Review and Optimization of the Hudbay Constancia Comminution Circuit

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Abstract

Constancia is a copper–molybdenum deposit in the southeastern Andes of Peru. The comminution circuit comprises a primary crusher, followed by two identical, parallel semi-autogenous and ball milling grinding lines. Hudbay started operations at Constancia in 2014, achieving commercial production within a few months, and through several improvements now consistently surpasses the design throughput of 76,000 tonnes per day. However, as mining progresses, the dominant ore type is the harder hypogene ore, which adversely impacts plant throughput and product size.

Hatch was engaged to conduct a comprehensive review of ore characteristics, run-of-mine fragmentation, circuit operating strategy and equipment configuration, and determine opportunities for optimisation. Mathematical models were developed, and simulations conducted to evaluate alternative operating strategies to increase throughput while maintaining or reducing the product size and its variability. Opportunities for improvement were identified and are expected to increase throughput by about 6% to 8% when treating harder ores, without capital expenditure.

Keywords

Comminution, process optimisation, throughput, drill and blast, crushing, grinding.

Introduction

The Constancia mine is approximately 600 kilometres (km) southeast of Lima in the southeastern Andes of Peru.

Hudbay Peru SAC (Hudbay) acquired the Constancia copper project in 2011, completed construction in 2014, and achieved commercial production within just five months. Ore is mined from Constancia pit, which is a porphyry copper–molybdenum system. In addition, since 2021 ore is being mined from the nearby Pampacancha satellite pit, a high-grade copper–gold deposit.

The Constancia comminution circuit consists of primary crushing followed by two identical, parallel semi-autogenous and ball milling grinding lines. Currently, there is no pebble crushing; however, engineering studies are underway to install a pebble crushing circuit in the near future. Each semi-autogenous grinding (SAG) mill feeds a ball mill operating in closed circuit with hydrocyclones. The current 80% passing (P_{80}) product from the grinding circuit is between 110 and 190 microns (µm), with a design of P_{80} 106 µm and a current target of P_{80} 160 µm.

Through several improvements, the Constancia concentrator now consistently surpasses the design throughput and treats between 80,000 and 90,000 tonnes per day (t/d). However, achieving this has resulted in coarser feed to the flotation circuit. As mining advances, Hudbay is also encountering increasing ore hardness at Constancia, which is adversely impacting plant throughput.

To address the challenges posed by the increasing ore hardness and coarsening product size, Hudbay contracted Hatch Consulting & Technology to conduct a comprehensive review and optimization of the Constancia comminution circuit. The project's objective was to identify the best operational strategies using the existing assets to either maximize the plant throughput or achieve the optimal balance between maximum throughput and optimal product size.

Constancia Rapid Ramp-Up and Continuous Improvement

Hudbay achieved ramp-up and commercial copper production just five months after construction was completed in 2014 (Figure 1). More specifically, the plant ramp-up commenced in December 2014 and commercial copper production was surpassed in April 2015.

The first quarter of 2015 featured a slow ramp-up due to an operation with one grinding line only. In conjunction with the series of improvement initiatives Hudbay implemented, when the second grinding line commenced operating, the plant achieved and consistently exceeded the design throughput of 76,000 t/d (Figure 1).

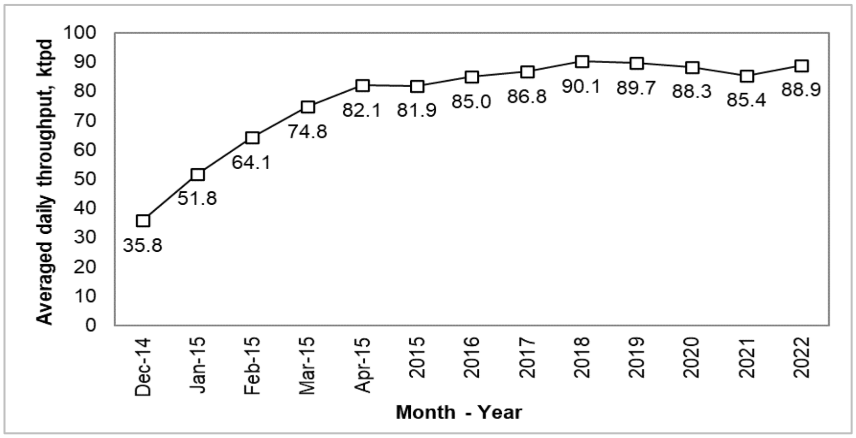

Figure 1—Evolution of plant throughput to 2022

Hudbay implemented several internal initiatives that have increased plant throughput since 2015. The increased plant throughput was sustained until 2019; however, in 2020 and 2021 production dropped approximately 2% and 5 %, respectively (Figure 1), due to increased ore hardness and the impact of the Covid-19 pandemic.

