Continuous Improvement of a Copper Concentrator by Advanced Flotation Control

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Mintek is applying advanced process control and optimisation techniques to improve the metallurgical performance of the Lubambe copper concentrator in Zambia. A continuous improvement approach is used to ensure smooth change management and maximal benefit from capital spent by the mine. The control implemented thus far has centred on the flotation circuit, which has entailed three aspects: stabilising the flotation cell levels, controlling the concentrate pulling rates of different cells to achieve the desired sectional mass pulls, and optimising the mass pull with flotation cameras by achieving a desired froth velocity profile within a flotation train. The first two have been successfully implemented and have shown to notably improve the stability of the flotation circuit about flotation concentrate setpoints provided, which has been shown to improve the copper recovery, while not sacrificing the product grade. The commissioning of the third aspect is underway, and it is expected that this will further improve the concentrator's performance.

INTRODUCTION

At the completion of its commissioning a number of years ago, the concentrator of the Lubambe Copper Mine in Zambia started what would become a long-term partnership with Mintek. This partnership entails the continuous improvement of the plant's operations, by means of advanced process control. Lubambe's concentrator consists of a milling circuit and a flotation circuit, of which the latter has been the main focus in improvements made thus far. This paper outlines the continuous improvement approach followed by Mintek to improve the performance of Lubambe's flotation circuit and reports on the benefits derived from the improvements made.

BACKGROUND

A diagram of Lubambe's flotation circuit is shown in Figure 1. Feed coming from the milling section enters the Sulphide Roughers, followed by Oxide Roughers. The Sulphide Rougher concentrate is cleaned in a column, of which the tails is treated in a Sulphide Scavenger train. The Oxide Rougher concentrate is cleaned in two trains of Cleaner and Recleaner cells. The pumps on the Roughers have variable-speed drives (VSDs), while the other pumps are fixed-speed pumps. All sumps have level measurements and are followed by flow meters.

Flotation cell tailing valves, as well as the air valves, are automated. Flotation reagents, such as frother, are added manually and are not available to automated control. There are no online grade measurements, and therefore concentrate flowrate targets are set based on sampled grade measurement feedback and metallurgical knowledge.

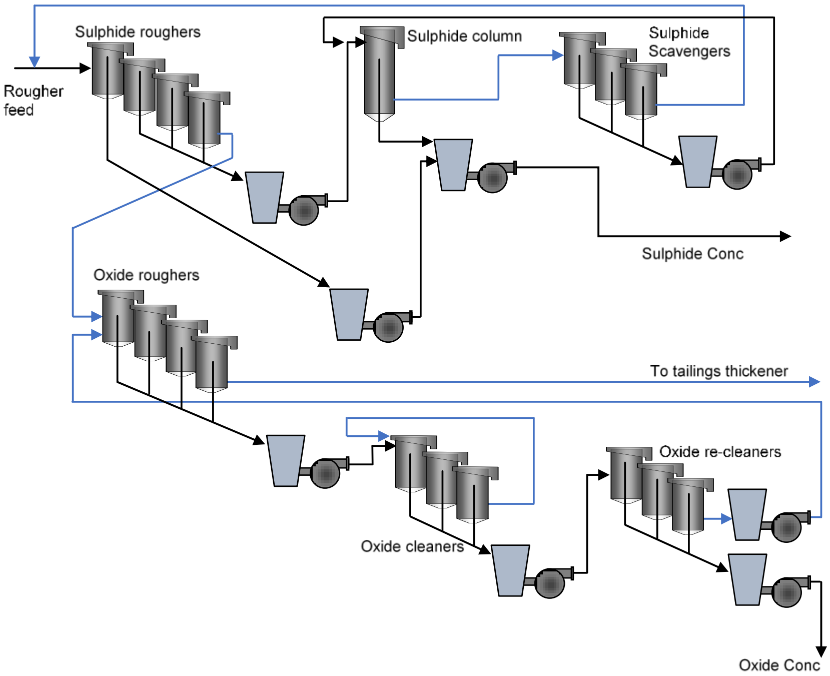

Figure 1: Diagram of Lubambe concentrator flotation circuit.

Before Mintek's involvement, the automated control on the flotation circuit was limited to individual cell level control on all cells using the corresponding tailing valves, and Rougher sump level control using the VSD pumps. This control was done by proportional–integral–differential (PID) controllers in the plant's programmable logic controller (PLC).

The milling circuit is still controlled by PLC-based PID controllers.

