Operational Debottlenecking of the Cadia 40-Foot SAG Mill Through Constraint Mapping Analysis

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Abstract

The Concentrator 1 comminution circuit at Newcrest's Cadia Valley Operation (Cadia) transitioned from a traditional semi-autogenous ball mill crushing flowsheet to a high-pressure grinding roll (HPGR)–semi-autogenous grinding (SAG)–ball mill flowsheet following the Cadia East Expansion Project in 2012. A period of operational optimisation followed which by 2018 had successfully shifted the Concentrator 1 circuit throughput constraint to the 40-foot (ft) 20-megawatt (MW) SAG mill. The SAG mill operated to 97% of installed motor power, for an annual throughput of 22.5 million tonnes per annum (Mt/a) in the 2019 fiscal year.

In 2019 the site metallurgy team endeavoured to operationally de-constrain the SAG mill to lift the nominal processing rate of Concentrator 1 with minimal capital expenditure. A theory of constraints methodology was applied, utilising robust circuit data from a recent plant survey to campaign improvement projects both upstream and downstream of the SAG Mill in the crushing and comminution circuits. This paper examines the approach taken and the initiatives executed, which within a period of 18 months enabled a 400 tonne per hour uplift in the annualised throughput rate (dt/h). The milling rate improvement was enough to shift the site processing constraint from the concentrator to the underground mine.

Keywords

Debottlenecking, SAG mill, HPGR, constraints, Cadia

Introduction

The 40-foot (ft) semi-autogenous grinding (SAG) mill at Newcrest's Cadia Valley Operation (Cadia) has been in operation since its commissioning in 1997. Over this period there have been several capital and operational changes made to debottleneck the throughput of the SAG mill. Many papers have been published describing these changes, their challenges and throughput outcomes (Engelhardt et al., 2011, 2014, 2015; Lane et al., 2018; Waters et al., 2018). In all cases what has remained true is the 40 ft SAG mill is the absolute constraint of the Cadia Concentrator 1 flowsheet. Every tonne of ore processed must pass through the SAG mill—and more specifically, through the SAG mill trommel. The Concentrator 1 flowsheet is illustrated in Figure 1.

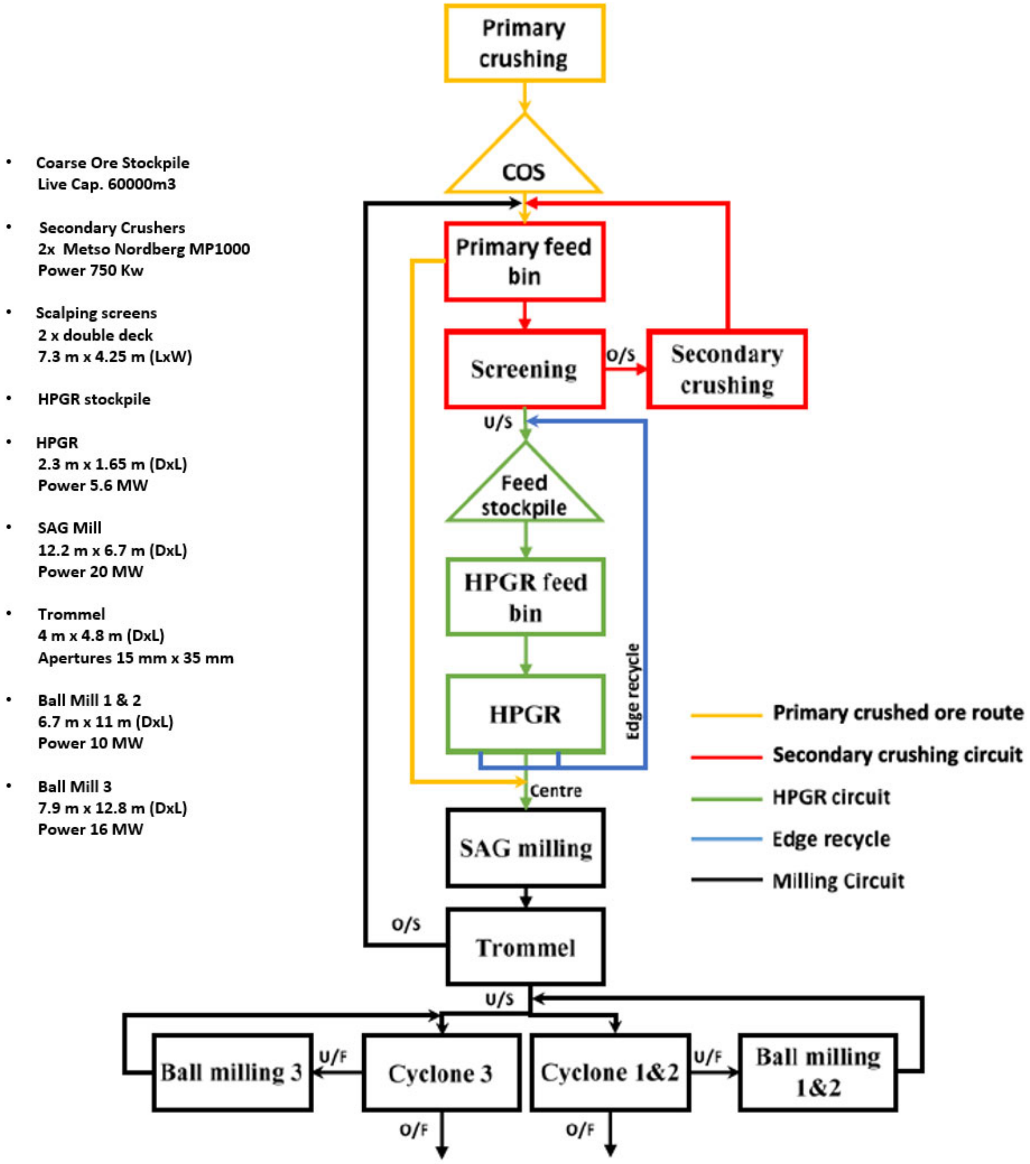
- Coarse Ore Stockpile
  Live Cap. 60000m3
- Secondary Crushers
  2x Metso Nordberg MP1000
  Power 750 Kw
- Scalping screens
  2 x double deck
  7.3 m x 4.25 m (LxW)
- HPGR stockpile
- HPGR
  2.3 m x 1.65 m (DxL)
  Power 5.6 MW
- SAG Mill
  12.2 m x 6.7 m (DxL)
  Power 20 MW
- Trommel
  4 m x 4.8 m (DxL)
  Apertures 15 mm x 35 mm
- Ball Mill 1 & 2
  6.7 m x 11 m (DxL)
  Power 10 MW
- Ball Mill 3
  7.9 m x 12.8 m (DxL)
  Power 16 MW

