SAG Mill Stability and Control Improvements at the Nova Nickel-Copper Operation

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ABSTRACT

Strategies introduced at IGO’s Nova operation have improved stability and control in the SAG milling circuit. These strategies relate to the development of a prediction model for SAG mill media volume (ball charge), and improvements to the SAG mill charge weight (total load) controller.

Prior to these improvements, poor control over SAG media charge volume and charge weight had resulted in process instability, downtime and overall reduced throughput.

Media overcharging and lack of control was tackled by development of a power-based model and a media consumption rate model of the SAG mill. These models are used to control media addition rates on a day-to-day basis to target the desired media charge.

Control of the SAG mill charge weight was improved by incorporating modelled disturbance inputs into the existing PID loop. The disturbances included were derived from an online mill feed particle size distribution measurement and a proxy for ore density/hardness, both of which were determined to be significant predictors of future mill weight changes. The issue of reducing mill weight resulting from liner wear over the reline cycle, rather than changes in actual charge weight, has also been compensated for using an adjustment to the mill weight setpoint based on measured liner consumption rates.

Following the introduction of these improvements, the issues resulting from overcharging and unstable weight control have greatly diminished resulting in improved overall throughput, reduced average SAG specific energy (kWh/t) and greater downstream stability within the flotation circuit. These models and controllers require occasional re-calibration but have proved robust over time.

INTRODUCTION

The Nova deposit was discovered in July 2012, with development of the current operation commencing in January 2015. Following a successful construction and commissioning phase, the operation commenced commercial production in July 2017, and reached its nameplate production rate in the December 2017 quarter.

The site has encouraged continuous improvement and although the plant was commissioned with the latest available technology, personnel continually strive for system and process improvements. This paper discusses a continuous improvement program centred around the operation and control of the SAG mill. A systematic approach was taken to clearly identify the problems and incrementally resolve these to increase efficiency, improve stability and reduce wear. The results of each of the incremental changes were evaluated to determine the effectiveness of the solution. This systematic approach aided in identifying changes that were of little to no benefit or changes that added complexity rather than improving the system.

The implemented systems are designed to accommodate for failures and compensation of various inaccuracies in components that may occur during live control. This allowed large changes to operating philosophy to be made without negatively impacting production on the site.

NOVA GRINDING CIRCUIT OVERVIEW

To contextualise the improvements implemented to the SAG mill operation and control, a brief overview of the comminution circuit is provided.

Run of Mine Feed Characteristics

The following description of the plant setup has been extracted from the paper written by Gomes-Sebastiao, et al, 2018. Nova-Bollinger (Nova) is a typical magmatic segregation deposit containing an assemblage of nickel, copper and iron-bearing sulfides (predominantly pentlandite, chalcopyrite and pyrrhotite respectively), with pyrrhotite being the dominant sulfide gangue mineral. A degree of variability exists within the Nova ore deposit, with six ore types classified in the PFS (prefeasibility study) according to lithology and mineralogical composition. Variation in ore supply from the mine necessitates good ROM (run-of-mine) stockpile management to minimise the variation in metallurgical responses stemming from variations in the relative abundance of ore types fed to the plant. Ore blending at Nova is based on a target nickel feed grade through the blending of ROM stockpiles that are classified according to grade.

Comminution Circuit Design

The Nova comminution circuit has a conventional primary crush followed by SAB flow sheet design, with key components described in Table 1.

Table 1 – Comminution circuit components

Circuit	Equipment	Flow path
Primary crushing	C120 Metso jaw crusher	Discharge to surge bin & mill feed
Primary milling (open circuit)	6.1 m ⌀ x 3.55 m Outotec SAG mill (variable speed drive)	Discharge to cyclone feed hopper
Secondary milling & classification (closed circuit)	4.7 m ⌀ x 6.25 m Metso ball mill (variable speed drive) 8x 400CVX cyclones	Discharge to cyclone feed hopper Overflow to flotation feed

The comminution circuit produces flotation feed to sequential copper and nickel flotation circuits via single stage crushing and a two-stage milling circuit (semi-autogenous grinding mill and ball mill). The flotation feed target is 80% passing 106 to 125 µm depending on liberation requirements to achieve optimum flotation performance. The comminution circuit was designed with the intent to provide the flotation circuit with a stable feed.

The discussion on the flotation circuits is beyond the scope of this paper, but for clarity the copper flotation circuit consists of rougher, scavenger, cleaner and cleaner scavenger circuits. The same is true for the nickel circuit consisting of rougher, scavenger, cleaner and cleaner scavenger circuits. With the nickel flotation circuit having higher capacity than the copper circuit.

INTEGRATED ADVANCED CONTROL SYSTEMS

Process automation at Nova was addressed early in the prefeasibility study (PFS) and included the adoption of advanced process control (APC) platforms and an extensive network of measurement devices. The APC platform interfaces with the underlying programmable-logic-controller (PLC) systems and is capable of adjusting controller set points and/or outputs depending on the operating mode selected by the user. The APC system is typically used for making higher level control decisions but also has an extensive range of tools that can be used for more advanced stabilisation strategies. Having an APC platform on site allowed the fast adaptation and trial of new strategies on the SAG mill.

SAG Mill Control Problems

Having operated the SAG mill for several years, various areas for improvement were identified from historical data. Firstly, the torque on the SAG mill motor ran close to its limits. The SAG mill motor is controlled by a Siemens Harmony drive, this drive has built in protection that will slow the motor down when the torque limit is exceeded. These events would cause subsequent losses in throughput and instability in the flotation circuit affecting recovery with manual intervention from the control room operator required to reduce load in the SAG mill by reducing or stopping mill feed.

Review of the design criteria for the mill demonstrated that the SAG mill should not operate this close to its torque limits. Analysis of the drivers that cause high torque events were reviewed and it was determined that having tighter management of the mill media charge would greatly assist in reducing the number of high torque events.

Reviewing historical data on SAG mill weight control demonstrated that there were multiple periods of high variability. This often-required manual intervention from the operating crew to stabilise the mill. The feed to the mill had previously been stabilised using a model predictive controller for the mill feeders. This strategy worked well, and it can be shown that the mill feed was stable and not the cause of the instability in the mill. The variability in the mill weight must therefore be related to variation in feed characteristics of the ore. In order to increase the mill stability and provide an automated solution it was determined that online measurement of feed particle size prior to the SAG mill was necessary. Additional instrumentation was sourced and implemented provide measurements for this purpose and are discussed in this paper.

Media charge control

The metallurgical team performed extensive work to monitor, predict and optimise the volume of grinding media in the SAG mill, motivated by past issues with low throughput, high torque faults (on the mill’s variable speed drive) and shell liner failures caused by overcharging the mill. Prior to this work, the solution to low SAG throughput had usually been to increase media addition with little regard for the volume of media within the mill.

Following a complete reline of the SAG mill, the team measured the media volume in the mill using the cord method on a fully ground out mill, and subsequently measured the total charge (media plus rocks) following a crash-stop of the mill. These measurements, along with the mill dimensions, operating speed, and power, were used to calibrate a power model of the mill, as described by Napier-Munn et al (1996).

Over several weeks of operation, the team recorded the media addition and ore throughput, and then re-measured the media charge following a full grind out to produce a calculation of steel media consumption on a g steel/t ore treated basis. This consumption rate formed the basis of a 'live' media charge estimate that enabled the metallurgy team to vary the media addition rate and target a desired ball charge volume with a reasonable degree of accuracy. Relevant data for this live calculation was logged and queried using the OSIsoft PI historian.

The model is periodically re-assessed, and small adjustments made based on crash stop measurements (using the power model to estimate rock and filling) or following a complete grind out and accurately measuring media filling (usually following a mill reline).

The team also noted that a fixed volume of media takes up a different volume % within the mill over the life of the mill shell liners, due to the increasing internal diameter of the mill. This factor was measured based on new and worn liners and ore throughput across a whole reline cycle. It has been included in the live media volume prediction model, ensuring that the estimate is more accurate across the reline cycle. The implementation and upkeep of this method has resulted in stable operation, and the ability to control and optimise the media charge as desired. Since its introduction, there have been no further issues with VSD torque protection faults or failure of internal liners.

SAG mill circuit controllers

The changes to the control of the SAG mill feed and weight controller took place in conjunction to the work that was completed to control the volume of media in the SAG mill. The two sets of work complemented each other to promote stability in the SAG mill.

The control is divided into several sections, namely, the feed to the SAG mill, the control of the SAG speed, the water addition to the SAG mill feed and the control of the ball mill discharge circuit.

Control of mill feed rate

In the APC setup the main control loops for the feed to the SAG mill are model predictive controllers which contain first order models for each of the apron feeders. Using a simple step test on the apron feeder speed and monitoring the weightometer readings, the following first order models were derived.