Plant availability also contributed significant improvements to increase and maintain plant productivity, considering that the drive system of the SAG and ball mills are of the pinion-crown gear type. Since the plant ramp-up in 2014, Hudbay experienced a gradual improvement in plant availability, reaching values above 95% in 2018 and 2019. However, in 2019 and 2020 there was a steep drop in plant availability, from 95.8% to 81.4%, due to a shutdown of the entire mining unit that lasted 54 days—a consequence of the collateral effects of the pandemic. Figure 2 shows the evolution of availability alongside the average daily plant throughput.

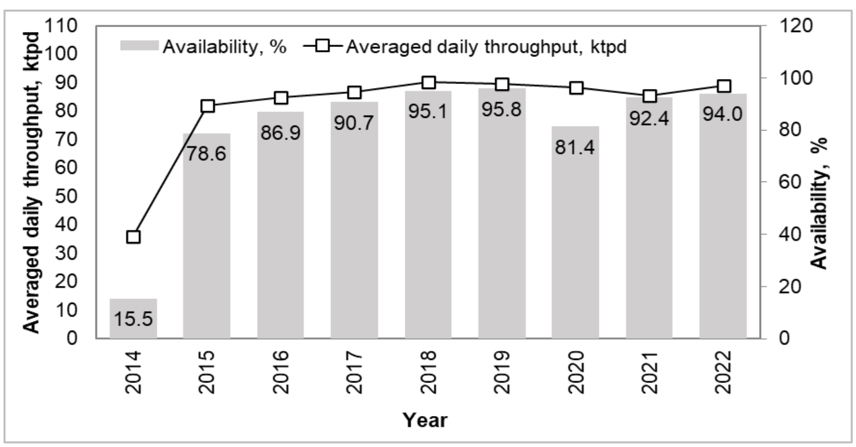

Figure 2—Evolution of plant availability

Another relevant impact on SAG mill performance is ore hardness. Figure 3 shows the increasing hardness in terms of the SAG Power Index (SPI) over time and the corresponding plant production on a yearly basis. At the beginning of the operation, ore processed from the first mining phases featured low hardness, as rock competence and alteration were of the skarn type with supergene and mixed mineralization, which favoured mill performance.

From 2018 onwards, mining commenced exploiting more competent rock sectors (hypogene mineralization, potassic and propylitic alterations), which slowed down the throughput increase in 2019, unleashing a series of challenges for both plant and mine teams.

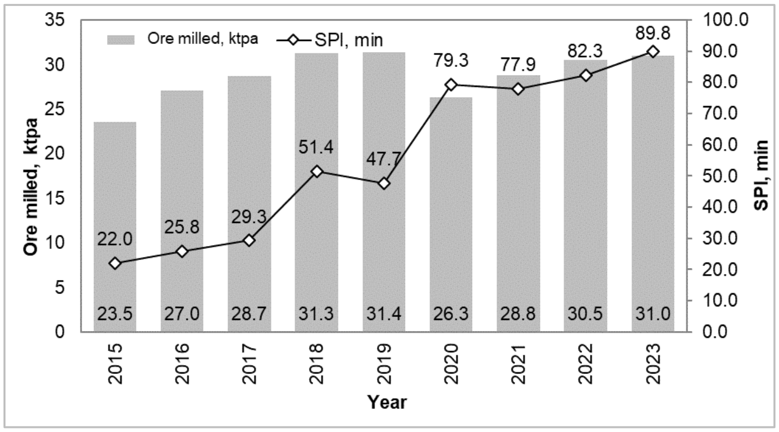

Figure 3—Evolution of SAG Power Index to Date and the Corresponding Ore Milled Per Year