APPROACH

The implementation of process control improvements, as with other plant improvements, can be approached in a number of ways. An approach generally followed is the *once-off project* model, where a single project is undertaken to take a plant/operation from its current state to a new, improved state. The main advantage of this approach is that a single, large technological leap is typically made, quickly and significantly improving the process, with minimal contact time between the plant personnel and technology providing consultant.

The once-off project approach does, however, have a number of disadvantages that are rarely considered:

- The limited engagement between plant personnel and the consultant, which is often confined to one or two visits, impacts the process improvement in two ways. Firstly, the consultant generally bases their recommended solution on a short-term analysis and diagnosis, rather than longer-term engagement with the plant. This often means that the implemented solution is limited by some of the consultant's preconceived ideas.
- Secondly, and more importantly, limited plant–consultant contact time – especially in the case of a project entailing a significant technological change – often leaves plant personnel in the dark concerning the exact workings of the implemented technology. This results in the new

solution being perceived as a *black box*, with plant personnel disengaging from it and therefore being disempowered by it, to a certain degree.

- The large technological leap typically brought about by such a once-off project is based on the knowledge that the relevant parties (if not only the consultant) has at the time of implementation. It is very improbable that this approach maximises the technological value-add. Put differently, it is likely that, if the large technology change were to be replaced by a series of smaller, consecutive technology changes that each seeks to maximise the key performance indicator (KPI) impact of capital spent, the path of these smaller changes would deviate from that of the single, large change and add more impact overall.

Owing to these factors, the once-off project model is often not the optimal approach. This was true in this case, especially because the Lubambe Copper Mine had investment uncertainties at this time and had to ensure that all capital invested in the plant technology added maximal value.

For this reason, an alternative approach was followed, more in line with continuous improvement practices. According to Ras and Visser's *Hexagonal Improvement Model (HIM)*, developed for minerals beneficiation plants, the first step is to identify the process KPIs (Ras & Visser, 2015). In the case of the copper concentrator as a whole, metallurgically this would be the product grade and recovery (with operational and other costs minimised). It should be noted that the throughput rate is not a KPI at this plant, because the ore supply rate from the mine is currently the limiting factor. The current point of potential improvement with the biggest impact on the identified KPIs needed to be determined by measurement and analysis.

With inputs both from Mintek and from experienced plant personnel, the flotation circuit was identified as the area with most scope for improvement in the light of the process KPIs. This is due to the fact that significant process variation was seen in the flotation circuit (more so than in the milling section), which is detrimental to the copper grades and recoveries. It was therefore decided to focus process control improvement efforts on flotation. The HIM states the next step is to optimise and improve the identified point by adding as little complexity as is possible. Because the levels of the cells in the flotation trains were the variables where most of the process variation was introduced, it was decided to first stabilise the cell levels. This was done with Mintek's FloatStar Level Stabiliser. The results are discussed in the next section.

After an improvement is made, the next point for most significant improvement needs to be identified. Because Lubambe's concentrator does not have online grade measurements, the flotation circuit is controlled to flotation concentrate flow setpoints as an indirect means of targeting the correct grades and recoveries. Analysis of the plant performance showed that there was significant variation on these concentrate flowrates, which meant that the copper grade and recovery would be compromised (Wills & Napier-Munn, 2006). As such, the second step taken was to stabilise and control the concentrate flowrates with Mintek's FloatStar Flow Optimiser. This controller layers on top of the Level Stabiliser, with the Flow Optimiser providing the Level Stabiliser with the cell level setpoints to which to control.

Hereafter, it was decided that the next area for best value-add was the individual flotation cell froth velocity control, because a whole train having the correct mass pull does not mean that the individual cells are pulling at a rate or in a relative profile conducive to optimising copper grade and recovery. Hence, in order to pursue the desired froth velocity profiles in the different flotation trains and thereby optically optimise their mass pulls, it was decided to install and commission Mintek's FloCam froth cameras. The resulting velocity measurements would then be incorporated into the FloatStar Flow Optimiser. This work is currently being performed.

It is expected that this process of continuous improvement will continue, with changes made incrementally at the points of maximum impact on the process KPIs. For example, Lubambe's acquisition of online grade measurements would allow for the direct control of copper grade and recovery. Alternatively, the focus could move to improving the copper liberation by means of optimising milling performance. That would, however, be subject to subsequent analyses of the process performance.

RESULTS AND DISCUSSION

This section outlines the performance changes associated with the two process control improvements made: the commissioning of the FloatStar Level Stabiliser and the FloatStar Flow Optimiser. The FloCams' commissioning project is currently underway and results are not yet available.