The model used for the primary feeder is:

$$\frac{6.5\, e^{-32s}}{75s + 1}$$

The model used for the e-feed (emergency stockpile feeder) is:

$$\frac{3.4\, e^{-15s}}{45s + 1}$$

When a feeder starts up, there is a 300 second delay where the speed of the apron feeder will be held at a constant value. This allows the dynamics of the modelled feed rate to come in line with the actual feed rate on the belt. Therefore, for the first five minutes after a feeder is started the control will hold a constant value. The start-up speed is established using an experimentally derived offset value and the gain derived from the controller model.

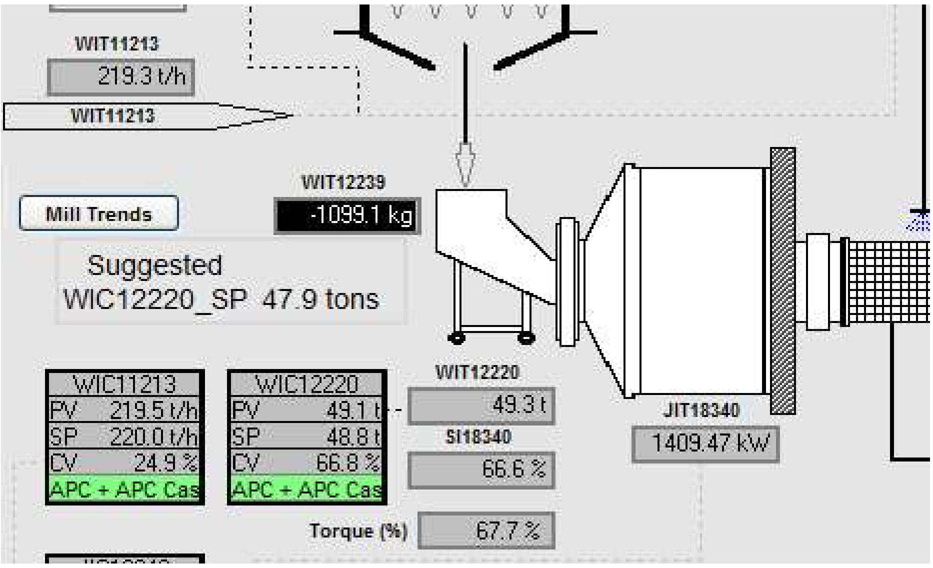
The APC controllers are setup to monitor the state of the apron feeders, so that the operator does not need to switch to manual control when changing between the primary feeder and the e-feeder. The feed rate controller in the APC system has been setup to accept a maximum feed rate setpoint of 240 t/h. When both feeders are off and the controller is in APC mode, the output of the control block will be 0% (apron feeders are still in motion in the field). When a single apron feeder starts up and the other is not running, the output of the controller will immediately jump to an appropriate value.

The SAG mill at Nova runs as a mill with a fixed feed rate and variable speed. The feed rate to the mill should therefore be constant for normal operation and specified by the operator. When the controller is in APC mode it runs the feed rate setpoint at a constant value, however this mode contains a safety controller which will reduce the feed rate to the mill when the mill weight setpoint is 3 t (2.5 t when on e-feed) above the specified weight setpoint. This is a protection for the mill to prevent it from being overloaded.

This safety controller utilises a PID style limit controller for setpoint adjustment, this means that the further over the mill weight setpoint the SAG mill is the more the feed is reduced. Additionally, the longer the mill weight setpoint is over the limit, the more the feed rate will reduce as well. Once the mill weight begins to reduce, then the feed rate will gradually increase back to the operator specified setpoint. The rate at which the controller reacts can therefore be tuned and has been helpful in adjusting the system response where feed has been reducing unnecessarily. This safety controller will only reduce the feed rate setpoint down to 140 t/h. If the mill is still overloading at 140 t/h (which is highly unlikely), then there is something wrong with the equipment and the operator must take action to prevent further damage to the plant's infrastructure.

Operator usage of SAG feed control

The SAG feed controller interface is both on the crushing and grinding page of the SCADA (supervisory control and data acquisition). The feed controller is labelled WIC11213 (weight indication controller in area 112, control loop number 13) and shown in Figure .



WIT11213 219.3 t/h

WIT11213

WIT12239 -1099.1 kg

Suggested
WIC12220_SP 47.9 tons

WIC11213
PV 219.5 t/h
SP 220.0 t/h
CV 24.9 %
APC + APC Cas

WIC12220
PV 49.1 t
SP 48.8 t
CV 66.8 %
APC + APC Cas

WIT12220 49.3 t

SI18340 66.6 %

Torque (%) 67.7 %

JIT18340 1409.47 kW

Figure 1 - WIC11213 interface on SCADA grinding page

Rock size analyser

By observing the process from the control room, it was noted that a visual change can be seen in the ore before a fluctuation in the mill weight occurred. There is a CCTV (closed-circuit television) system used on site that allows the control room operator to monitor certain parts of the plant and in particular the feed that is on the conveyor to the SAG mill. The visual difference on the ore can be described as a change in the amount of fine material that is present. An increase in fine material would indicate to the operator that the mill weight was likely to decrease, with the converse being true as well. It can be clearly seen in Figure 2 that there is a difference in the percentage of fines, this is what the operators were able to remark on.

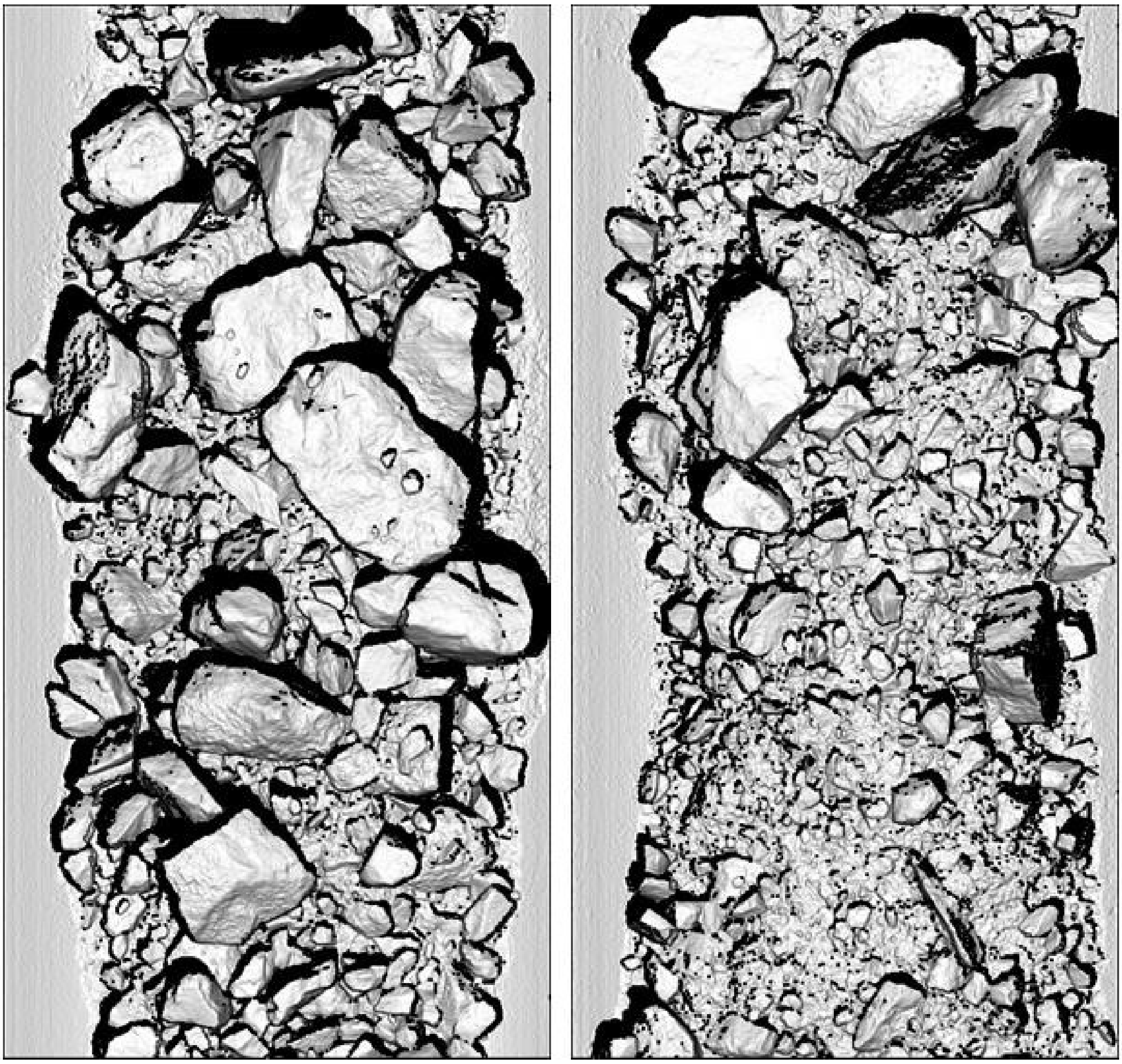


Figure 2 – Coarse material on left, fine material on right (images from IGO Nova site)

Given that the reaction of mill weight vs the visual inspection of rock size distribution showed a strong correlation the decision was made to automate the process to obtain better control of the mill and reduce the operator input required. For this reason, several vendors were engaged for information on trialling an online rock size distribution instrument. The following factors were considered when selecting an instrument:

- Ease of installation
- Technical support
- On-going costs and maintenance required
- Technology used

It was found that the majority of instruments that were available in the market at the time (2017/18) utilised 2D images. Few offered systems that obtained a 3D scan of the material on the belt. Having called several sites it was found that the 2D systems were considered to be “mostly accurate”, but the image processing was not readily able to distinguish fines that were lumped together from larger rocks. From research and white papers released, 3D scans used for size distribution showed the potential to more accurately identify lumped fines and measure smaller rock sizes to obtain more accurate size distributions.

