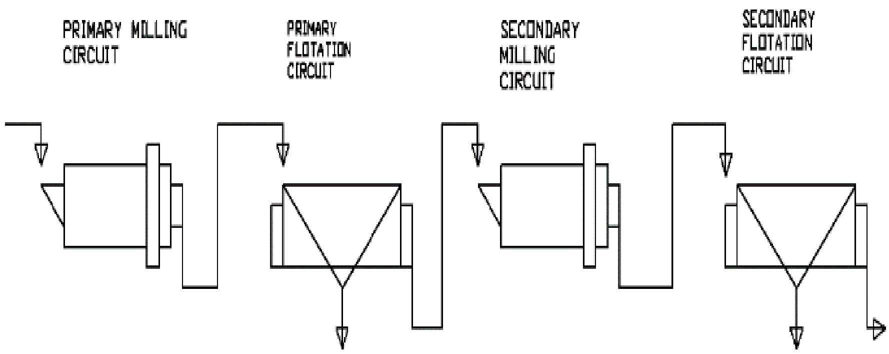
2.2 Pre-crusher in the circuit

While additional equipment can be capital intensive it was vital for the ore that was eventually fed into the SAG and ball mills to be consistent for the sake of efficiency. Therefore, pre-crushing of the ore prior to feeding into the mills would not only reduce the feed residence time but would also reduce the loading time for recycling pebbles for regrinding and ultimately the energy consumed by these processes (Silva and Casali, 2015). However, the gyrasphere cone crusher may still be required for the odd cases where the SAG mill would have failed but this would be minimal and thus a worthwhile investment to consider as less energy was consumed.

2.3 MF2 Configuration

The major processes in the concentrator are milling and flotation, which are accomplished through different combinations such as; mill-float (MF1), mill-mill-float (M2F), mill-float-mill-float (MF2), mill-float-mill-float-mill-float (MF3) but all dependent on the primary, secondary and tertiary milling of the platinum (Liddell and Adams, 2012). Although the most commonly used configuration was the M2F (Liddell and Adams, 2012), the case study company employed the MF2 circuit due to the use of the cone crusher as supplementary milling. Figure 2 shows the schematic for the MF2 configuration.

Figure 2 Schematic for the MF2 configuration



The SAG and ball mills represented primary and secondary milling respectively. The flotation tank cell that recovered sulphides from the SAG mill discharge represented the primary flotation while the rest of the flotation processes represented secondary flotation. Capacities of the equipment in the two circuits such as the SAG and ball mills and the gyrasphere cone crusher were obtained from the company's records while the periodical feeds through these workstations were recorded during the research. The inclusion of a unit cell for releasing base metal sulphides in the MF2 configuration from the coarse ore enabled the removal of coarse but valuable ore in primary milling before overgrinding. This configuration depended on content of the PGM ore and base metal sulphides that were resident in host mineral grain boundaries as well as those locked in silicates (Liddell and Adams, 2012).

2.4 Cleaner scavenger cells

The use of cleaner scavenger cells is also an alternative cycle of the froth flotation process for cleaning the concentrate from the rougher and scavenger (Jovanovic and Miljanovic, 2015). The use of this type of configuration in flotation is not only useful for enhancing the recovery rate and concentrate grade but also improved the removal of undesirable particles. It also enhanced the recovery of slow floating minerals, thereby improving the grade of the granulated matte.

2.5 Rougher cells residence time and volume

The information collected during the research, particularly the feeds and throughput in the concentrator revealed that the rougher cells delayed the processes and hence they were the bottleneck for the flotation circuit due to the high scheduled resource utilization. The rougher scavengers also treated the rougher cells' tailings, some of which were fast floating PGMs. Therefore, in order to increase the volume of the rougher cells and residence time, the rougher cells were made to process only slow floating minerals (Jovanovic and Miljanovic, 2015). This had the net effect of enhancing mineral recovery and efficiency of the flotation circuit. To augment this and improve the continuous flotation process, equation (1) was used (Yianatos et al., 2012), where *R* was the recovery at time *t*, $R\infty$ was the maximum recovery at infinite time, *k* was the kinetic rate constant for all sub-processes, *F(k)* was the constant distribution function for mineral types with different flotation rates and *E(t)* was the residence time distribution for continuous flotation, which was dependent on the hydrodynamic state, a function of the flotation cell design and circuit configuration (Yianatos et al., 2012).