Figure 1—Cadia Concentrator 1 Flowsheet as of 2019 (Engelhardt et al., 2015)

By 2019 the highest annual process throughput achieved at Cadia was the 2019 fiscal year (FY) production period (June 2018–July 2019) of 29.3 million tonnes (Mt); however, this was short of the permitted maximum processing rate of 32 Mt per annum (MT/a). The processing plant was the site production bottleneck; the mine was consistently outperforming the mill, and as of January 2020 there was a surface stockpile inventory of 2.5 Mt.

Concentrator 1 treats 75% of the mined tonnage and was selected for an applied debottlenecking program of work in 2019. In 2019 a detailed comminution survey was completed on the Concentrator 1 flowsheet. This was to re-baseline the circuit operation following the successful operational debottlenecking begun following baselining surveys in 2013 and 2016 (Waters et al., 2018). The Concentrator 1 circuit (Figure 1) is designed for 2,455 dry tonnes per hour (dt/h) but was able to operate beyond this rate through the sustained application of continuous improvement practices (Figure 2). By FY19 the annual throughput rate was 2,859 dt/h, 454 dt/h above the Cadia East design assumption for the circuit flowsheet. This paper discusses the operational debottlenecking activities undertaken in the following period, between 2019 and 2021, to further elevate the throughput rate of the 40 ft SAG mill.

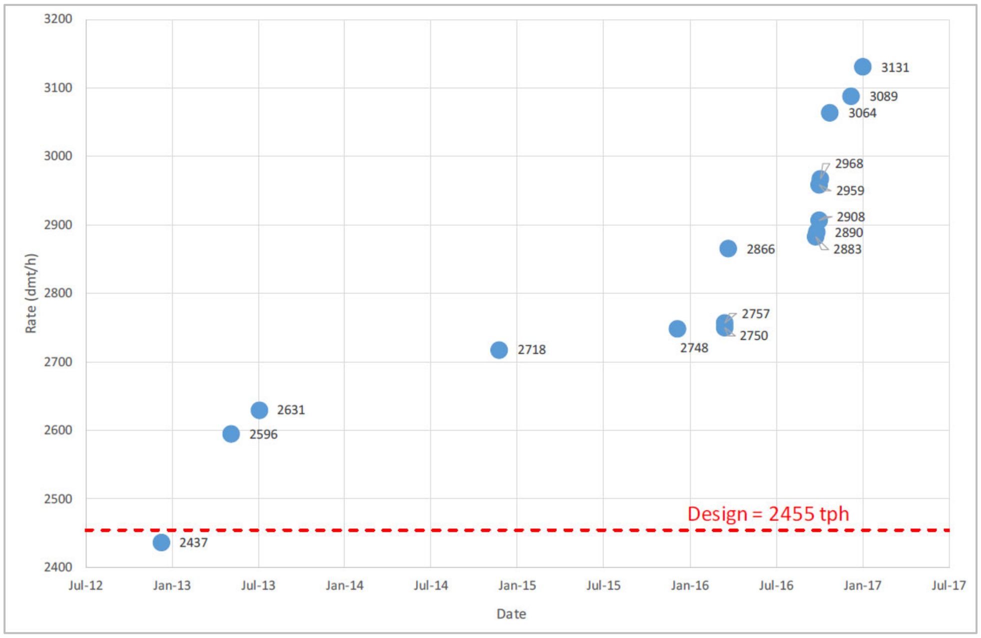

Figure 2—History of Concentrator 1 Daily Record Rates on Majority Cadia East Ore (Waters et al., 2018)

Debottlenecking Philosophy

Given the circuit was already operating 15% above the design throughput rate, expectations of achieving another sizeable step change were muted. The analysis proceeded despite this because the site was mine constrained, and every additional tonne milled was additional free cash flow to the business. The philosophy taken to debottleneck and uplift the performance of a circuit drew on the principles of the theory of constraints (Goldratt and Cox 1984) and the targeted challenge questioning Giblett and Putland (2018) laid out on the topic of grinding circuit optimisation. The theory of constraints was adapted for mineral processing debottlenecking as illustrated in Figure 1. Significant capital uplift projects were not considered, due to the parallel work occurring as part of the Cadia Expansion Project Feasibility Study, which had an execution timeline of 2021/2022; the objectives and outcomes of the feasibility study are not discussed in this paper.

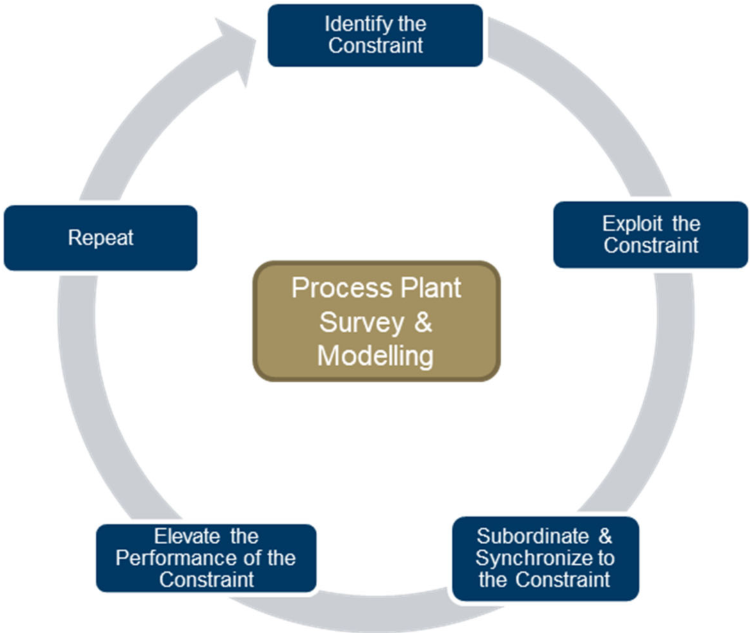

Figure 3—Theory of Constraints Continuous Improvement Cycle; Underpinned by Sound Process Survey Data and Circuit Models

Critical to the success of the process was understanding the true system constraint, in the case of Concentrator 1 this is the 40 ft SAG mill—identifiable from the flowsheet design. The metric defined as the measure of success was an uplift in the annualised throughput rate. This was to be achieved by lifting maximum instantaneous rate and /or improving the reliability of rate loss inducing assets. Rate loss is a significant driver of instantaneous throughput rate at Cadia owing to the complex nature of the flowsheet.