For the reasons previously mentioned a decision was taken to contact Optimation (formerly MBV Systems) and Innovative Machine Vision, who developed the 3DPM system. As there were no reference sites available in Australia at the time, it was not possible to obtain reviews and references within Australia. A paper was however presented at a technical conference on the use of the system at Boliden Mines in Sweden, Thurley, et al (2018). For this reason, it was requested that the instrument be trialled for a 3-month period before purchase. Remote commissioning of the instrument was also arranged with Optimation to reduce the risk and cost associated with a trial.

Having the rock size distribution enables one to see how the ore broke up when passing through the crushing circuit, softer material produces more fines and harder materials produce less fines. Having this live data allows one to derive some conclusion on how easily the ore would break up in the mill. The raw data shown in Figure 3 shows the variations in mill weight vs rock size distribution before the control strategies were implemented:

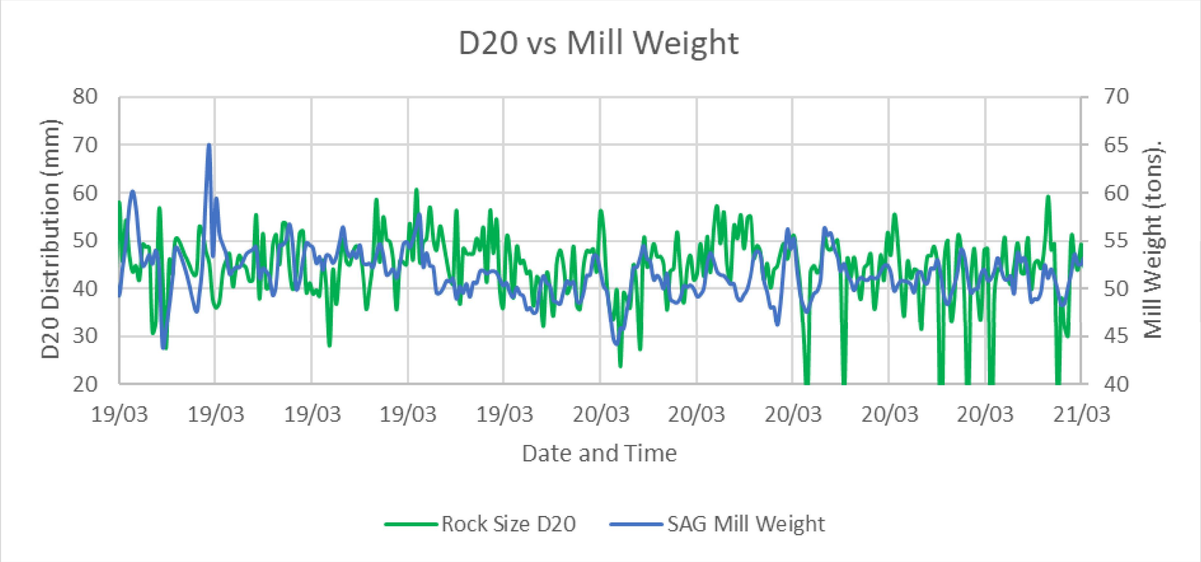


Figure 3 - Rock size distribution D20 vs mill weight

The correlation between the mill weight and the D20 for Figure 3 is 0.1611. However, the rock size analyser is located just after the weightometer on the feed belt, which is a substantial distance from the SAG mill. The feed conveyor to the mill runs at a fixed speed, with the amount of material being delivered onto the belt being variable. For this reason, the time that material takes to travel from the rock size analyser to the SAG mill was assumed to be constant. This time delay was measured several times and repeatedly shown to be 110 seconds.

By time delay compensating the data (software time compensation) shown in Figure 3, the data correlation increases to 0.2436. For the data period specified it is known that the SAG mill speed is not running at a fixed speed during this time, but rather adjusting speed to compensate for weight fluctuations. This would then dampen the correlation between the data sets, for this reason the correlation of 0.2436 was taken to be a strong enough correlation to attempt to utilise the D20 in the SAG mill speed controller.

The instrument installation was completed above the conveyor that feeds the SAG mill and located approximately 2 metres after the weightometer. The installation and remote commissioning were both completed with minor hardware changes made to suit the site conditions. The data also showed a strong correlation with the mill operating measurements. For these reasons it was decided to purchase the instrument after the trial had completed. The instrument has been running reliably for the last 5 years with only minor maintenance required on the computer parts (additional cooling fan in enclosure and replacement of ethernet card). The instrument is an active part of the mill control strategy on an on-going basis.

Bulk density approximation

As discussed in the previous section the SAG mill weight controller was adjusted to receive a feed forward signal from the rock size analyser, which adjusts the SAG speed based on changes in the D20 fraction (fines in the ore). To further improve stability, an additional feed forward signal was introduced using the feed rate/feeder speed ratio data.

Based on experience at a previous sulfide flotation site, it was known that a relationship may be established between the feed tph and the feeder speed as a proxy for the plant feed grade. The relationship was based on the linear relationship between the weight and volume of ore delivered by the apron feeder. With higher-grade ore having higher density, it requires a lower speed to deliver the same feed rate. This same relationship was observed at Nova, and work was conducted to approximate the density of the ore, given that ore with a higher density and require more energy for comminution. Density increases are related to sulfide content, most of which is Fe Sulfide (pyrrhotite). Sulfides are both softer (require less grinding energy input) and more dense than oxide gangue minerals. Thus higher iron (proxy for sulfide) content results in higher density and softer ore. Fe is a better indicator of this than Ni, as the ratios of Ni:Fe change with Ni head grade.

To determine the ore density without installing additional equipment, several assumptions were made to utilise the available resources. It was assumed that for a fixed speed, the apron feeder delivering material onto the feed conveyor would deliver a fixed volume of material. By dividing the throughput measured on the weightometer by the speed of the apron feeder, a proxy for density was calculated. The ratio, inverted as speed/feed rate, was used to directly adjust the mill speed in response to changes in feed grade, instead of in reaction to changes in weight.

Figure 4 illustrates the ratio and mill speed data collected at 1-minute intervals over a 1-hour period, although the data was validated over a larger period. The average ratio was calculated each minute, and the cumulative sum of differences was plotted. The results, as shown in Figure 4, showed a delay of approximately 5 minutes between the cumulative ratio falling and the mill speed falling in response to the change in weight, with a resulting change in speed of about 8% per 0.04 change in cumulative ratio.

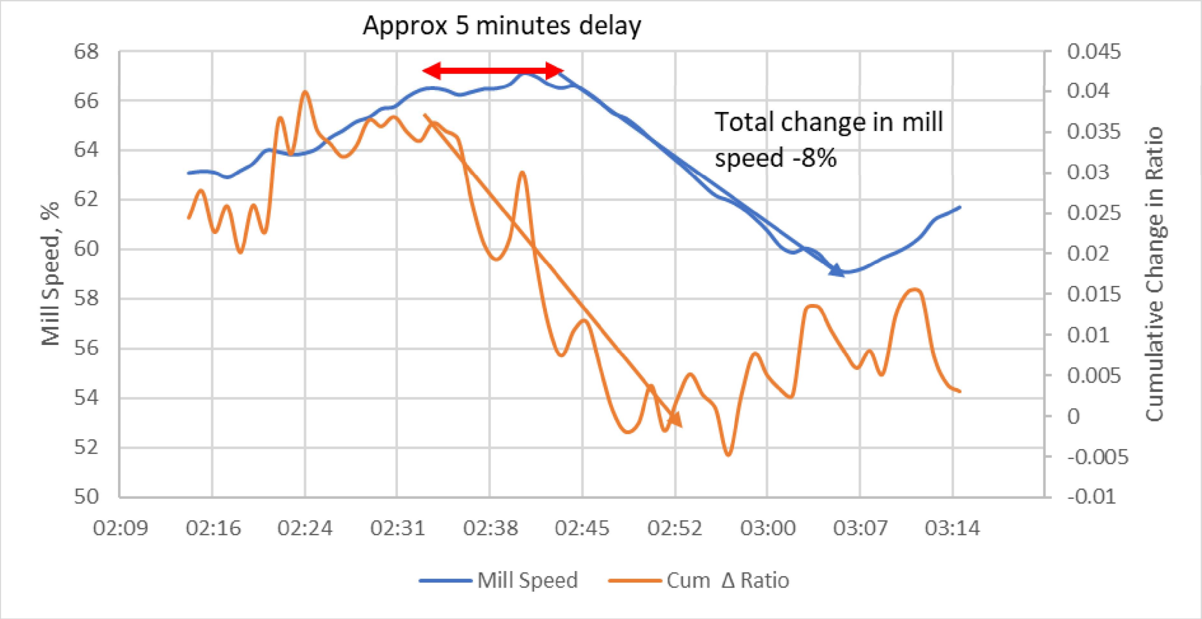


Figure 4 - Change in mill speed vs changes in the feed density proxy

SAG mill weight control

The SAG mill speed control (WIC12220) is setup as a conventional PID feedback loop. There are however two feed forward components that have been added to this loop which have greatly enhanced the control of the SAG mill as previously discussed. Because of the control actions based on the feed forward components, the PID loop has been tuned with a small gain and long integral time which makes the action from the feedback loop slow to react.