Flotation Level Stabilisation

The FloatStar Level Stabiliser is a specialised feedback–feedforward controller that compensates for and prevents disturbance propagation through a train of connected flotation cells. It was commissioned on the whole flotation circuit, amounting to 18 cells in total (with the column included as a "cell").

As a means of quantifying the improvement, the integral of the absolute value of the errors (IAE) was calculated for each cell. This was done with the following equation:

$$IAE_{cell} = \frac{\sum_{i=k-m}^{k} |SV_i - PV_i| \times \Delta t_i}{\sum_{i=k-m}^{k} \Delta t_i}, \qquad [1]$$

where k is the current loop counter, m is the window period, SV is the setpoint value, PV is the process variable and t is time.

The IAE for every cell was calculated over a moving window of 1 h, with the average of these IAEs giving the total IAE value for the cell. The 95th percentile of the IAEs, used in this paper, is the value under which 95% of the window IAEs fall. This was used because it prevents outlier process events from skewing the analysis.

Figure 2 shows these 95th percentile IAE values for the flotation section, both while under the plant's PLC-based PID control and while controlled by the FloatStar Level Stabiliser. A continuous dataset of 15 h has been used in each case. This was limited by the amount of good data logged for the case where FloatStar was off. The matching 15 h of "FloatStar on" data were logged right after commissioning of the Level Stabiliser was completed.

Table I summarises the average percentage by which FloatStar improved the level control performance on every flotation section.

Table I: Average sectional cell level IAE improvements.

Section	Average improvement* (%)
Sulphide Roughers	58.7
Sulphide Column	24.4
Sulphide Scavengers	64.1
Oxide Roughers	62.4
Oxide Cleaners	59.7
Oxide Recleaners	61.4

* Based on the 95th percentile IAEs shown in Figure 2

It can be seen that the level stability across the flotation circuit was improved significantly, with IAEs more than halved for all cells but the column. This has brought about a significant decrease in process variation. As a more visual way of displaying this, a histogram of the errors between the actual levels and their setpoints is provided in Figure 3 for the Sulphide Roughers. It can be seen how the errors centre more on the zero point (making a sharper peak) when under FloatStar control than when under the plant PLC's PID control. This means that the level is more frequently at setpoint while under FloatStar level control.