Once the constraint is identified, the options to exploit the constraint must be defined and challenged. Effort should only be exerted to influence the performance of the constrained asset. The process to exploit the constraint drew on the challenge questioning themes identified in Giblett & Putland (2018), site subject matter expert analysis, circuit surveys and process modelling.

Upstream and downstream processes from the constraint should either subordinate or synchronise to the constraint. A process element that can subordinate to a constraint is one which can be readily adjusted or changed in a way which benefits the constraint. Examples of this in a comminution context may be underutilised upstream comminution energy or over-maintaining upstream assets. A process that can synchronise to the constraint is one which is being wasteful in its operation, as its speed is not in alignment with the constraint. An example of this in a comminution circuit would be a planned shutdown whose critical path is misaligned to the constraint resulting in downstream capacity being underutilised.

The largest opportunity in a de-bottlenecking project is to elevate the performance of the constraint itself. This typically necessitates modifying the constraint in some way. An example of this in a comminution circuit would be the installation of a larger motor. Collaboration and subject matter expertise informed with timely and accurate data is key to good decision making here. If the change is not acting directly on the constraint, it is likely that another process is only subordinating to the needs of the constraint to realise improvement.

IDENTIFY AND EXPLOIT

In the case of the Cadia flowsheet, the SAG mill is identifiable as the true or theoretical constraint based on design. Any other assets which are upstream or downstream may also be running close to limits, but they are not capable of being the true constraint, they only lack ability to subordinate or synchronise.

To identify levers to exploit the constraint, the circuit flowsheet was simply mapped against the basic metrics of power and recirculating load, with filtering only applied on equipment utilisation, not performance (Figure 4). Reviewing the circuit in this lens quickly shows the SAG is utilising its full power effectively, similarly to the immediate upstream and downstream assets (high-pressure grinding roll [HPGR] and ball mills). Prior to enacting any physical changes, hypotheses were developed, and data gathered to prove them. Key to effective hypothesis testing was the use of an accurate circuit simulation tool built on accurate survey data.

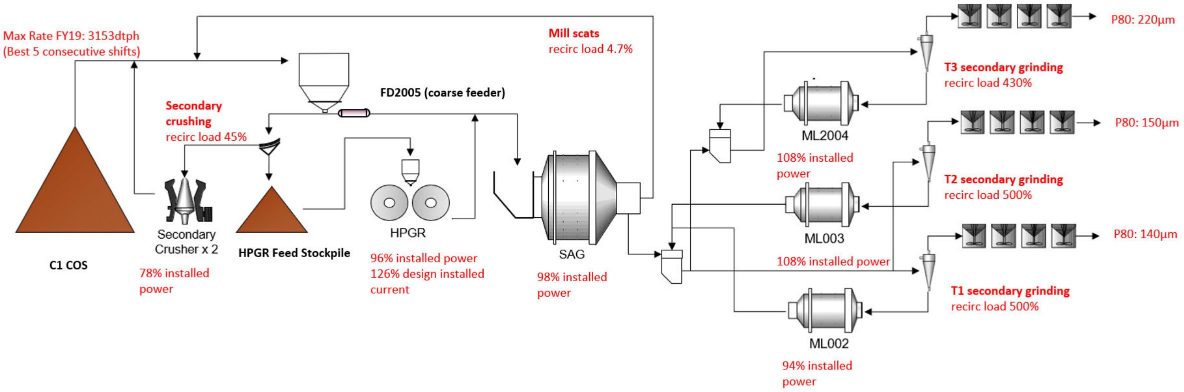

Figure 4—2019 Concentrator 1 Flowsheet and Unit Operations Nominal Operational Power Draw and Recirculating Loads

The salient hypotheses formed were;

1. SAG maximum rates are limited by the onset of mill instability (colloquially referred to as 'spits'), typically driven by either coarse feed to the mill or trommel under-performance (Waters et al., 2018) (Elevate the Constraint).
    a. Question 1: Define the critical size fraction in the SAG and test methods to relieve its retention within the SAG Mill.
    b. Question 2: How can trommel screen flux (t/h/m2) be increased without destabilizing the downstream ball milling circuits?
2. SAG feed 80% passing (F_{80}) is reduced when solely fed with HPGR product. When this operating state exists, the HPGR cannot meet the demand of the SAG mill and the supplementary coarse ore feeder (FD2005) variable speed drive is at minimum speed (Subordinate to the Constraint).
    a. Question 1: Can the minimum operating speed of FD2005 be reduced?

b. Question 2: How does the secondary crusher Closed Side Setting (CSS) and power utilisation impact downstream SAG milling?
c. Question 3: How much excess capacity exists in the secondary crushers?
d. Question 4: Based on the excess capacity in the secondary crushers and frontend conveyor assessment - Can the screen bottom decks be closed to reduce the F100 of the HPGR feed, improving the kWh/t of the HPGR unit and uplifting the HPGR throughput rate for the same power input and pressure set point? Can the front end crushing and screening circuit match the uplifted HPGR demand in this case?

To quantify the hypotheses a more detailed understanding was required of current circuit performance. The previous circuit survey was performed in 2016 and the characteristics of the circuit had changed markedly since that point in time.

PROCESS PLANT SURVEY 2019

A full Concentrator 1 comminution circuit survey was completed in July 2019 to baseline current circuit operation and update the simulation model. Ore samples were collected from the underground primary crusher collection belts, front-end crushing and screening plant, HPGR, and the primary and secondary grinding circuits. Key survey results are displayed in Table 1, alongside results from the previous circuit survey in 2016 and the Cadia East circuit design parameters.