$$\frac{R}{R_\infty} = \iint_0^\infty (1 - e^{-kt})\, F(k)E(t)dkdt \tag{1}$$

3 Data collection and modelling of existing circuits

The processing of platinum from the Run-of-Mine (ROM) through the various stages until the granulated matte, ready for export for further refining is highly mechanized and technology intensive (Steyn and Brooks, 2017). Several factors influence the throughput and mineral recovery through these stages. The recovery of minerals can also be derived from the assay values of the concentrate *c*, feed *f*, as well as the tailings *ta* using equation (2) (Asbjörnsson, 2013).

$$R = \frac{c\,(f - ta)}{f\,(c - ta)} \times 100 \tag{2}$$

The stages and workstations in the comminution and flotation circuits for platinum were dependent on each other as they were all connected in series such that a breakdown along the line affected the throughput and mineral recovery (Duclos et al., 2016), hence the need to maintain an uninterrupted running system for maximum throughput. The workstations at the case study company, particularly the flotation section of the concentrator were fully automated and largely operated unattended but controlled and monitored centrally. Figure 3 shows a model of the comminution and flotation circuits extracted from the process flow models developed during the work study while Tables 1 and 2 show some of the data obtained from the SAG mill and cone crusher feeds. The case study company had 2 concentrators at the time of carrying out the research, one close to the portals and the main one at the metallurgical processing complex, 80 km away. Typically, the concentrators had the capacity to process 2.2 million tons of platinum ore per annum.

Figure 3 Platinum comminution and flotation circuits

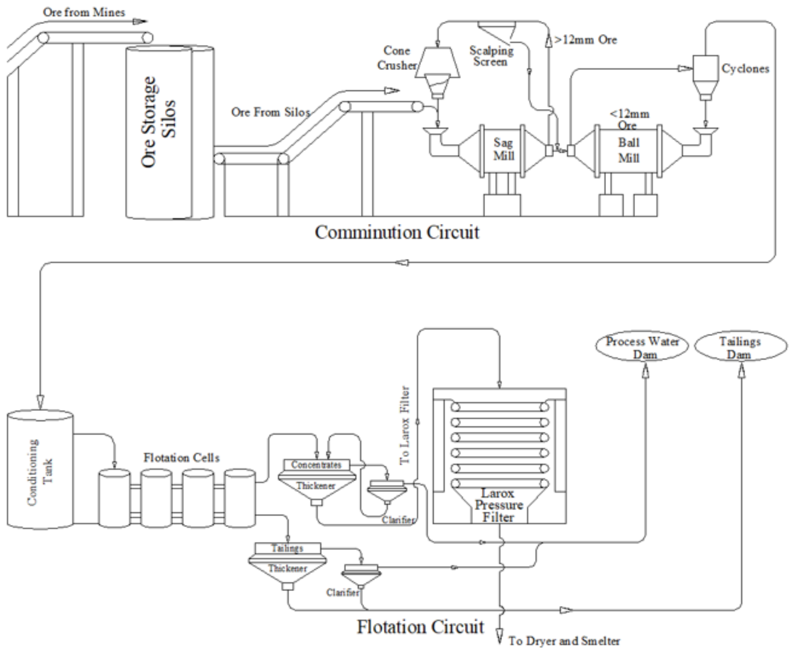


Table 1 SAG mill feed

Screen Size (mm)	Mass Distribution (kg)	Percentage Distribution (%)	Cumulative Percentage Retained (%)	Cumulative Percentage Passing (%)	Targeted Particle Size Distribution (PSD)
300	0.0	0.0	0.0	100.0	100.0
212	0.0	0.0	0.0	100.0	96.5
150	12.2	11.4	11.4	88.6	72.4
95	15.7	14.6	26.1	73.9	53.7
75	10.5	9.8	35.9	64.1	45.2
53	14.6	13.7	49.5	50.5	36.6
38	9.3	8.7	58.2	41.8	30.1
27	5.7	5.3	63.5	36.5	25.8
19	4.8	4.5	68.0	32.0	22.4
13	4.2	3.9	71.9	28.1	19.2
9.5	30.0	28.1	100.0	0.0	
Total	**106.9**	**100.0**			