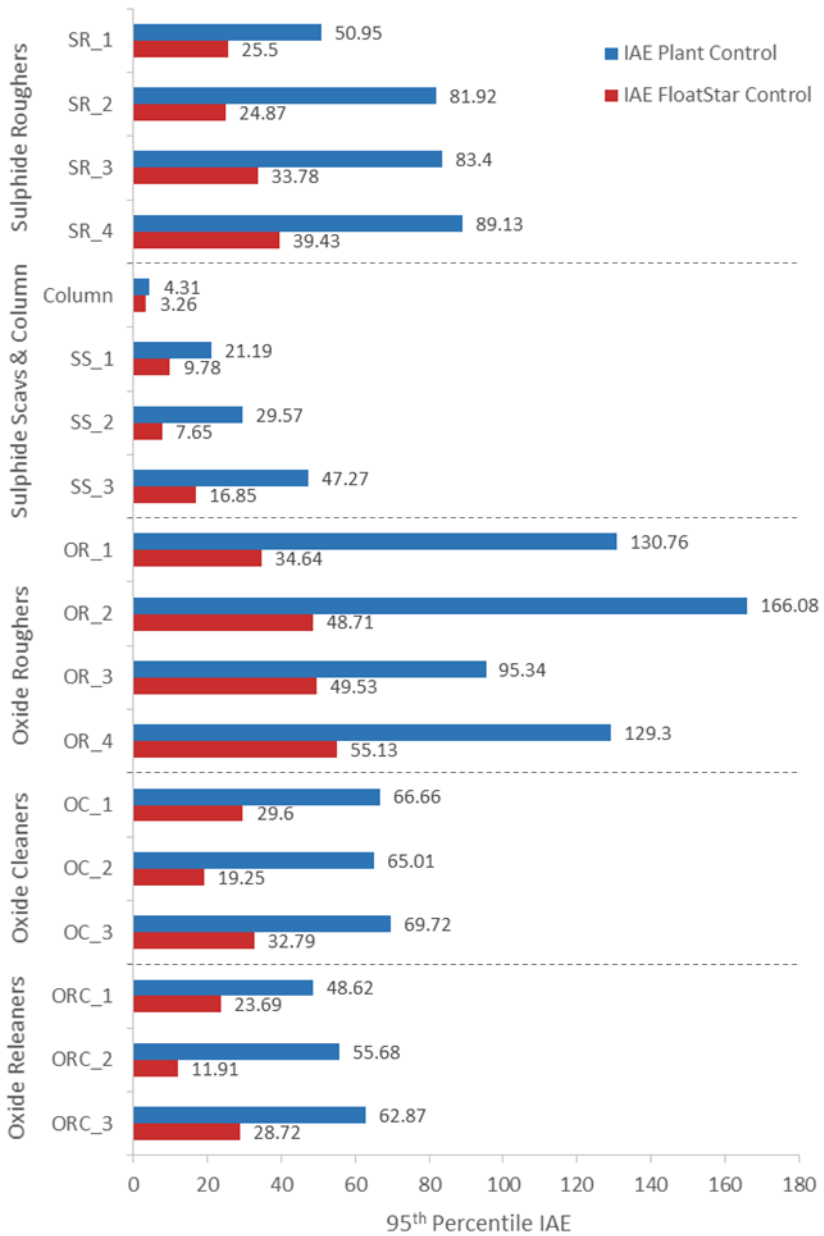

Figure 2: 95th Percentile IAE values resulting from 15 h each of plant and FloatStar control.

The implementation of the FloatStar Level Stabiliser therefore brought about the improvement intended – decreasing the process variation in the flotation cells by stabilising the cell levels. Additionally, a utilisation rate of above 99% over the past year demonstrates that the system has been successfully adopted and that the plant personnel are comfortable with the FloatStar Level Stabiliser.

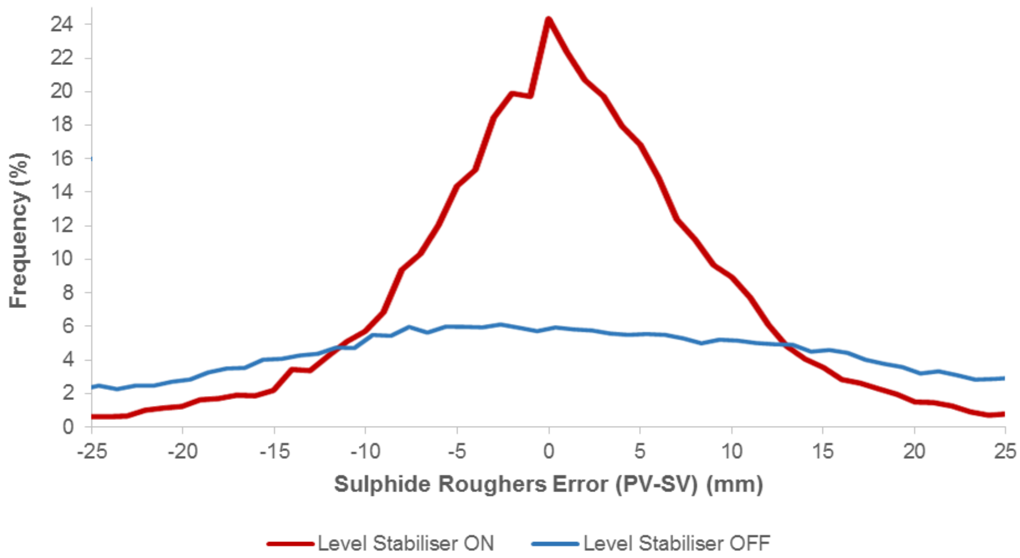

Figure 3: Histogram of the Sulphide Roughers actual level error.

Flotation Flow Optimisation

The FloatStar Flow Optimiser is an advanced controller specifically designed to control the flowrate of the concentrate coming from a train of flotation cells/banks to a setpoint provided by Lubambe. It does so by changing the manipulated variables available, such as cell level and air setpoints, in the correct ratio such that both the overall flowrate setpoint and the desired relative mass pull profiles are achieved. In the case where a VSD pump is available, the pump speed is also changed by the controller.

The FloatStar Flow Optimiser was commissioned at the copper concentrator in two phases. During Phase One, the Flow Optimiser was installed on two Sulphide Rougher sections (high grade and low grade) and on the Oxide Rougher section, as seen in Figure 4. These are the flowrates that needed to be controlled more tightly. The corresponding sumps have VSD pumps fitted to them. Phase Ttwo of the FloatStar Flow Optimiser commissioning entails the control of the Sulphide Scavengers, the Oxide Cleaners and Oxide Recleaners sections. Phase One has been completed, with the completion of Phase Two delayed by required plant instrumentation upgrades. Hence, only the performance of Phase One is reported.