Table 1—Comparison of Circuit Survey Results 2016 and 2019

Parameter	Unit	Cadia East Design	2016 Survey	2019 Survey
BWI	kWh/t	21.5	20.7	19.7
DWi	kWh/m^3	10	8.81	9.49
Axb		27	33.4	28.7
Secondary Crusher Recirculating Load	%	-	57	44
Scalping Screen Efficiency	%	-	80	86
SAG Fresh Throughput Rate	t/h	-	2,817	3,239
SAG F_{80}	mm	-	16.5	17.6
SAG Trommel Undersize P_{80}	mm	-	1.84	1.64
SAG Power Draw	MW	-	16.0	19.4
SAG Ball Charge	%	-	14	17
Primary Cyclone Overflow P_{80}	µm	150	124	170

Note: BWi = Bond work index; DWi = drop weight index; Axb = JK rock breakage parameters, F_{80} = Feed 80% passing, P_{80} = Product 80% passing, MW = megawatt.

The key drivers for the variance in circuit throughput rate and SAG mill operating conditions from 2016 and 2019 are attributed to the previous plant debottlenecking work (Waters et al., 2018).

PROCESS MODELLING

An external third party was engaged to update the existing Concentrator 1 comminution model using the recent plant survey data and to undertake hypothesis testing to explore options to address identified bottlenecks. The model was originally developed in 2016 using the third party's proprietary comminution modelling techniques, and had been a robust predictor of circuit performance to date.

The model had not, however, proved capable of predicting SAG mill instability (spit events). As such, the unconstrained, maximum modelled plant throughput rate was significantly higher than historically demonstrated (Table 2). This identified a significant opportunity to uplift plant throughput rates if SAG instability issues could be addressed.

Table 2—Actual and Modelled Plant Throughput Rates

Parameter	Unit	2019 Survey	2019 Modelled (unconstrained)
Throughput Rate	t/h	3,239	3,568

Subordinate, Synchronise, and Elevate

SAG mill instability issues originally presented following the commissioning of the HPGR in 2012. It is generally understood that these events are triggered by a change in feed material characteristics, resulting in differential breakage rates within the mill, which leads to a localised build-up of rock and slurry. Once the material reaches the critical mass for effective transport, it presents to the discharge end as a large volume of rock and slurry, and will subsequently overload the trommel and downstream materials handling system (Waters et al., 2018). The understanding of this phenomenon formed the approach to debottleneck the SAG mill, namely, minimising and stabilising SAG mill F_{80} through front-end modifications, alleviating coarse-material hold-up within the mill and improving downstream dewatering capability to mitigate the severity of spitting events. It was accepted that spitting events were a manifestation of an overloaded mill, and that eliminating such events was not feasible. Rather, it was necessary to increase the achievable milling rate before such an event presented.

SUBORDINATE CRUSHING AND SCREENING: REDUCE SAG MILL F_{80}

HPGR Throughput Uplift

SAG mill feed size is strongly influenced by the blend ratio of HPGR product (P_{80} 16.3 mm, P_{99} 55 mm) to the coarse bleed stream from the front-end distribution bin (P_{80} 48 mm, P_{99} 200 mm). Maximising HPGR throughput rates directly translates to a reduction in SAG mill F_{80}. The HPGR previously operated to 90% of installed power and was limited by the feed conveyor belts' volumetric load constraints. To debottleneck the feed supply system, conveyor belt speeds were increased by adjusting the variable-speed drive settings, enabling a 10% increase in maximum belt throughput rates and shifting the HPGR circuit constraint to the HPGR's installed power. To subordinate the upstream circuit to the constraint of HPGR power, we leveraged the relationship between HPGR feed top size and unit-specific power draw (kWh/t). A reduction in HPGR-feed top size reduces roll torque, and subsequently the power draw for a set throughput rate. The two levers available to reduce HPGR feed top-size included reducing scalping screen cut point and improving product size from the secondary crushers.

As highlighted in Table 1, front-end recirculating load had diminished since 2016, partly due to improved screening efficiency and a reduction in P_{80} of primary crushed underground ore. As a result, secondary crushers were operating at 78% of their installed power, presenting an opportunity to increase secondary crushing duty and reduce particle top size presenting to the HPGR. Screen bottom-deck aperture sizes were reduced from 65 to 55 mm, which was found to be the optimal trade-off between maintaining HPGR feed stocks and optimised HPGR operation, as determined by circuit modelling. A screen bottom-deck open area of 38% was retained before and after the change. HPGR feed rates increased following the screen cut-point changes. Figure 5 displays the shift in HPGR feed tonnage over 12 months resulting from the upstream changes.

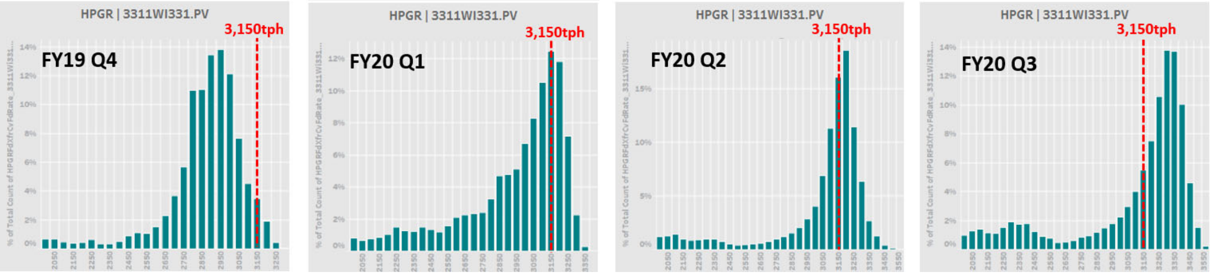

Figure 5—Quarterly Histograms of Hourly Pi Data on the HPGR Feed Rate (wtph)

While the HPGR had been de-constrained, the proportion of HPGR product in the SAG feed stream was still limited by the minimum feeder speed of the coarse bleed stream. The HPGR alone could not meet the SAG feed demand, but conversely could not be fully utilised when running in conjunction with the coarse feeder. To alleviate this and provide a wider range of operating conditions the coarse feeder minimum motor speed was slowed to reduce the minimum tonnage output of the feeder by 190 t/h. The reduction of coarse feed presenting to the SAG mill opened up demand from the HPGR at a ratio greater than unity.