The first feed forward components are based on the quantity of fines in the feed to the SAG mill which is measured by the 3DPM rock size analyser D20 (size passing under 20% distribution). The other feed forward component is based on a proxy for the density of the feed to the mill where the volume of material delivered by the apron feeder is taken to be constant for a given speed and therefore the density of the material should be proportional to the feed rate divided by the apron feeder speed. The derivation of these components and their relation to the SAG mill was discussed in the previous sections.

Error checking and filtering is applied to the feed forward component calculations. If the measurements' fault, then the values passed to the PID loop as feed forward component will simply retain their last known good value. A measurement fault in this context means that the values have not updated for more than 60 seconds or our outside of their normal bounds. This means that the SAG mill speed will vary based only on the feedback loop for the PID controller. Since the PID controller has been tuned with both feed forward components, the PID alone will respond very sluggish and will not be able to tightly control the mill weight. There are two feed forward components, and the control can utilise these independently but having only one of the components will mean the controller tuning will be poor.

The controller has also been setup so that the mill speed will not decrease speed as rapidly as it can increase. This approach reinforces the stability of the mill, as the mill possesses a greater intrinsic capability to recover from low weight conditions in comparison to high weight conditions. This is accomplished by having a "limit controller" override the normal control whenever the mill speed is requested to decrease at a high rate of change. The limit controller is simply a PID with a slow response, the normal PID controller is prohibited from going below the limit controller.

The various parts of this controller were implemented in stages, including stages where strategies were trialled and removed. The following stages have been identified as being most significant for the controller changes:

A. Simple PID loop in PLC. No feed forward components or other interactions, only a single input, single output (SISO) system.
B. The D20 measurement from the 3DPM was incorporated into a MPC controller.
C. The MPC controller was removed and a PID loop with a single feed forward component was added that utilised the D20 from the 3DPM.
D. Compensation was added to adjust the mill weight setpoint to account for liner wear (discussed in next section)
E. The feed forward component for the ore density proxy was added to the control loop.

The functional diagram, shown in Figure 5, illustrates the final running controllers configuration for the SAG mill weight controller.

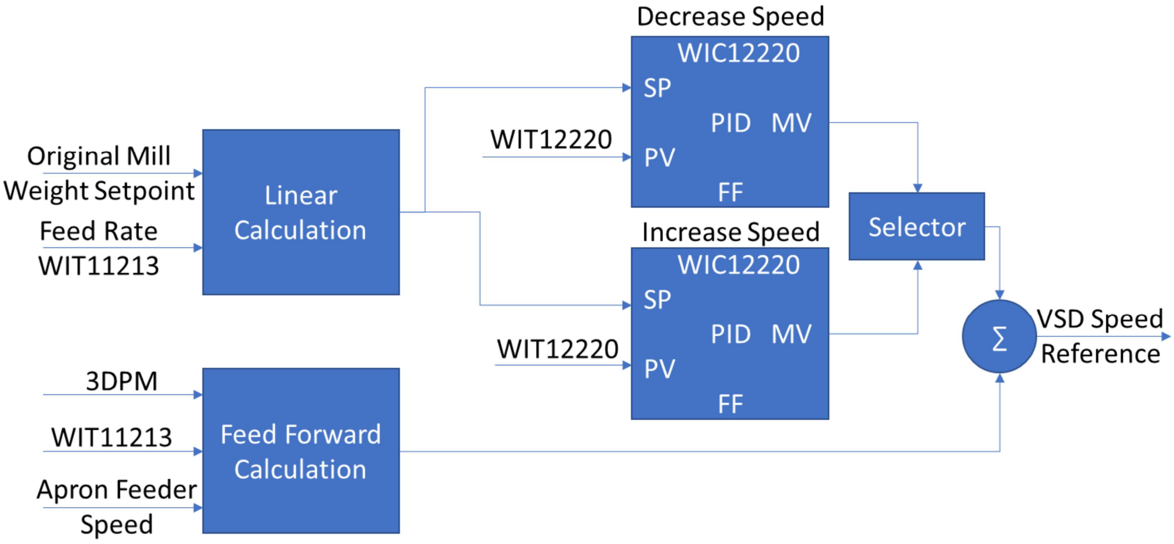


Figure 5 - Functional diagram for SAG mill speed control in APC mode

SAG mill weight setpoint

In an ideal situation the SAG mill weight setpoint is set so to maintain a constant/optimal fill volume. Since the internals of the SAG mill change over time (e.g. wearing of the liners), the SAG mill weight needs to be adjusted so that the fill volume is maintained.

To assist the processing team in setting the mill weight setpoint, a continuous calculation will reduce the mill weight setpoint as material is processed by the mill. This adjustment to the setpoint only takes place when the operator grants the APC permission to alter it. Since there may be times when this adjustment is not running an all-time monitor is kept running and displayed for use. When a re-line occurs, the metallurgical team has access to adjust the suggested mill weight setpoint.

The rate at which the setpoint is reduced has been determined by the IGO metallurgical team and is a linear formula based on historical data of production throughputs and liner wear rates. The mill weight setpoint is dropped by 31.2 kg (actual wear rates excluded from this paper) per 1000 tonnes of ore processed. The mill weight setpoint can also be manually adjusted when liners are replaced (or as determined by the metallurgical team), this is accomplished through a graphical interface setup on the process control system.

Loading grinding media

An additional feature was implemented to reduce disturbances when grinding media is added. This is because grinding medium is added in batches of 1.8 to 2.0 t, this abrupt addition of media results in a corresponding fluctuation in the mill weight. A button was added on the SCADA grinding page that was to be used by the operator when balls are going to be loaded into the SAG mill.

Pressing the aforementioned button does the following:

- Creates a record of when balls are loaded
- Reduces the mill weight setpoint (internal to the controller logic) by two tonnes for ten minutes
- Once the ten-minute time expires the mill weight setpoint would gradually be increased to its value prior to pressing the button

By reducing the mill weight setpoint the controllers will increase the mill speed (and drop feed if required) so that the mill is better able to handle the sudden surge of weight that occurs when grinding media is loaded into the mill.

This part of the controller worked well if the button is pressed 10 minutes prior to the balls being loaded. However, this is reliant on human interaction to trigger the system at the correct time. Due to inconsistencies with the use of this button, it was not included in the final control solution. The other improvements made to the control system enable it to sufficiently cope with the surge in introduced weight when grinding medium is added.

SAG mill feed water

The feed water to the SAG mill (FIC12200) can be run in several modes, the following gives a description of each:

- Auto – The setpoint is specified in the flow control block and the valve (VLV) is altered to maintain the specified flow rate.
- Ratio: The user will specify the percent solids required in the mill. The controller will then calculate the required water flow based on the amount of material being fed to the SAG mill.
- APC+APC Cas: Works the same as Ratio mode, with a few exceptions. When the feed to the SAG mill is dropped abruptly, the controller will use the feed rate setpoint for up to 20 minutes to calculate the water flow rate required rather than using the actual feed rate to the mill. This reduces disruptions if the feed to the mill is temporarily disrupted. Additionally, if the SAG torque measurement is above 77%, additional water will be added to the SAG mill in attempt to flush more material out of the mill and reduce the mill weight.

Additional pre-processing control actions

To enhance system performance, several auxiliary features have been integrated into the control system to address exceptional scenarios such as blockages or start-ups.

To maintain a stable operational environment, the system is programmed to limit the speed of both the primary and emergency apron feeders to 55% of their maximum capacity if the belt feed rate falls below 60 t/h for more than five seconds. This limitation helps to prevent excessive winding of the apron feeders during instances of material underloading or non-passage through the weightometer. Additionally, upon the re-establishment of material feed on the belt, the maximum apron feeder speeds are restricted to 55% for a duration of five minutes.

A single controller has been employed in the PLC setup, and the same output is directed to two separate apron feeder outputs with a 4-20 mA output. To ensure seamless transitions between the feeders, which can operate simultaneously in the field, the APC logic has been configured to switch between the primary and emergency stockpiles feeders smoothly by using a model predictive controller.