Table 2 Cone crusher feed

Screen Size (mm)	Mass Retained		Cumulative % Passing
	kg	**%**	
75	2.00	2.8	97.2

53	18.800	26.3	73.7
38	17.600	24.6	49.1
27	15.800	22.1	27.0
19	13.600	19.0	8.0
13	2.900	4.1	3.9
6	0.800	1.1	2.8
Total	71.50		

Due to the grinding media required and energy consumed, the comminution circuit accounted for the highest operating costs in platinum processing (Carrasco, et al., 2017). On average, the company processed 275 tons of ROM per hour which was fed through a single SAG mill and single ball mill at each of the concentrator plants. The ball mill operated in conjunction with 8 hydro-cyclones to classify mill discharge to produce overflow of concentrate of 75 μm for the flotation circuit.

4 Simulation and experimentation

The focus for the research was to utilize the data obtained during the work study together with the fixed data from the operating capacities of the available equipment to experiment on the alternative circuits in order to optimize the operations. Following the work study and modelling of the entire operations, data collected was used to simulate the alternative circuits using Arena Simulation Software for the discrete and continuous simulation and modelling of the entire plant (Sanz et al., 2013) and Limn Flowsheet Processor to establish connectivity of process units and paths (Hand and Wiseman, 2010). The combination of both packages was used to establish performance, identify bottlenecks and ultimately optimize the circuits for productivity, capacity utilization and efficiency. Appropriate assumptions in simulation are necessary for the success of modelling and eventual simulation of the processes (Walter et al., 2014).

A number of such assumptions were made before modelling and experimentation of the different alternatives. For the simulation in Arena, the assign module was used to ascribe the size of the ROM ore from 300 mm boulders down to 75 μm throughout the stages of the comminution. For consistence in the results obtained from the simulation, the delivery of the ROM to the bunkers was assumed to arrive at a constant rate of about 105 tons in 15 minutes. The modelling of the processes was assumed to be discrete event simulation in the concentrator with reasonable delays or nominal residence times that were normal, uniform, constant or followed a particular mathematical distribution. The process modules were assumed to be value adding activities during the seize-delay-release stages of the comminution circuit. Due to the volumes of the ROM ore that was handled periodically and the limitations of the academic version of the Arena simulation software that was used, the entity value of 1 was used to represent 100 tons in the plant.

For the Limn Flowsheet Processor simulations, model assumptions were also used. The data structures and processes in the models were assumed to be based on one dimensional data layout while the data layout for the comminution circuit was size based. The standard 2 rate per mineral flotation bank model could not be developed because the available data did not provide for distinct fast and slow floating mineral recoveries. The tails for the granulated matte comprising the main 4Es (Platinum, Palladium, Gold and Rhodium) determined the residence times derived from predetermined formulae. The mathematical models that were referred to in the Limn simulations and for specific workstations were as follows;

- ROM silo: Simple mixer model (Tengende et al., 2014),
- Cone crusher: Generic crusher model (Johansson, 2009),
- SAG mill and ball mill: Austin model (de Oliveira and Tavares, 2018),
- Cyclones and trommel screen: Whitten efficiency model (Narasimha et al., 2014)
- Flotation banks: Modified Kelsall model without entrainment (Bu et al., 2017)

5 Results and optimization

The effective utilization of equipment in process industries had a positive bearing on a company's productivity, capacity utilization and efficiency (Heshmat et al., 2013). The results that were obtained from the Arena and Limn simulations gave a direct indication of the performance of the plant after a number of replications. The Arena simulation runs for the comminution circuit were conducted with 200 replications with a 95% confidence interval for the cycle time analysis. The model outlays the half-width value of the 95% confidence interval at an average output statistic of 70 across all replications. Flotation simulation runs were conducted with 1000 replications also with a 95% confidence interval for the cycle time analysis.