Secondary Crusher Product Quality

Optimisation of secondary crusher product size involved reviewing feed conditions and improving crusher liner profile design. It is well documented that operating cone crushers in a choked condition provides benefits in terms of size reduction and stability of operation. The crushers were nominally operated under trickle-fed conditions, so the opportunity was taken during the 2019 survey to collect crusher product samples under choke-fed conditions. Crusher CSS was increased from 26 to 42 mm to achieve choke-fed conditions. The sampled product stream was significantly coarser compared to nominal trickle-fed conditions (Figure 6).

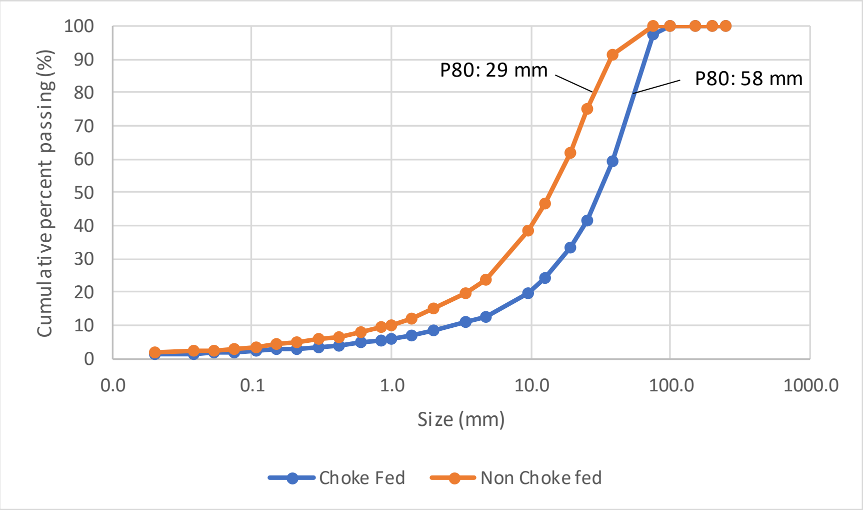

Figure 6—Secondary Crusher Product Size Distributions Under Choke Fed and Non-Choke Fed Condition

Crusher modelling later demonstrated that there was not enough crusher power available to choke feed at the product size required to sustain front-end throughput rates. Crusher gap would need to be increased to remain within the power limits, but this would subsequently increase the recirculating load, causing the crusher chamber to run out of volumetric flow capacity at front-end rates well below the minimum requirement (Figure 7).

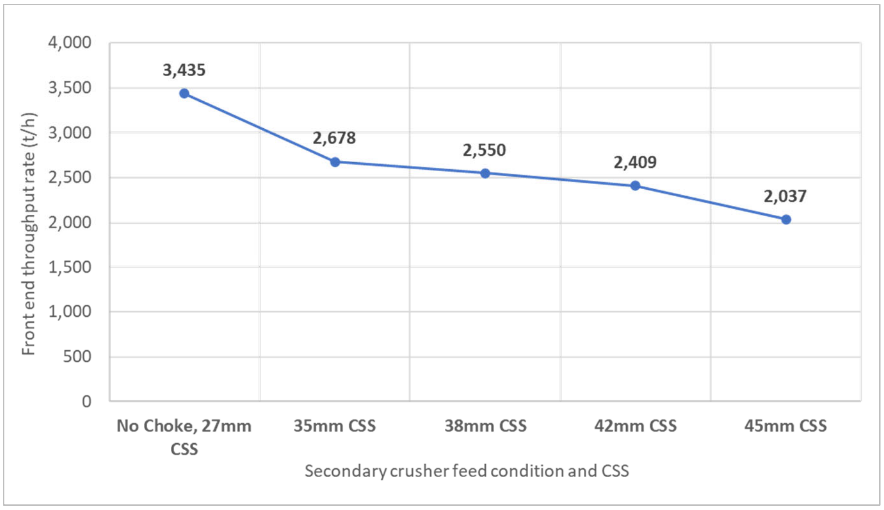

Figure 7—Modelled Secondary Crusher Choke Scenarios and Impact on Front-End Throughput Rate

A third party was engaged to complete an independent review on liner profile design. Through crusher liner scanning it was identified that the existing liners wore to a highly parallel chamber, which resulted in a loss in staged, incremental crushing. It also shifted crushing forces to locations in the frame and bushes that caused mechanical failures. Premature failure of crusher components resulted in unplanned maintenance and a direct impact to milling rate. A new mantle and bowl liner profile was developed which allowed a more controlled reduction process down the length of the chamber, which continued into the worn condition. This enabled the design CSS of 26 mm to be maintained for the entirety of the liner campaign without risk of mechanical failure.

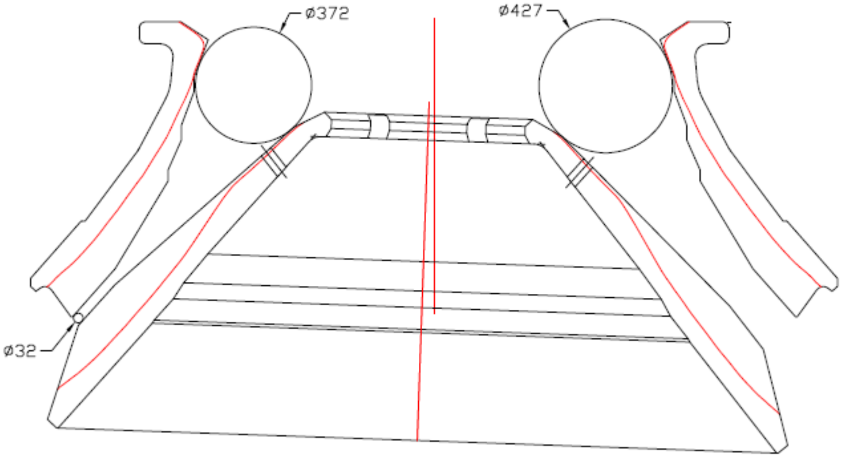

Figure 8—Previous Secondary Crusher Bowl and Mantle Liner New (Black) and Worn (Red) Profiles

MOBILE SECONDARY CRUSHING PLANT

The final lever to elevate the front-end constraint was supplementation of feed material through a mobile secondary crushing plant to offset periods of low front-end utilisation. The mobile crushing plant, supplied and managed through an external third party, was set-up and operated adjacent to the HPGR feed stockpile. The circuit treated primary crushed material from the coarse-ore stockpile through an open circuit jaw-crusher, scalping screen, and cone crusher at 5,000 t/d (6% of the fixed plant circuit's production rates). The mobile crushing plant achieved a product size that closely matched the particle-size distribution of the fixed plant scalping-screen undersize stream (Figure 9).