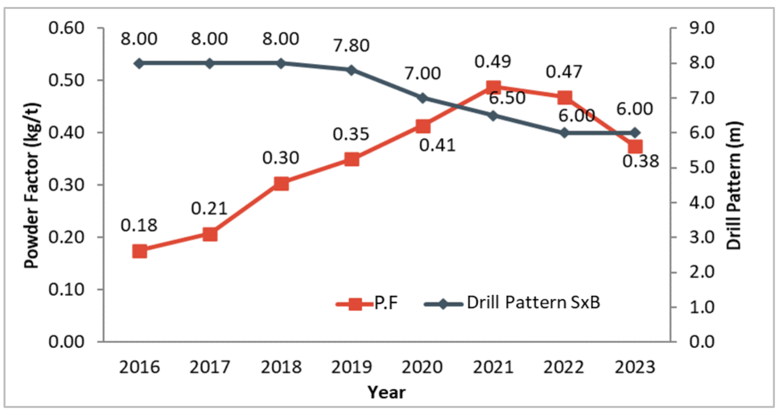

Figure 4—Variation of Powder Factor and Drill Pattern—2016 to 2023

Based on the performance results derived from new rock properties, Hudbay activated the mine-to-mill project led by the Plant Operations and Technical Services areas (including mine planning, mine operations, drill and blast, geology, among others) with the aim of determining the best ore particle-size distribution (PSD) to be fed to the plant. The blast powder factor (PF) was adjusted progressively and aligned to the corresponding ore hardness (Figure 4). However, in 2023, PF decreased due to mining new sectors from the new Pampacancha satellite ore body, which features softer ores. Burden and spacing were kept the same.

After several industrial trials at the plant, a target for the SAG feed size was finally defined, equivalent to 47% of fines (−1 inch). Then, Split-Online cameras were installed to monitor continuously the PSD from trucks dumping at the primary crushing chamber, as well as the primary crusher product and SAG mill feed.

In addition to this improvement, a series of initiatives were implemented in the plant, described below:

Implementing a New Expert System for Grinding

In late 2018, an expert system was implemented for primary and secondary milling based on fuzzy logic and "IF–THEN" rules, whose main goal was to maximize the primary milling feed rate. The evaluation of the expert system's effectiveness was carried out through an ON–OFF test every 12 hours for 4 weeks. Validation of the results was performed using the student's t-test hypothesis for difference of means. The evaluation concluded that the ore treated in primary milling increased by +3.7% with the expert system ON versus OFF. Similarly, a reduction of feed rate variability was observed.

Replacement of Krebs Cyclones by Cavex Cyclones

In the last quarter of 2019, Krebs cyclones (design) were replaced with Cavex cyclones with Air Core Booster (ABC) (Figure 5). The cyclone replacement was implemented in grinding Line 1 only, and the impact on classification performance was evaluated by comparing with the performance of Line 2 (original Krebs cyclones).

After six months of operation, the results indicated that Cavex cyclones were able to process higher slurry flow in the cyclone feed (which increased from 13% to 15%) while using from two to four fewer cyclones. This enabled better dilution of the cyclone feed and reduced the fine particle by-pass by up to 5% to 7%. Moreover, the overflow P_{80} was not affected by reducing the number of operating cyclones.

Figure 5—Photos of Cyclones Cavex with ACB Devices Installed at Constancia Grinding Circuit

Installation of Hybrid Liners in Ball Mills

Constancia mine was the first operation in the world to implement 100% hybrid liners in large ball mills (26 feet [ft] x 41 ft) (Figure 6). In 2016, the first industrial trials were carried out by installing hybrid rubber–metal liners on the feed and discharge trunnions of the ball mill; subsequently, in the first half of 2017 hybrid liners were installed in the entire mill (feed head, shell, and discharge head). The main benefits identified with this change were:

- Reducing mill weight by 170 tonnes
- Increasing ball charge level by 2%

- Increasing mill protection due to lower weight and reduced starting torque
- Reducing bearing pressure by 640 kilopascals
- No effect on the PSD sent to flotation.