5.1 Resource utilisation and queues

Resource utilization of the milling plant was measured by actual throughput against design throughput. Queues were derived from process and residence times, and were also indicated by throughput. So a queue was a process delay that potentially affected downstream or upstream processes in terms of throughput. The simulation results provided the resource utilization and queues for the comminution and flotation workstations from where Figures 4 and 5 were derived. Figure 4 was used to compare the utilization of the equipment against their availability. The results showed that the SAG and ball mills had the highest scheduled utilization with machines being seized at 73.3% and 79.6% of the time respectively. However, these two machines also had the highest value of waiting times which resulted in queues of 19.55 and 9.35 tons per hour respectively. This implied that the SAG mill was the bottleneck in the comminution circuit and effectively affected the capacity utilization of the concentrator plant. There was no storage before the ball mill. However, from simulation, through 200 runs, it showed that for different levels of equipment utilization, it affected the overall throughput, as measured by queuing time (defined in reduction of throughput). Production rate in the comminution circuit was measured through flow measuring devices.

Figure 4 Comminution circuit resource utilisation

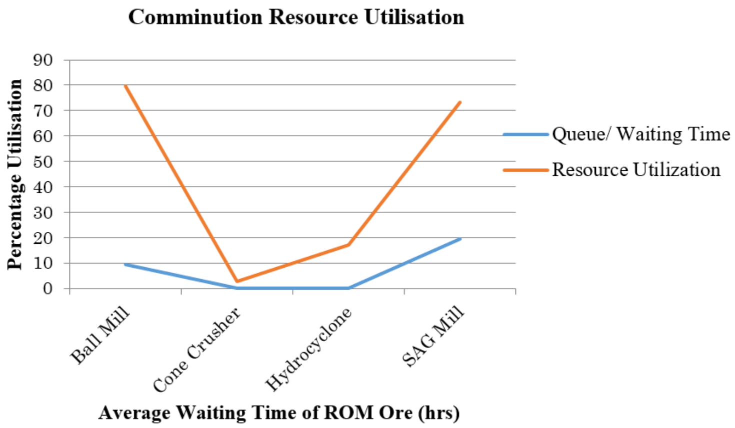
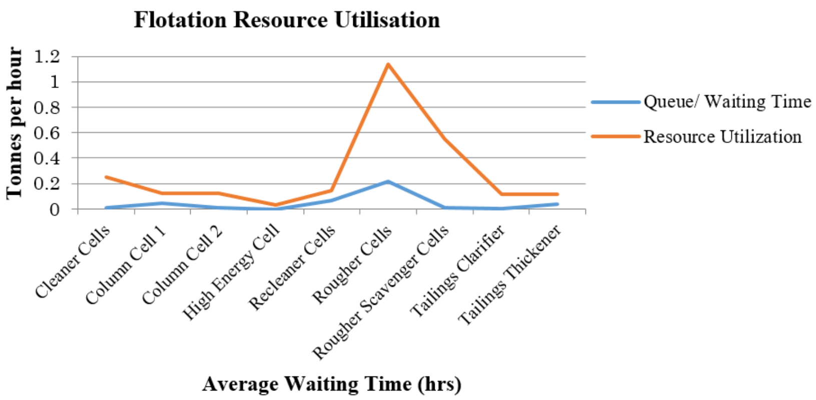


Figure 5 compared the utilization of the flotation cells against their availability. The circuit was designed to recover minerals from high grade or fast floating elements through the roughers and maximum recovery by cleaners and re-cleaners, column cells and high energy cells. The rougher cells had the highest scheduled utilization as well as the queueing time. The six $28m^3$ roughers which were the primary high grade and fast floater froth recovery equipment were evidently the bottleneck in the flotation circuit.