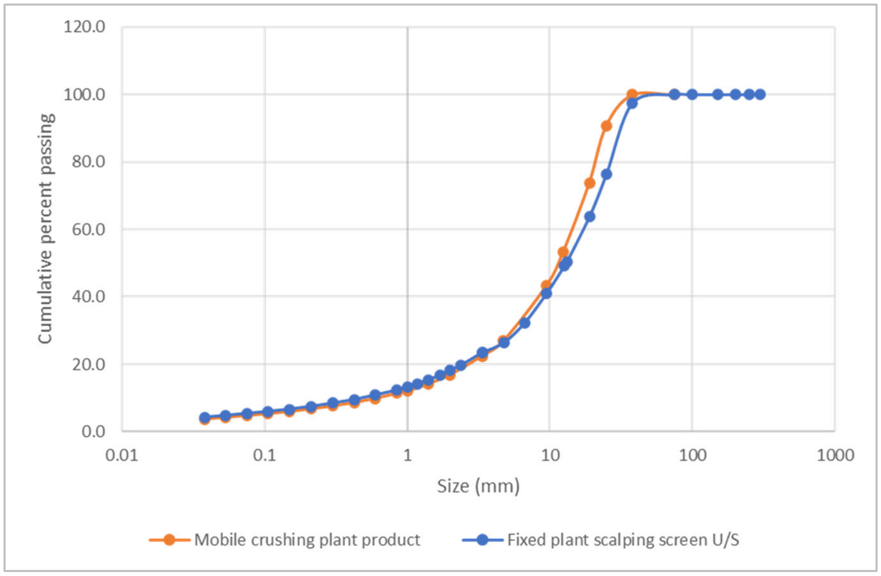

Figure 9—Particle Size Distributions of Mobile Crushing Plant Product and Fixed Plant Screen Under Size Streams

Material produced from the mobile crushing plant was stored on the perimeter of the HPGR stockpile footprint. As such it did not hinder maximum production rates from the fixed plant and provided additional feed to meet the HPGR demand. A total of 760,000 tonnes was processed by the mobile crushing plant and consumed by the SAG mill in FY21. Uplifting 40 ft SAG mill production rates as the HPGR product, when available to the mill, will displace coarse feed at a ratio above unity.

ELEVATE THE CONSTRAINT: SAG MILL DEBOTTLENECKING

SAG Mill Discharge Grate Design

The SAG mill discharge grate design had not fundamentally changed since the transition from a SAG mill, ball mill, and recycle crusher to an HPGR–SAG–ball mill circuit in 2013, maintaining a 25 mm slot size. The existing grates exhibited excessive metal flow (peening) between slots, causing slot aperture to diminish by up to 5 mm, with a resultant 27% reduction in relative open area. The frequency of SAG mill spitting events was observed to increase with liner wear, indicating that the progressive reduction in grate open area and effective slot size was directly contributing to the hold-up of coarse material within the mill.

A review was conducted into the design of the SAG mill discharge grates using the updated simulation model developed from the 2019 comminution survey. Through modelling of the SAG mill particle breakage rates, it was identified that effective grate aperture size could be increased to prevent hold-up of critical-size material within the mill (Figure 10). The revised design is detailed in Figure 11, showing the slot aperture size was increased by 5 mm and slot orientation was changed from 180° to 45°. The slot orientation change was an attempt to reduce peening. Ball-on-liner impacts would now be parallel as opposed to perpendicular to slot direction when the mill is operating.

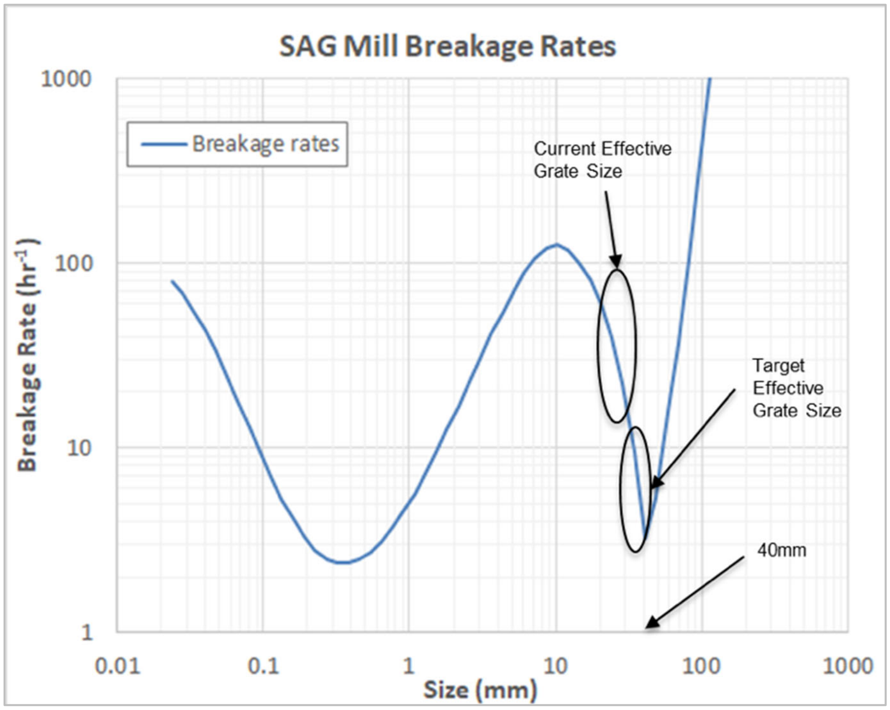

Figure 10—SAG Mill Breakage Rates

Table 3—Previous and Redesigned Grate Dimensions

Parameter	Unit	Previous Grates	Redesigned Grates
Slot Sizes	mm	25, 40	30, 45
Pebble Port Size	mm	60	60
Grate Open Area	%	8.15	8.44