The signals from the rock size analyser are passed through a stochastic filter as described by Baas, D. and Mikhael, G.L. (2018). This filter decreases the impact that outlier measurements have on the control actions, while allowing the system to react appropriately to changing conditions. This is particularly helpful for measurements that have an update rate that is relatively slower than other measurements in the plant. The rock size analyser provides updates every 15 seconds and has multiple outliers due to the variable nature of the ore which influences the manner in which it is delivered from the feed bins.

RESULTS

A full two years of data was used for the analysis of the results from 2019-11-01 until 2021-11-01. The following stages, as discussed in the paper, have been compared to determine the effect that each change had on the performance of the SAG mill stability:

- A (01/11/2019 to 1/03/2020): Simple PID loop in PLC. No feed forward components or other interactions, only a SISO system.
- B (1/03/2020 to 6/04/2020): The D20 measurement from the 3DPM was incorporated into a MPC controller.
- C (6/04/2020 to 25/01/2021): The MPC controller was removed and a PID loop with a single feed forward component was added that utilised the D20 from the 3DPM.
- D (25/01/2021 to 23/03/2021): Compensation was added to adjust the mill weight setpoint to account for liner wear (discussed in next section)
- E (23/03/2021 to 01/11/2021): The feed forward component for the ore density proxy was added to the control loop.

The following timeline in Figure 6 shows the implementation of the changes to the controls chronologically:

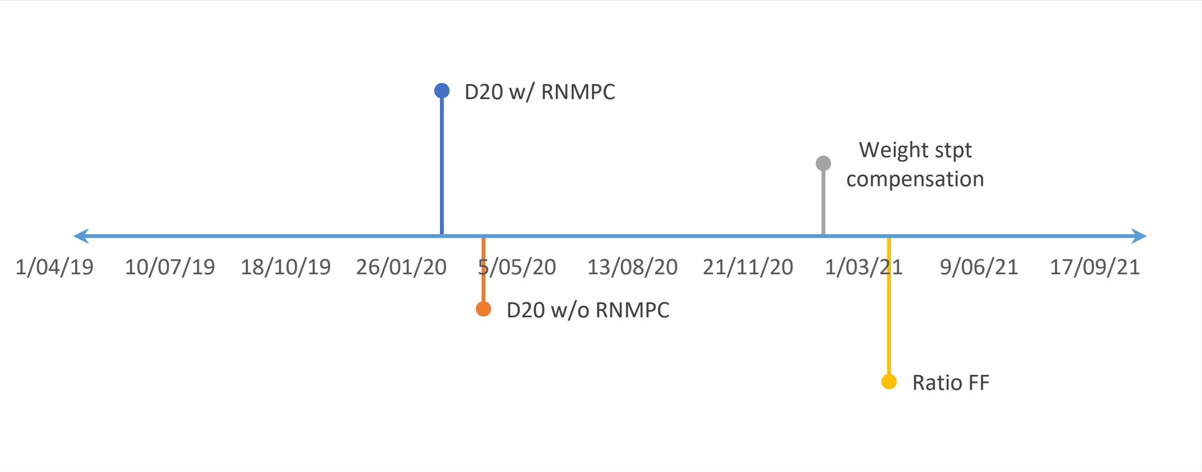


Figure 6 - Timeline to illustrate control change implementations

As the torque was the main concern, the ability to control the torque was evaluated at each stage. The following chart shows the torque measurement over a two-year period, sampled at ten-minute intervals. Times when the mill was not running have been excluded from the dataset. The five intervals listed, marking the five major distinct control strategy implementations have been illustrated [A, B, C, D, E] on the chart in Figure 7. No other data filtering has taken place on this chart.

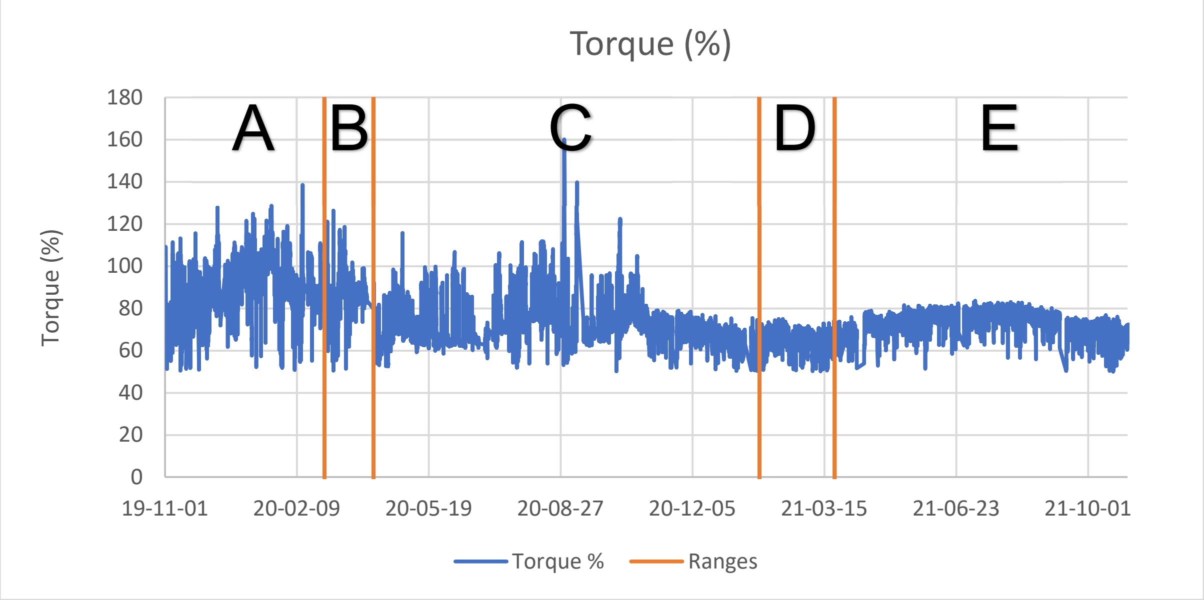


Figure 7 - Plot of SAG mill torque measurement over a 2-year period

Figure 8 aims to quantify the number of times the torque limit on the SAG mill was exceeded (> 80%) and the severity of each violation. A rolling sum of the violations over 80% torque has been plotted on Figure 8 (the data set is the same as the ten-minute sampled data from Figure 7). It can be seen that during period A and B, a high number of severe events occurred, which drastically reduce in period C and have all but gone in period D and E.

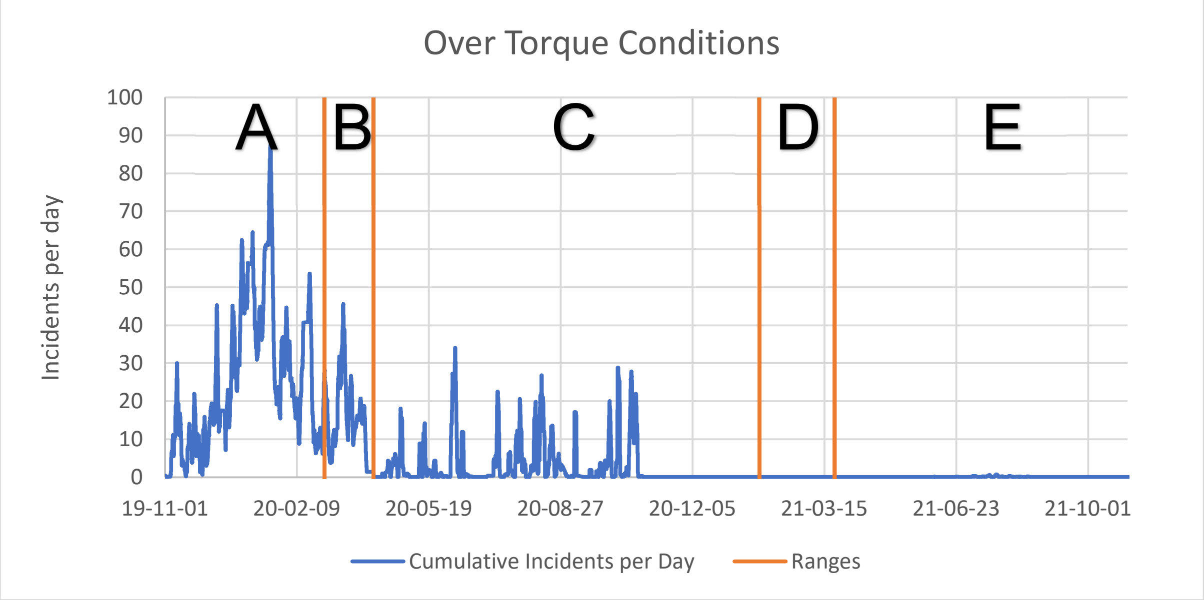


Figure 8 - Time series plot of the cumulative weighted over torque incidents per day

As can be seen from Figure 8, the number of over torque events has greatly reduced due to the improvements in the control and control of the grinding media content. Quite noticeable is the further reduction of high torque even occurrences during the C period. This is attributed to continual review and tuning of the controllers, not to a fundamental change in the control philosophy. Plotting the normal distributions for the torque measurement over the same periods (shown in Figure 9), shows that after the final control changes, the mill is operating far closer to its torque limit and the data quoted illustrates that the number of over torque events has considerably subsided. These two factors indicate that the control of the SAG mill has greatly improved.