Figure 5 Flotation circuit resource utilisation

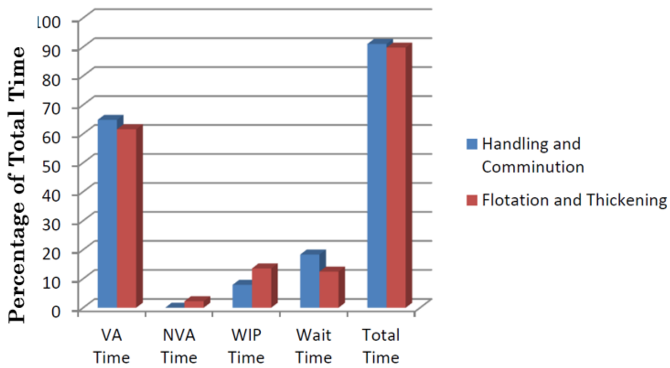


The availability, efficiency and productivity of the SAG mill affected the rest of the equipment, hence the use of its performance as a measure for the availability of the concentrator. The reduction of accumulation of ore at the SAG mill was the most critical task to achieve efficiency of the entire plant despite the high resource utilization. The ball mill also exhibited a high resource utilization while the hydro-cyclone and cone crusher did not have any queues as the former was assumed to have an equal underflow rate to that of the overflow. Resource utilization for the flotation circuit was generally low due to the re-routing of the tailings to several flotation columns, cells and banks. The cleaners and rougher scavengers had queues of between 0.05 to 0.8 tons per hour. Except for the roughers, the other flotation equipment was seized and utilized between 9% and 25% of the time as the overflow was gravitated to other banks.

5.2 *Entity value added and queueing time*

The results obtained from the simulation runs were comparable for Value (V) and Non-Value Addition (NVA) as well as Work in Process (WIP), queueing for comminution, flotation and thickening as shown in Figure 6. The allocation or characterisation to which the entity's incurred delay time and cost are shown. This is the information shown in the graph to represent the valid entries for the simulation. However, the costs were not included in the simulation, hence the allocations that were only taken into account were entity value added time, non-valued added time and waiting time. The value added time was the total time for the machine delay less the stoppages encapsulated in the resource. The stoppages were added as failures with a specific failure rule, hence this rule was considered in the simulation run to give valued added time as non-failure times in the simulation run. The value addition constituted the total productive time of 71.2% and 68.6% for comminution and flotation respectively. Work in process constituted between 8.7% and 15.1% of the total time, which represented the re-circulating loads in different stages. The grand total of the time from work in process and non-value added time gave an indication of the process efficiency. An efficient process would naturally have a higher availability and high performance as well as reliability (Carrasco et al., 2017).

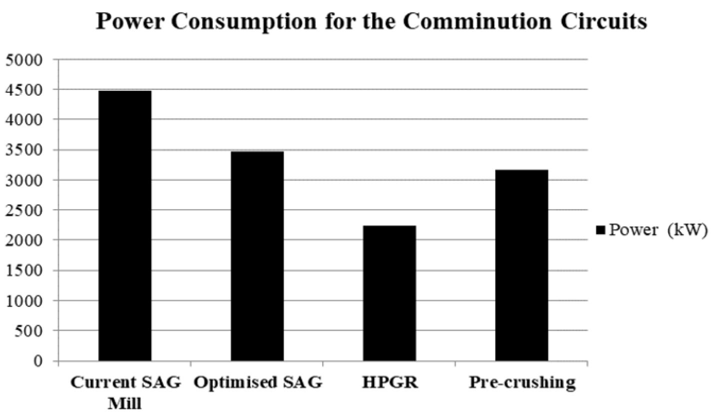
Figure 6 Entity value added, non-value added and waiting times



5.3 *Comparison of power consumption*

The power required by the different alternative circuits was derived from the Limn Flowsheet Processor and is summarised in Figure 7. The existing SAG mill consumed 4,475 kW but the modelled configuration with variable parameters required 3,477.3 kW. If the HPGR were adopted in place of the SAG mill, 2,240 kW would be required to maintain the current throughput of 300 tons per hour, thus a 49% saving in energy. The use of a pre-crusher would reduce the amount of power required by the SAG mill to 3,157.5 kW, a 29% saving of energy. This comparison showed the advantage of using HPGR over the conventional SAG mill, confirming the efficiency of this configuration as noted by Fuerstenau and Abouzeid, (2007).