Owing to the fact that plant operators have control of the minimum and maximum values of the individual cell level and air values, it is possible that the concentrate flow rate setpoint provided for a certain section might not be achievable given the limits provided, even with FloatStar working perfectly. Becausee this does in fact happen, a histogram best shows the variation decrease brought about by the control improvement.

Figure 5 shows a histogram of the deviation from setpoint for the High Grade Rougher sump (in m^3/h), both for the case where FloatStar is off and on. Three days' consecutive data have been used in each case. It can be seen that this Rougher cell is generally limited and in both cases it could not reach its setpoint. In spite of this operational limitation, it can be seen that the FloatStar Flow Optimiser successfully decreased the variation of the concentrate flowrate. This is most clearly indicated by the peak at an error of -15 m^3/h for when the Flow Optimiser was on, compared with a wider spread of flowrates when it was off. This means that FloatStar stabilised the concentrate flowrate at a consistently attainable value nearest to the setpoint provided. This is shown for a shorter time period as time-series data in Figure 6.

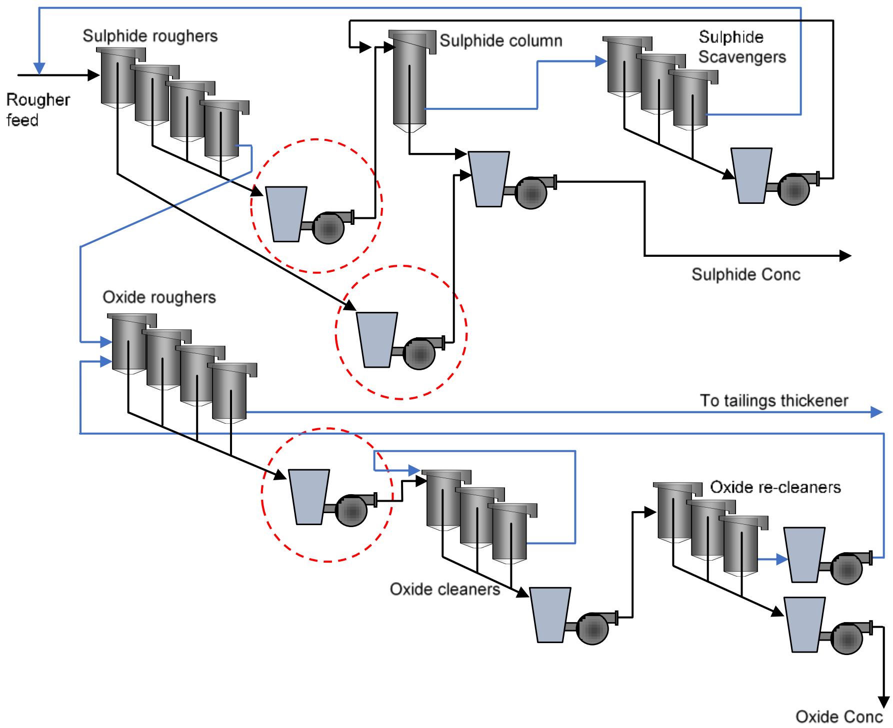

Figure 4: Diagram showing loops commissioned during phase 1 of the FloatStar Flow Optimiser commissioning.