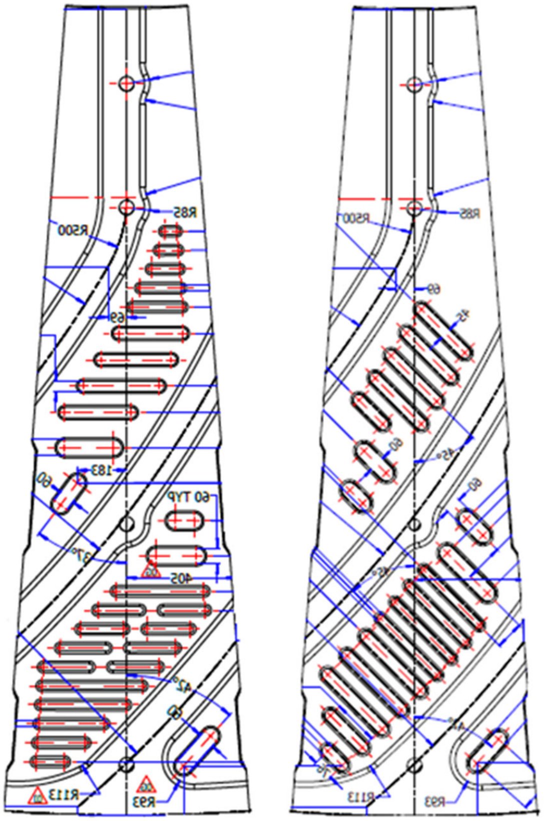

Figure 11—SAG mill Grate Liner Design (Fit Face) Previous (Left) and Redesign (Right)

The grate design change resulted in a significant reduction in SAG rock load due to reduced material hold-up. This reduced SAG power draw by approximately 1.5 MW for a given tonnage, enabling an increase in SAG ball charge from 17% to 19 %. Targeting ball charge over mill speed to draw the additional power was selected as the preferred approach. Site experience consistently demonstrated that improved mill stability, leading to higher average throughput rates, was achieved at higher ball charges and high ball-to-rock ratios.

SAG Mill Pebble Dewatering

The modelled increase to overall scatting rate with the grate aperture change was negligible. Therefore, the SAG mill trommel aperture remained unchanged (15 x 13 mm slots) to maintain SAG mill transfer size and prevent overloading of the downstream ball milling circuits.

There was need to improve SAG trommel dewatering capacity at the higher volumetric throughput rates, and during surge events. To achieve an improved trommel screen flux (t/h/m^2) without significant capital expense, the trommel dam configuration was modified to increase slurry residence time. The existing trommel dam arrangement was suited to a bi-directional mill, with rings of dams positioned perpendicular to the flow of slurry. The SAG mill had been operating as a unidirectional mill since 2001 (Hart et al., 2006). A modified layout was installed, which included angled dams positioned against the direction of slurry flow, pushing slurry backwards in the trommel to increase screen residence time. The layout also included forward-facing angled dams, to act as “gates” to allow material and media to pass through to the discharge end. The trommel layout before and after the change is displayed in Figure 12.

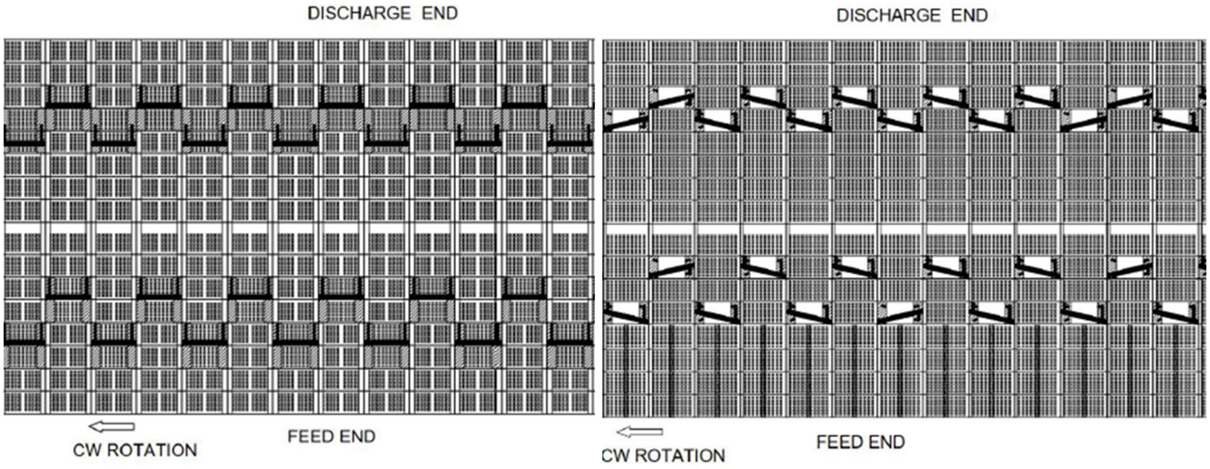

Figure 12—SAG Trommel Dam Layout, Previous (Left) and Redesigned (Right)

SYNCHRONISE DOWNSTREAM CONSTRAINTS

At high plant throughput rates the downstream secondary ball milling circuits' volumetric recirculating loads became an operational constraint to throughput. High recirculating loads were required to minimise the increasing flotation feed size and subsequent flotation recovery loss. Note that at no point did the recovery loss resulting from coarser flotation feed-size outweigh the benefit of additional throughput.

Ball mill trommel oversize material reported to a drive-through sump, where material was then retrieved by a front-end loader. At high throughput rates, slurry would misreport to trommel oversize and flow to the drive-through sump (Figure 13). When the rates of discharge into the drive-through sump exceeded what the loader could remove, milling rates were reduced. An aggressive trommel dam arrangement and 30 x 40 mm apertures were already in place prior to the upstream SAG mill debottlenecking work. These measures were not sufficient to prevent slurry carry-over at the elevated milling rates achieved. Trommel aperture sizes were larger than that on the SAG mill (30 x 40 mm versus 15 x 35 mm), therefore all material reporting to trommel oversize was theoretically already below the SAG mill transfer size (T_{80}). Circuit modelling was completed to test the impact on the ball milling circuits. Modelling indicated a negligible change to ball circuit recirculating load by reintroducing all ball mill discharge material back into the circuit. To synchronise the performance of the ball milling circuit to the SAG mill constraint, the decision was made to remove the trommels and replace them with a discharge chute.