Figure 7 Power consumption for the comminution circuits



5.4 Validation and verification

Possible errors in simulation and experimentation can occur from wrongly interpreting processes, thus leading to incorrect inferences, hence the need for validation and verification (Walter et al., 2014). The RUN tool in Arena was used to debug such errors and verified the models that were developed and experimented on. The models were verified and the programs edited in stages as the processes progressed from one module to another. It also allowed the 'break on module' and 'highlight module' with animations done to view how entities progressed along the system, with queues, delays and process times being observed. These animations also enabled any abnormal behaviour to be corrected through logical movements. The model was verified by event validity i.e. through comparison of model results to the real system. This comparison was tested by a 95% confidence interval. In ARENA, the "Run tool" verified the model as it allowed the Break on Module and Highlight Module with animations done to see visually how entities moved along the system, with queues, delays and process times being visually observed. Half-width values were obtained using equation (3) (Liotta et al., 2016) for the (1-α) confidence level, where α = 0.05, *s* was the standard deviation and *n* were the number of replications.

$$H = t_{n-1,1-\alpha/2}\frac{s}{\sqrt{n}} \tag{3}$$

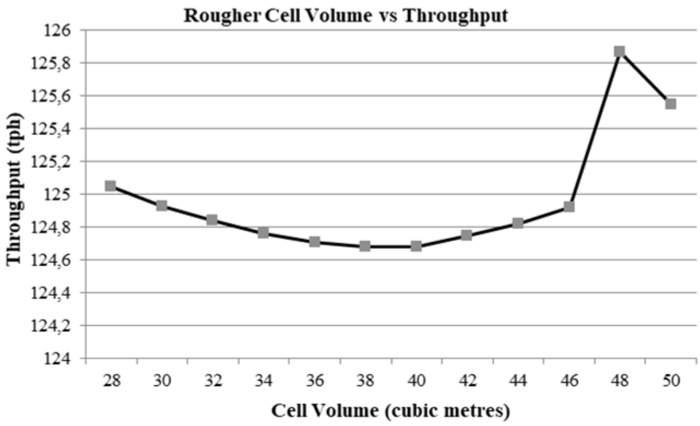
6 Discussion and recommendations

The SAG mill had the highest waiting time of up to 20 tons per hour in the comminution circuit, implying that although it had a very high resource utilisation of 73%, it was still a process bottleneck. The ball mill had a high throughput of 825 tons per hour because it handled a 300% hydro-cyclone circulating load, and also showed the highest resource utilisation in the comminution circuit of 79% and a queue of 9 tons per hour. The hydro-cyclone and the cone crusher had no queues due to the scheduled resource utilisation simulation run. According to the model developed, the hydro-cyclone was assumed to have equal underflow and overflow rates. Despite this being questionable, this was meant to avoid serious challenges in estimating underflow and overflow rates. The cleaners, re-cleaners, rougher scavengers, and the dewatering unit all had waiting times and queues between 0.05 and 0.8 tons per hour, which was insignificant as far as affecting the overall throughput of the flotation process. The rest of the equipment (except for the process bottleneck- the roughers), were seized and utilized between 9 and 25% of the time, as the overflow was either pumped or gravitated to other flotation banks or concentrate sump.

6.1 Cell volumes and throughput

The rougher bank volume was increased in order to improve residence time, throughput and mineral recovery. 6 cells were used to simulate the rougher bank with a 45% concentration, initial volume of each cell at 28m^3 and nominal residence time of 53.417 minutes. Simulation runs were conducted for cell volumes ranging from 28m^3 to 50m^3. As the cell volume was increased gradually, there was a gradual decrease in throughput but this rapidly increased to a peak of 125.87 tons per hour at 48m^3, a 1% increase in throughput as shown in Figure 8. Among the PGM 4Es, platinum and palladium recovery improved with increases in cell volumes but there were decreases in gold and rhodium. The optimal peak for the recovery of the 4Es was at 48m^3 where the recovery gain averaged 81% to 83.97% with platinum recording 82.37%, palladium, 79.83%, gold, 82.3% and rhodium, 91.36% as shown in Figure 9.