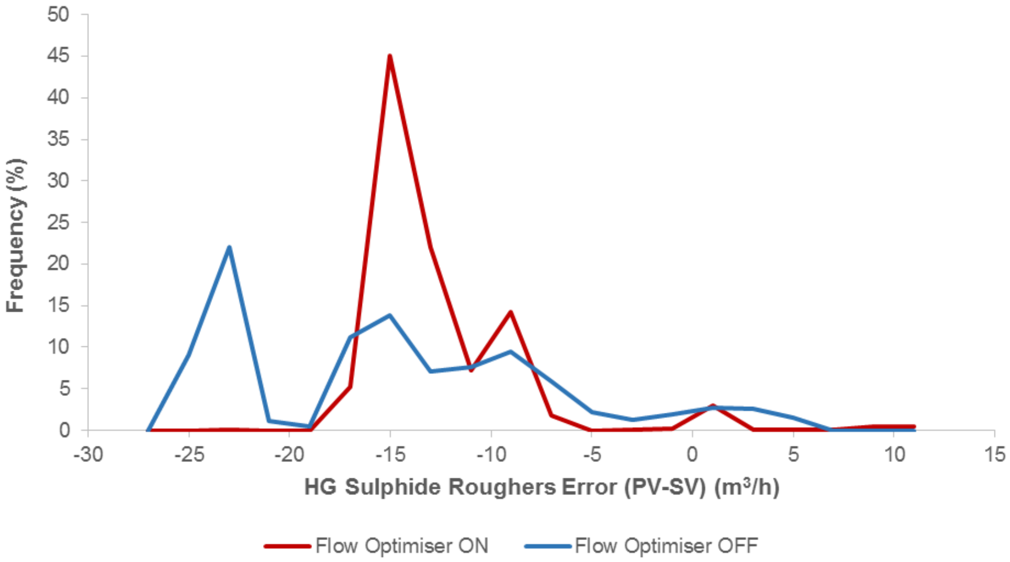

Figure 5: Histogram of the High Grade Sulphide Roughers concentrate flow rate error, with 3 days' data used.

In the case of the Low Grade Sulphide and Oxide Roughers, the control is not limited and it was possible for the concentrate flowrates of these sections to reach their respective setpoints. This can be seen from Figure 7 and 8, where five days' data were used in each case. In the case of the Low Grade Sulphide Roughers, it can be seen that the introduction of the FloatStar Flow Optimiser changed performance from a wide dispersion of flowrates to a narrow variation about the setpoint (zero error). On the Oxide Roughers, it can be seen that, in a similar way, the setpoint was attained in a much more stable manner.

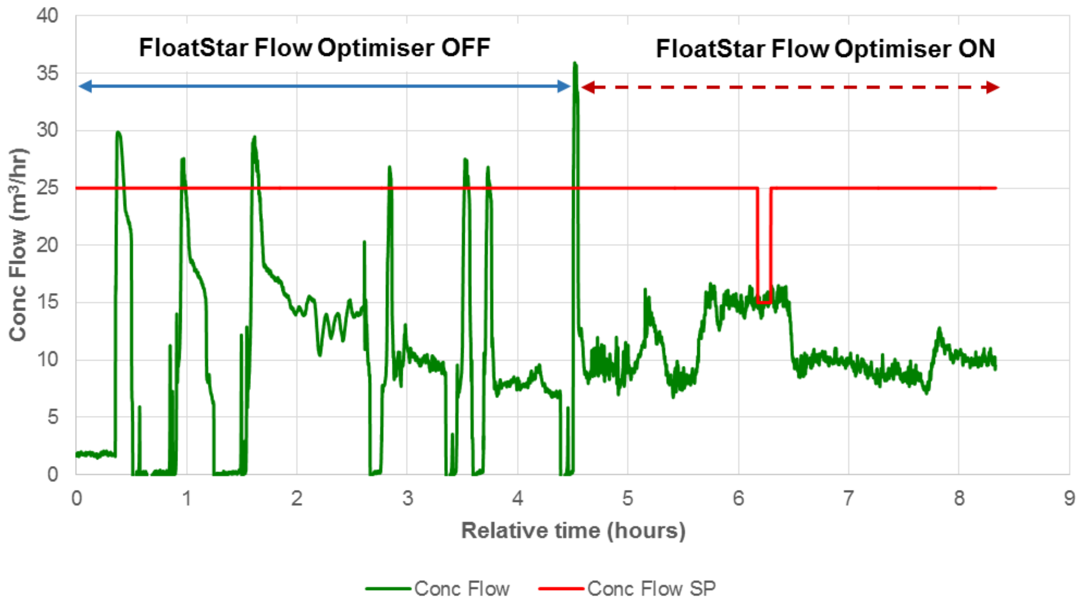

Figure 6: High Grade Sulphide Rougher concentrate flow rate data.