Figure 13—Ball Mill Trommel Oversize Chute Discharge to Drive Through Sump

Outcome

The progressive implementation of circuit debottlenecking initiatives over the course of 14 months yielded an uplift in Concentrator 1 milling rates beyond expectations (Figure 14, Figure 15). By FY21 the annual throughput rate was 3,207 dt/h, 752 dt/h above the Cadia East design (2,455 dt/h) for the circuit flowsheet and 400 dt/h above the FY19 baseline. This was achieved without an increase in comminution energy and with minimal capital expenditure. The absolute circuit constraint remained to be the SAG mill, which continued to operate to 98% of its installed 20 MW power.

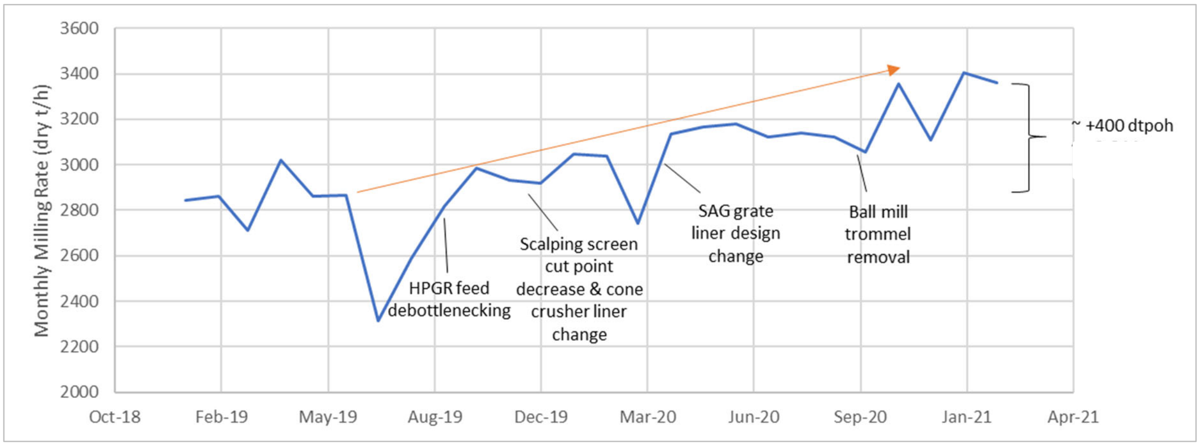

Figure 14—Monthly Milling Rate Ramp-Up

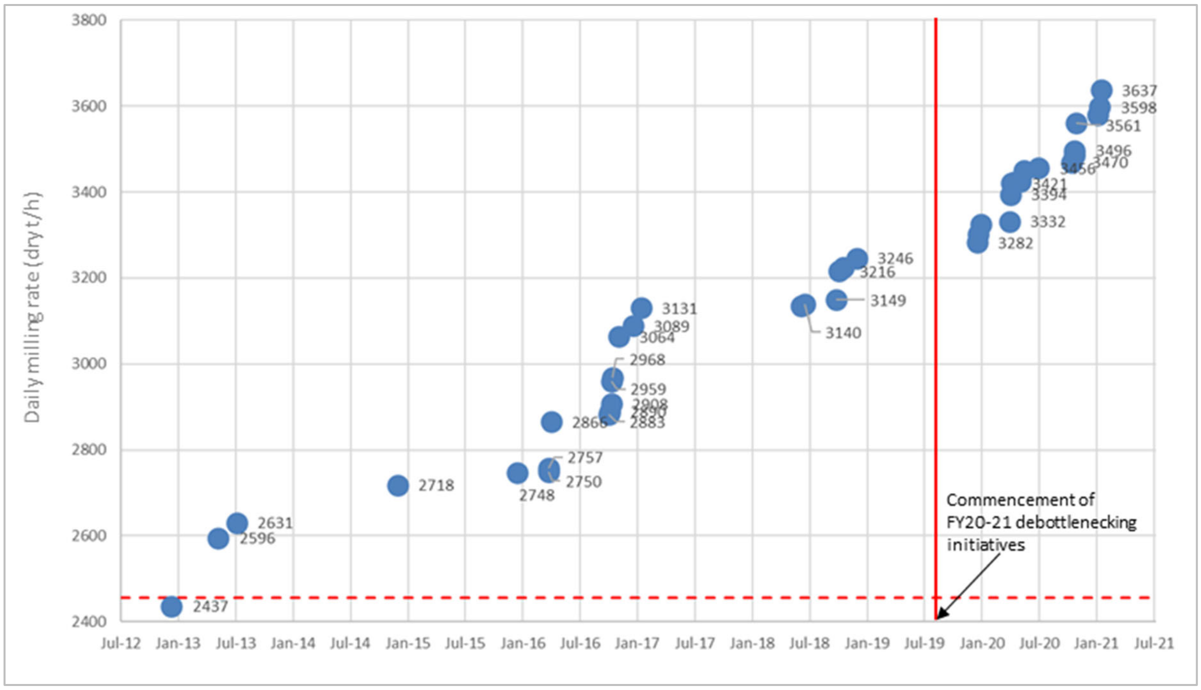

Figure 15—Concentrator 1 Daily Throughput Rate Records when Treating Majority (>50%) Cadia East

Conclusion

All processing circuits have latent capacity. This capacity can only be judiciously exploited through a combination of methods and diversity of opinion. Three salient methods have been applied in combination to deliver the operational outcomes presented in this paper:

1. The theory of constraints framework to guide effort - subordinate, synchronize and elevate around the true constraint.
2. Diversity of technical and empirical subject matter expertise guided by fundamentals and alignment to the true constraint.
3. Detailed survey data which is accurate and contemporary to the operational state.

Such optimisation of a seemingly constrained system was not possible without the combination of methods presented:

1. Identifying and proving the true constraint through contemporary data.
2. Gathering a diversity of technical and empirical knowledge to exploit the constraint in the context of the contemporary data.
3. Applying a tenacious continuous improvement approach which celebrates results and execution. Yesterday’s record is today’s target.

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