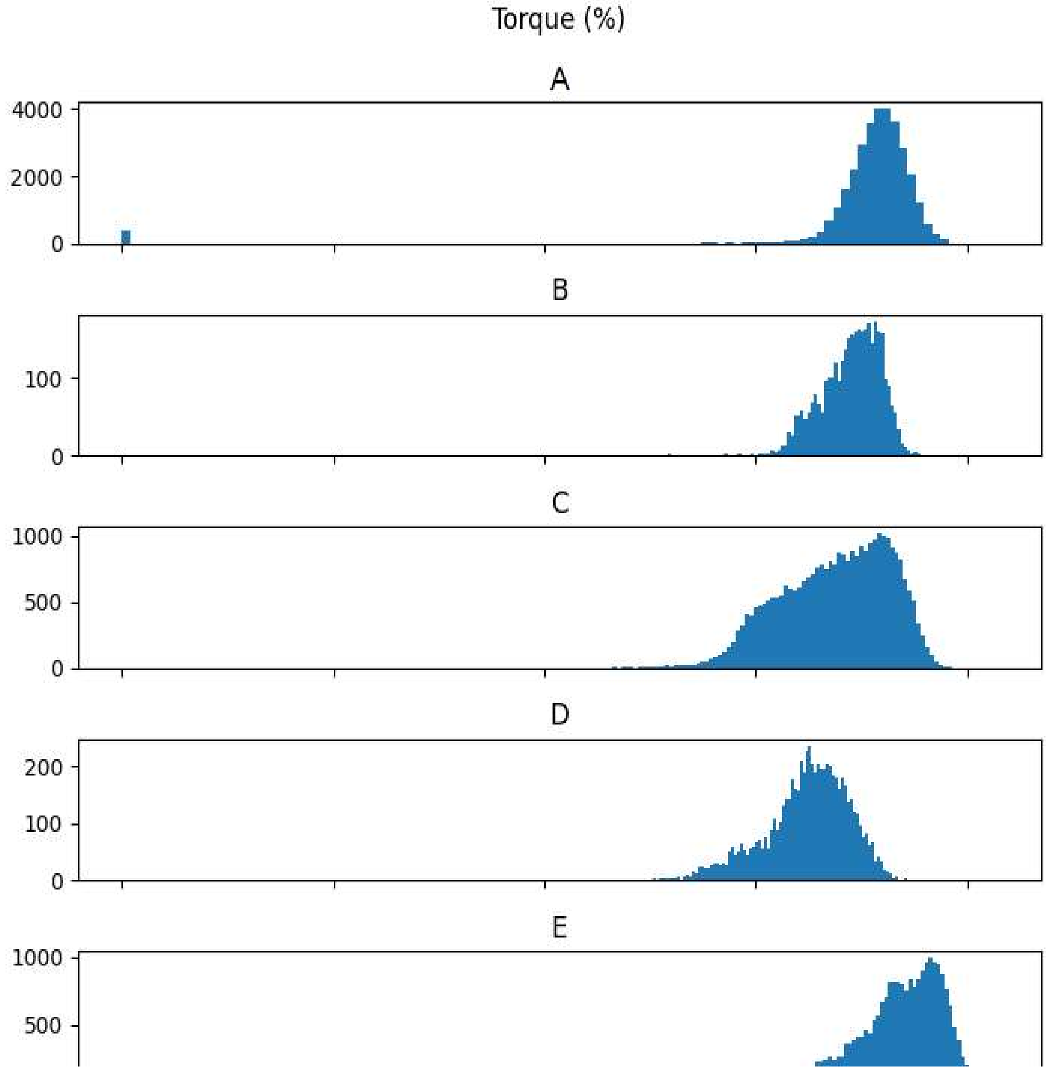


Figure 9 - Normal distribution of SAG mill torque measurement

Improvement to the control can further be highlighted by plotting the error in the SAG mill weight control as shown in Figure 10. The narrowing of the error band in the following plots shows that the mill is better able to hold setpoint and less susceptible to disturbances in the system.

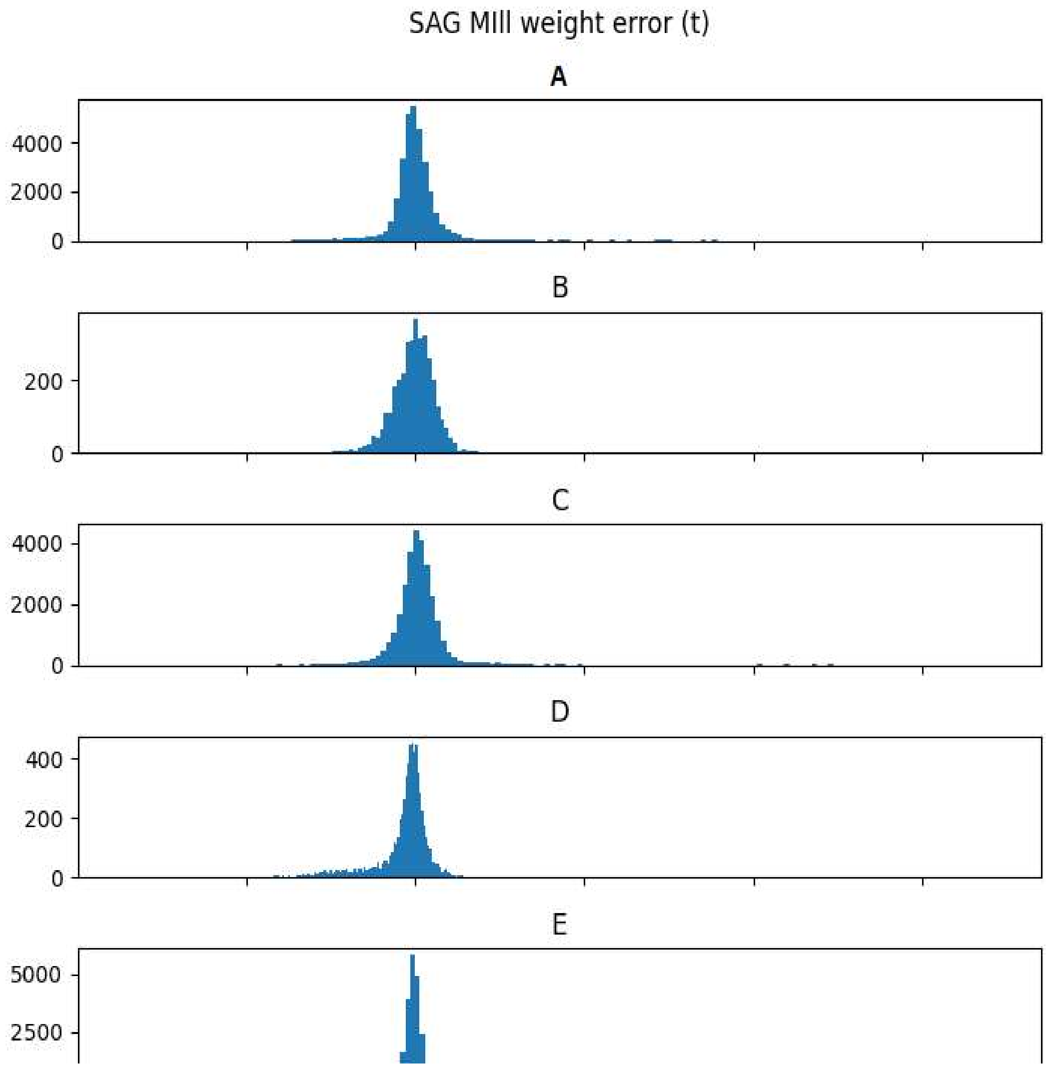


Figure 10 - Normal distribution of the SAG mill weight error (setpoint - process variable)

The mill work index was plotted over the same periods, with the combined mill work index showing a decrease in the energy required for grinding as shown in Figure 11.