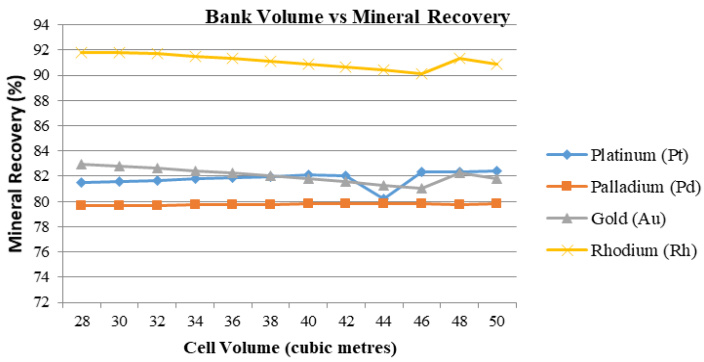
Figure 8 Relationship between cell volume and throughput



6.2 Cleaner scavenger cells

The introduction of cleaner scavenger cells in the cleaning circuit to augment the cleaners and re-cleaners increased the residence time, enabling the slow floating PGMs to be captured before they were disposed to the tailings dam. 12 cells of 8m^3 each, a residence time of 87.012 minutes and a recovery of 119.41 tons per hour were used and simulated in Limn for the scavenger. The results obtained from the introduction of the cleaner scavenger cells in the PGM 4Es showed mineral recoveries of platinum at 81.8%, palladium, 84.87%, gold, 72.99% and rhodium, 86.93%, an average of 81% to 81.67%. However, this also resulted in a drop in the overall throughput from 125 to 119.41 tons per hour because of the circulating load and long nominal residence time. Mugadza (2015) also recommended the Metso Reactor Cell System (high energy cells) for similar use as a way of improving recoveries by increasing the pulp residence time in the circuit in order to capture the slow floating value fraction. However, since the introduction of cleaner scavengers may be capital intensive, it was more cost effective and prudent to use high energy cells than cleaner scavengers. Generally, the effect of increasing the cell volume reduced the recovery of the PGM 4E minerals. However, there was a compromise between the resultant throughput and the recovery as shown in Figure 8.

Figure 9 Relationship between cell volume and mineral recovery



6.3 Pre-crushing and HPGR

The purpose of a pre-crusher before semi-autogenous grinding was meant to influence the feed size distribution for the SAG so that the grinding was more efficient, faster and consistent. The Limn Flowsheet Processor simulation of the crusher was aimed at reducing the maximum size of ore from 300mm to a size that was greater than the critical size of 53mm, say 150mm. The action of the tumbling mill required huge boulders since breakage was due to boulder-to-boulder impact, grinding media-to-boulder and attrition of the ore. The Limn model for the crusher closed side was set at 150mm and the ROM particle size distribution was altered as shown in Figure 10(a). The discharge of the crusher was the mill feed and ultimately this size distribution required less net mill power consumption and holdups as shown in Figure 10(b), extracted from the Limn Flowsheet Processor output. However, pre-crushing required more routine maintenance and was power intensive compared to HPGR.

Figure 10 (a) Size distribution in pre-crusher (b) SAG mill details and power

(a)

		Feed		Mill Feed
	Water t/h			0.00
Size	Mean			
+300	173.21	100.00		71.053
+150	212.13	88.60		-35.967
+75	106.07	64.10		147.667
+38	53.39	41.80		93.651
+19	26.87	32.00		33.44
-19	15.72	28.10		44.757

(b)

Mill Physical Details	
mill diameter [m]	7.599
mill length [m]	3.536
mill speed fraction of critical	0.70
fractional filling of mill with balls	0.30
true density of balls [t/m3]	7.80
Estimated net mill power and holdups	
Mill power [kilowatts]	3,157.212
Hold up of rock solids [tons]	23.683