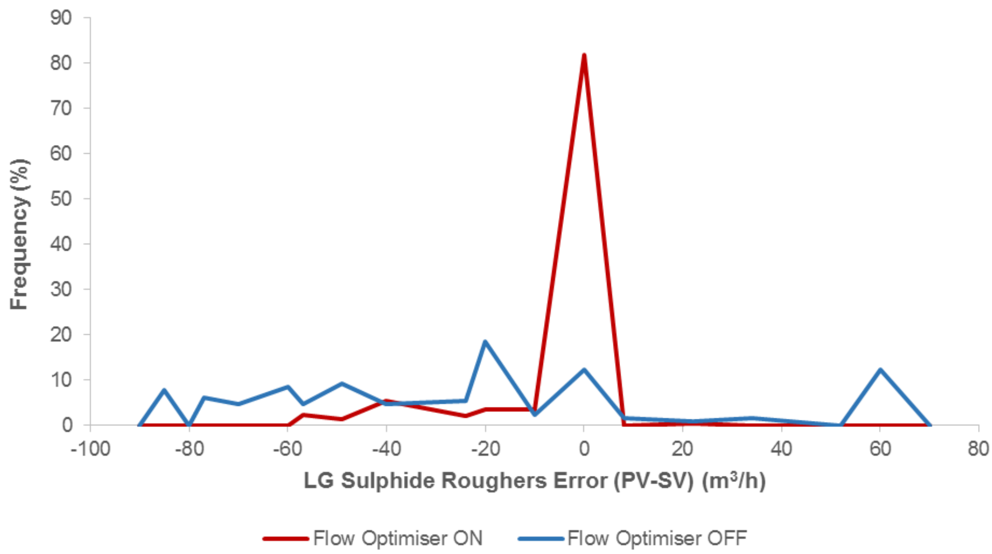

Figure 7: Histogram of the Low Grade Sulphide Roughers concentrate flow rate error with 5 days' data used.

To verify that the FloatStar Flow Optimiser's Phase 1 improvements do indeed have the desired impact on the plant's KPIs (chief of which was identified as the copper grade and recovery), a grade-recovery curve was plotted for the flotation circuit as a whole. This can be seen in Figure 9. Data is plotted for the 5 months right before commissioning of the Flow Optimiser (FSFO) took place, and 4 months following the acceptance of the system.

Throughout this period, the percentage of copper in the feed that is acid soluble steadily increased, impacting the product recovery (Kalichini, 2015). Hence, the recovery data in Figure 9 was adjusted for this faction change – assuming a constant fraction for the sake of comparison.

It can be seen how the FloatStar Flow Optimiser's performance improvements in phase 1 alone translate into a notable recovery improvement (of more than 1 %, mean to mean), while the total copper grade is maintained within in a similar band. Note that comparable data prior to the installation of the FloatStar Level Stabiliser could not be obtained, and this 1 % improvement is over and above the benefit provided by the Level Stabiliser.

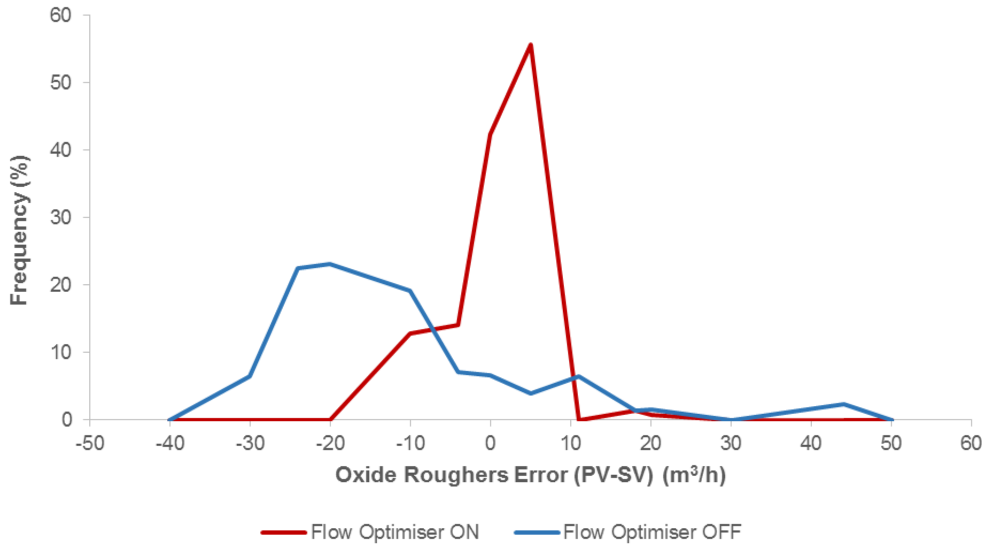

Figure 8: Histogram of the Oxide Roughers concentrate flow rate error with 5 days' data used.