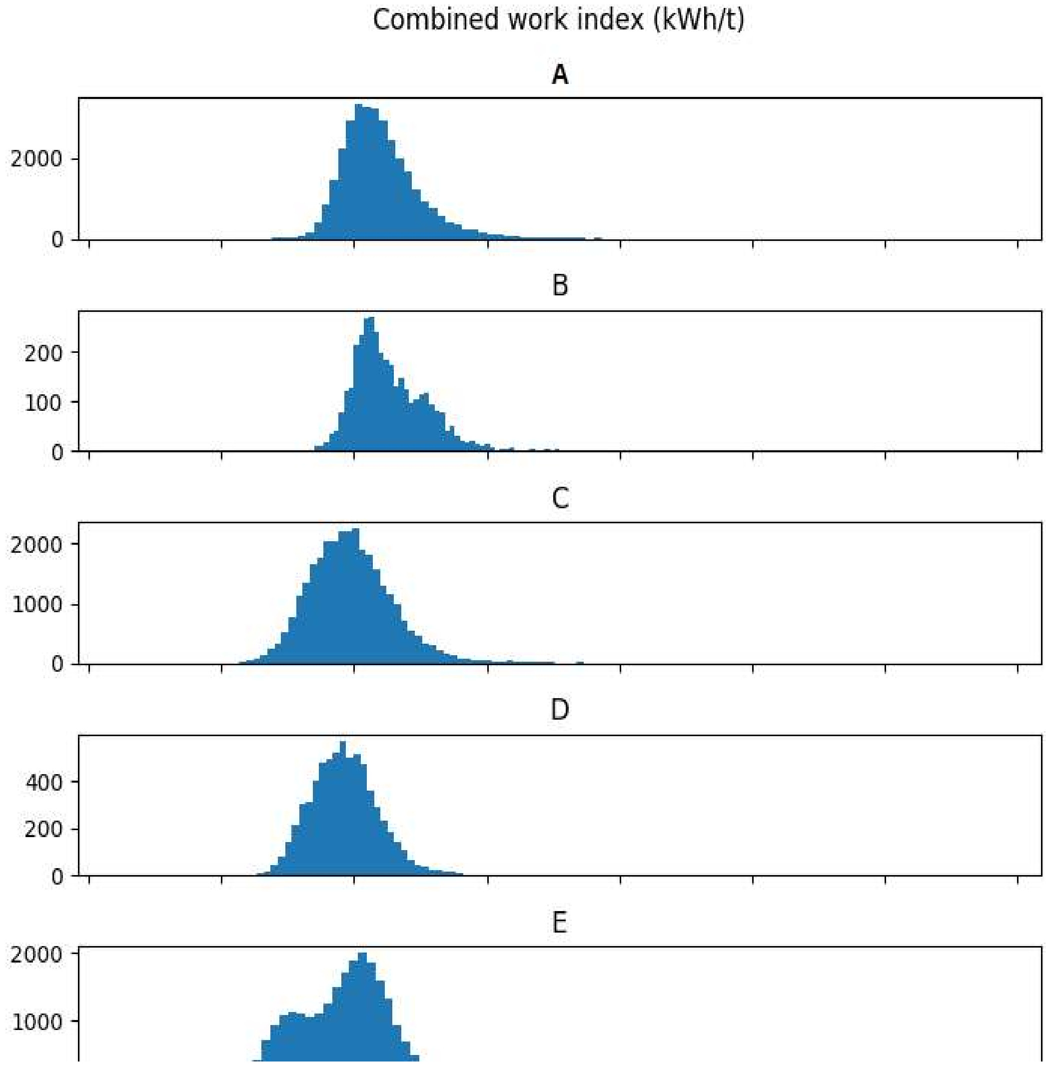


Figure 11 - Normal distribution of the combined work index for the grinding circuit

As previously mentioned in this paper the feed to the plant is quite variable. This means that the mill work index may be associated with variations in the orebody. Plotting the normal distribution for the Ni feed grade does reveal a large variation in the ore. However, one can see that the distribution of %Ni feed grades for periods A and E are quite similar in Figure 12. This shows that the improvements in the SAG mill control are not primarily due to changes in the ore.

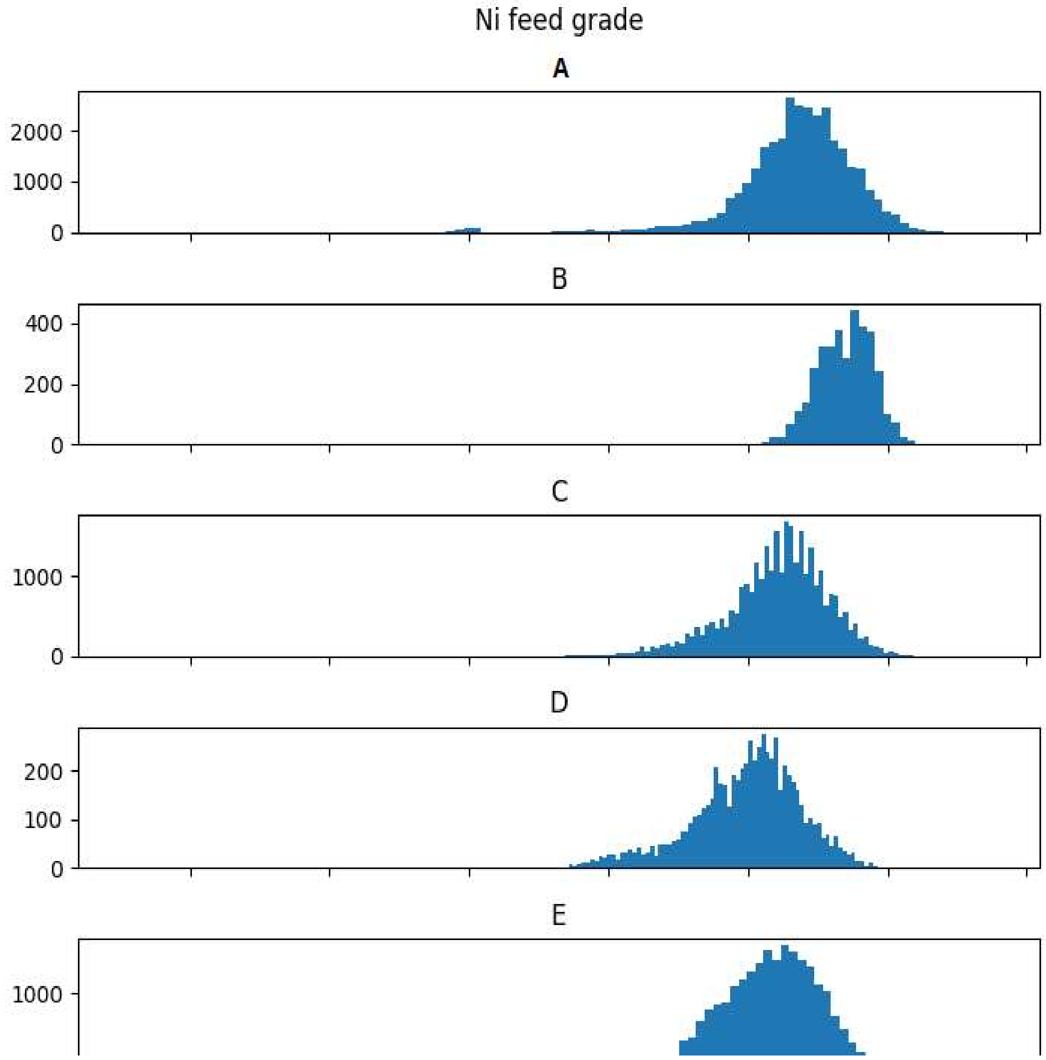


Figure 12 - Distribution plot showing the %Ni in the feed to the circuit

3DPM ANALYSER ON/OFF TRIALS

The effect of the 3DPM feed forward D20 signal on SAG mill weight control and specific energy consumption was investigated using data obtained from on/off trials conducted at Nova. These trials involved turning off the forward D20 used as part of the SAG weight/speed control scheme for two periods of week on and two periods of week off.

Results showed that the 3DPM signal being part of the control "tightens up" weight control around the SAG weight setpoint, as evidenced by a statistically significant lower standard deviation of weight error. Additionally, the feed forward D20 signal reduces the SAG specific energy consumption as a result of better weight control. This is due to less time spent either over or under filled, both of which result in inefficient grinding.

To observe the control improvement, the data had to be analysed at 30-second intervals as the dynamics of SAG weight control are shorter than the one-hour or ten-minute intervals that were first analysed.

A potential confounding factor in this result is Ni head grade and ore hardness. It was observed that during the on periods, the average Ni head grade was higher. Previous studies have shown that SAG mill specific energy stays fairly constant as head grade increases within the normal range of operation; very high head grades approaching 3% result in a reduced SAG specific energy as shown in Figure 15. The measured reduction in SAG specific energy during the 3DPM on periods is therefore attributed to the improved weight control.

Histograms and descriptive statistics of this trial are shown in Figure 13, Figure 14, Figure 15 and Table 2.