The Limn model for the HPGR used the Daniel and Morrell model (2004) but not the Bond working index (Todorović et al., 2017) although the action of the HPGR potentially affected the index of the crushing product as the former was sufficient to define the crushing characteristics of the ore. The model parameters for the HPGR gave the critical gaps for the several stages of the comminution with the pre-crusher having a gap of 109.55 mm. The pre-crusher reduced the feed from 300mm to at least 110mm, then the edge effect crusher and the compressed crusher had a gap of 60mm. The resultant effect was that the percentage retained was 96.97%, which implied that the HPGR provided a consistent throughput of 275 tons per hour, retaining 97% of the product with the product mass distribution. This was an improvement from the SAG mill which did not have a consistent throughput of 250 tons per hour and had a circulating load of 150 tons per hour that was recycled to the gyrasphere cone crusher.

6.4 Recommendations

Based on the results obtained from the simulation and experimentation in Arena and Limn, the use of the HPGR was recommended in place of the SAG mill and gyrasphere cone crusher. The HPGR produced a consistent grind (size distribution) in the comminution of PGM ore and saved up to 49% of power. It was also coupled with efficient operation since it did not require grinding media and had a higher and consistent throughput of 275 tons per hour with minimal routine maintenance.

The rougher cell volumes for the 6 cells were recommended to be increased from $28m^3$ to the peak of $48m^3$ which invariably enhanced the recovery of PGM 4Es from 81% to 83.97%, thus maintaining a constant throughput. High energy cells such as those used in the Metso Reactor Cell System can be introduced in the circuit to improve the grade of concentrate from 132 to 136 grams per ton. High energy cells also helped to clean the concentrate and thus enhancing the grade. Trapping of slow moving PGM minerals can be improved by increasing the nominal residence time of the rougher cell bank from about 53 to 87 minutes. The resource utilisation of the various workstations in the comminution and flotation circuits, namely; SAG and ball mill, cone crusher and hydro-cyclones were essential in determining and identifying the process bottlenecks which were used to advise management at the platinum processing company to focus on in terms of optimisation in order to process the ore sustainably.

7 Conclusions

The case study was carried out at a platinum mining and processing company in Zimbabwe, a key establishment in the country's beneficiation and value addition drive as it had the only smelter in the country. Competitiveness of such a company in the PGM mining industry was anchored on improving the key drivers of the value chain for PGM processing up to the precious metal recovery stage. Metal recovery in the concentration of mineral ore is a function of the mineralogy, comminution regime, flotation kinetics, flocculants, variables and parameters. Observations during the research revealed that comminution and flotation made up the bulk of the processing equipment. Although the smelter was evidently the bottleneck due to queues observed at the plant, focus for this research was on the concentrator. The data collected during the research comprised mainly the feed and processing times for the comminution and flotation equipment and was used in the modelling and simulation of alternative circuits that were proposed to improve throughput, mineral recovery, productivity, energy consumption, concentrate grade and efficiency. The comminution and flotation circuits were simulated using Arena while the Limn Flowsheet Processor was used to calculate the power required and to derive the connectivity of process units and paths.

From the optimized process flows and reconfigurations, the use of high pressure grinding rolls (HPGR) was recommended ahead of a pre-crusher or modified SAG mill as this was not only energy efficient but required less maintenance. The installation of bigger rougher cells of $48m^3$ and increase in the rougher bank residence time were also recommended as they maximised or maintained the throughput at 275 tons per hour. The HPGR also eliminated a recirculating load in primary crushing and had less mill residence time. The HPGR provided a consistent discharge for downstream processes while the bigger rougher cells with more residence time increased the capacity to trap slow floating PGMs. The optimized and proposed system had the potential to increase mineral recovery from an average of 81% to 83.97%. The enhancement of the concentrate grade was achieved by introducing the high energy cells, which according to the simulation results, improved the grade of the final concentrate from 132 to 136 grams per ton. The specific energy consumption for the HPGR-based circuit was 8.0 kW/ton, an improvement from 16.3 kW/ton. The proposed reconfigurations reduced the cost structure for sustainable platinum production and thus improved the productivity and profitability of the platinum mining and processing company.

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