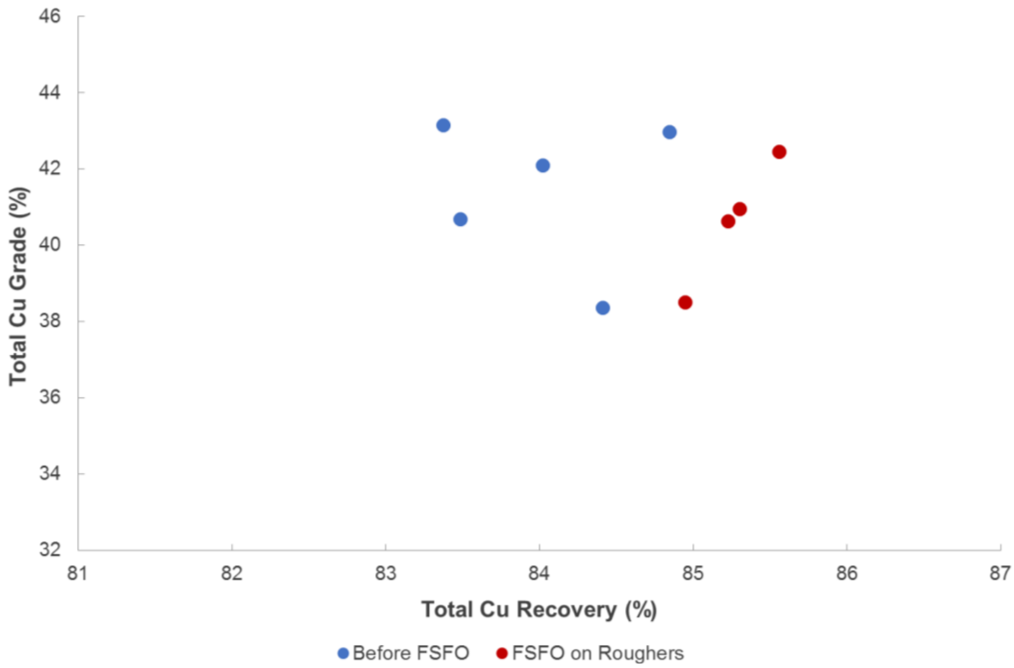

Figure 9: Copper Grade–Recovery curve for Lubambe's flotation circuit.

This shows that the FloatStar Flow Optimiser commissioning is bringing about the intended performance improvement: ensuring that the Roughers produce flotation concentrate at a stable rate, as close to the desired value as is allowed by the process limits set. This is translating into an improvement of the section's copper recovery at a similar product grade. It is expected that a performance evaluation of the second phase's implementation will show similar improvements. The utilisation rate in the last year of more than 97% on the Roughers shows that the Flow Optimiser has been successfully adopted and is being used with confidence by Lubambe's personnel.

Approach Benefits

Utilisation rates of more than 99% and 97% for the FloatStar Level Stabiliser and the FloatStar Flow Optimiser, respectively, highlight the benefit of implementing technology upgrades in such a way that every part of the process improvement is done in partnership with Lubambe's personnel and that proper technology uptake is facilitated (Li *et al*., 2011). The continuous improvement approach followed has been and is assisting with this, maximising the impact of the changes made and the plant's capital spent. Additionally, the ongoing partnership between Mintek and the Lubambe Copper Mine means that Mintek checks in with the concentrator at least monthly, providing remote support when not on site. In this way, Lubambe is regularly assisted with training and controller fine-tuning, and a discussion on challenges and potential improvements is continued.

CONCLUSIONS

A continuous improvement approach is being followed to improve the Lubambe concentrator's control performance. This ensures that every technology improvement made, and related capital spent by the plant, has maximal impact on the plant's KPIs, of which the copper product grade and recovery are metallurgically the most important. Additionally, it ensures that the plant personnel are part of guiding the improvement process and are empowered by the technology changes implemented.

The FloatStar Level Stabiliser and FloatStar Flow Optimiser have been installed to improve the stability of the flotation circuit, so that the plant's metallurgical performance can be thereby improved. The FloatStar Level Stabiliser has significantly decreased the variation of cell levels across the whole circuit and ensured smaller deviations from their setpoints, generally decreasing the 95th percentile IAEs by more than 50%. The FloatStar Flow Optimiser, as a layer on top of the Level Stabiliser, has also significantly reduced the concentrate flowrate variation on the Roughers, ensuring tight setpoint tracking where it is operationally achievable. This has shown to improve the flotation circuit's copper recovery performance, while the product grade remains within the same band. The sum of these FloatStar implementations has significantly improved the concentrator's flotation circuit and allowed Lubambe to more precisely pursue their grade and recovery targets. Utilisation rates of 99% and 97% for the Level Stabiliser and Flow Optimiser, respectively, demonstrate successful system adoption and highlight the benefits of the continuous improvement approach followed.

This continuous improvement will continue, with Mintek's FloCam currently being commissioned to enable the control of individual cell froth velocities. It is expected that the partnership between Mintek and the copper concentrator will ensure that the latter keeps performing better, year after year.

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