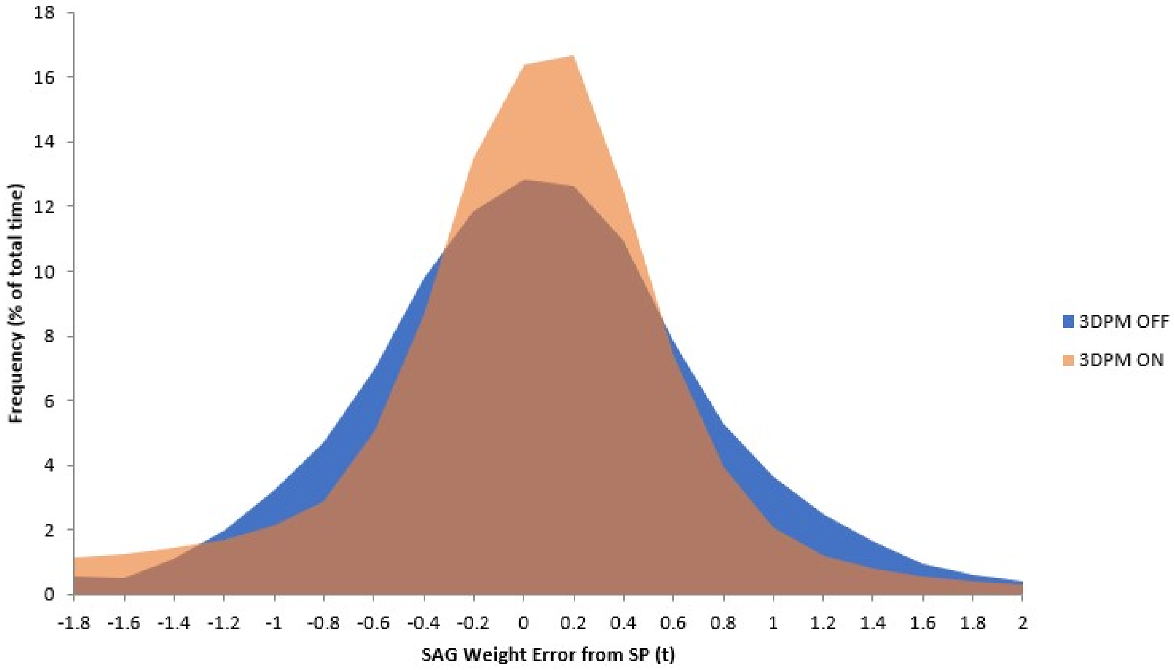


Figure 13 - 3DPM trial histogram of SAG weight control

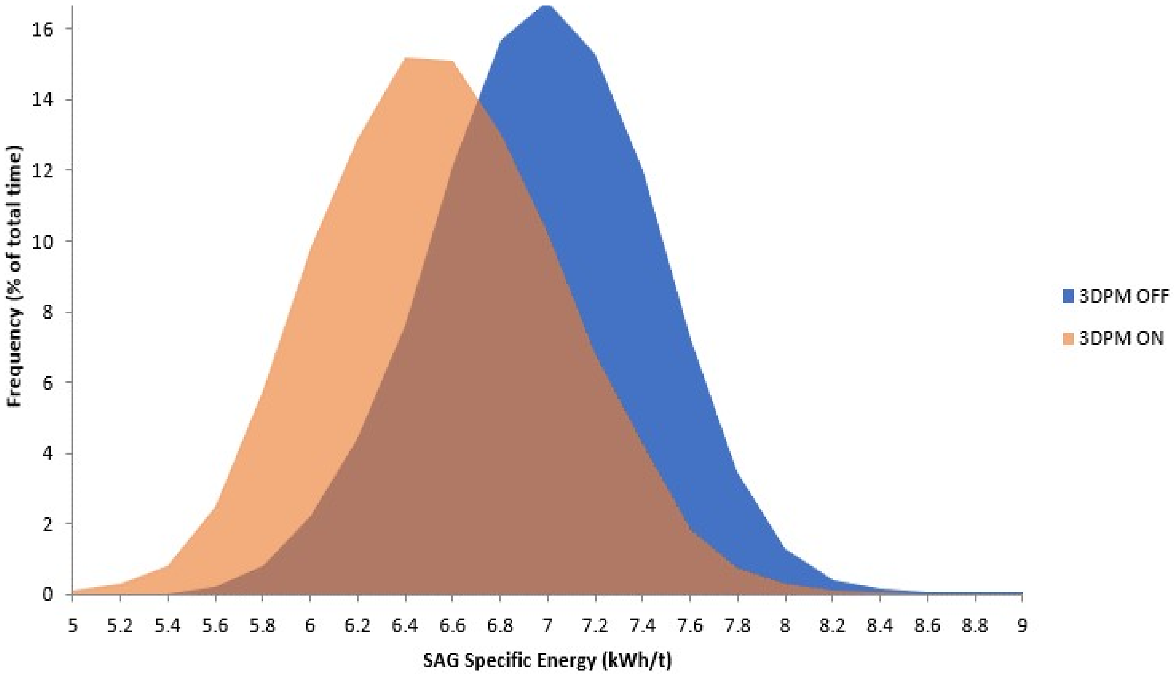


Figure 14 - 3DPM trial histogram of SAG specific energy

Table 2 - 3DPM trial descriptive statistics

Parameter	**Unit**	**3DPM on**	**3DPM off**
Throughput average	t/h	198.22	192.88
Throughput std dev	t/h	9.57	10.61
Ni grade average	%	2.12	1.69
SAG SE average	kWh/t	6.45	6.88
SAG SE std dev	kWh/t	0.51	0.47
SAG SE 2 sample test for different means	P(T=t) two tail	0.0000	
SAG weight error average	tonnes	-0.09	-0.05
SAG weight error std dev	tonnes	0.61	0.66
SAG weight F test for 2 sample variances	P(F<=f) one tail	0.0000	

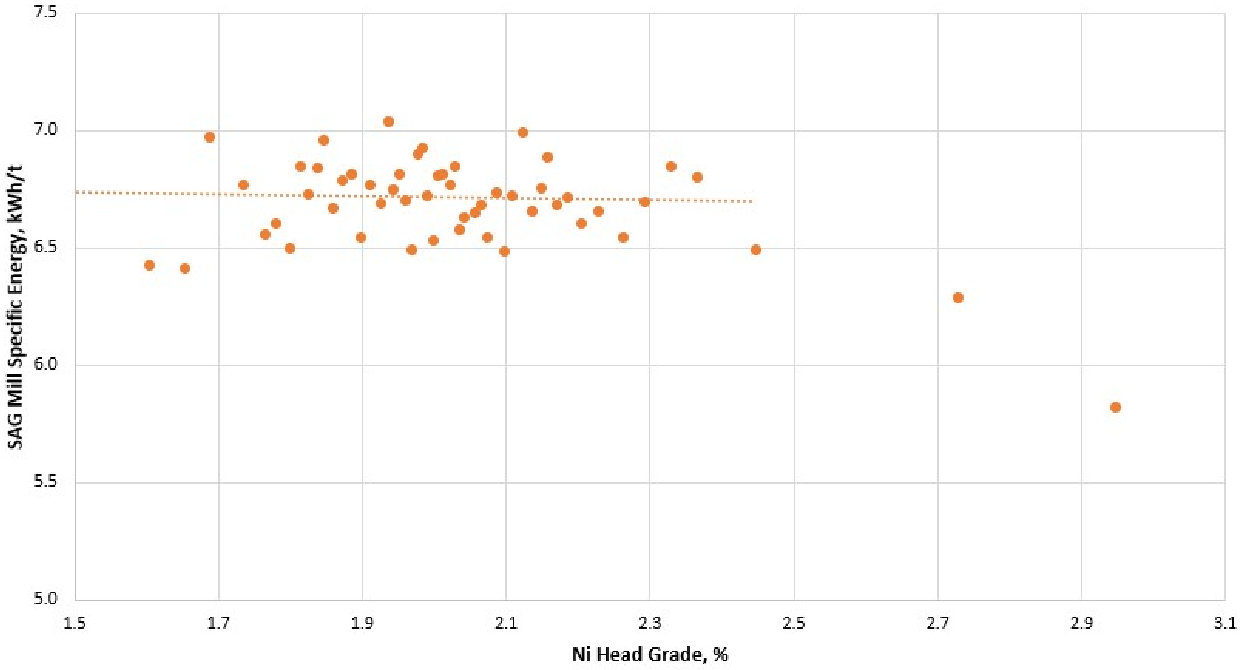


Figure 15 - Plot of SAG specific energy vs Ni head grade

CONCLUSIONS

The grinding circuit efficiency and stability greatly improved when comparing the first half of the dataset (12 months from 01/11/2019 to 01/11/2020) to the last half (12 months from 01/11/2020 to 01/11/2021). These improvements are attributed to the sum of several improvement initiatives including the introduction and use of a rock size analyser, predictive controllers and improved control of grinding media addition and SAG mill fill volume.

The methodology followed implemented control strategies in a systematic and modular manner to build on improvements. This allowed the improvements to be reviewed to determine their benefit. From these reviews some systems were excluding from the final system, such as the exclusion of the "ball loading" trigger and removal of the MPC control of the SAG mill weight controller. Even though the MPC control has shown to be highly effective on other parts of the circuit such as the feed controller to the SAG mill and discharge of the grinding circuit, it was not well adapted at maintaining the SAG mill weight. This is likely due to the non-linearities in the system. The approach of determining the ore characteristics and the effect on the SAG mill weight allowed for a simpler and more effective feed forward controller to be implemented.

Overall, the project was successful and reduced the number of over torque conditions that were experienced on the mill. Additionally, the liner wear of the mill has decreased, and the work index of the grinding circuit is lower by an average of 0.43 kwh/t.

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