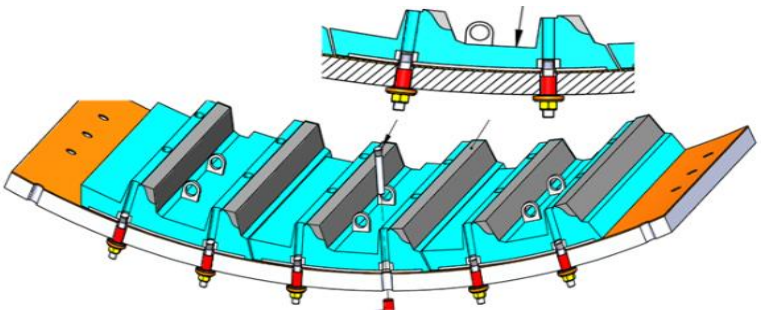

Figure 6—Schematization of Hybrid Liner System Installed at Constancia Ball Mills

Increase of the Slot Aperture of SAG Mill Trommel

Original dimensions of the trommel slots of the SAG mills were 15 x 40 millimetres (mm). Subsequently, the slot dimensions were increased to 20 x 40 mm for SAG 01 (Line 1) and to 18 x 40 mm for SAG 03 (Line 2). The main objective of this change was to increase the 80% passing transfer size (T_{80}) from SAG mills to ball mills. The comparative results of the trials conducted in Line 2 are shown in Figure 7.

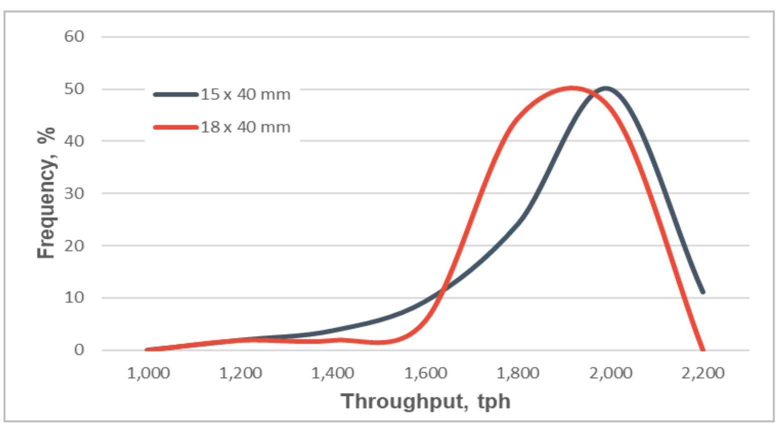

Figure 7—Comparing Plant Throughput with Trommel Slots of 15 x 40 mm vs. 18 x 40 mm in Line 2

Although the impact of this change was not significant (small gains of +43 tonnes per hour (t/h) for Line 1 and +22 t/h for Line 02 were obtained), it is worth mentioning that increasing the slot aperture did not result in significant negative impacts; nonetheless, the following were noticed:

- Increased circulating load in ball mills
- Higher stress on cyclone pumps
- Increase of P_{80} to flotation (+5 µm).

Minimal impact on copper recovery can be expected from a slight coarsening of P_{80}. However, the production of fine copper increases significantly despite the small decrease in recovery due to the increased production rates.

Grinding Media Size in SAG Mills

In late 2021, Hudbay changed the reloading ball size of SAG mills from 5 to 5.5 inches. The change to a larger ball size was justified due to the need for increased kinetic energy at the toe, especially due to the increased ore hardness and consequently coarser SAG feed.

Particle energy spectra simulations showed that the 5.5 inch ball distribution and its interactions with the different ore fractions generate a higher energy input in the range of ore size between 1 and 3 inches. Another benefit was the reduction of steel consumption rate due to lower specific surface area (362 grams per tonne [g/t] to 325 g/t).

Change from Radial to Curved Grates and Pulp Lifters in SAG Mills

Throughout the years of Constancia's operation, several evaluations have been conducted regarding the design of liners in both SAG and ball mills. Some of the most noticeable evaluations include the use of different profiles (High–Low, High–High), shell angle face (25°–32°), metal–rubber components in the feed and discharge heads and grates, and different grate apertures (50–70 mm), among others.

To improve the discharge capacity of the SAG mills, grates and curved pulp lifters were assessed. The curved discharge system is compared to the original radial design with 50 mm aperture in Figure 8.

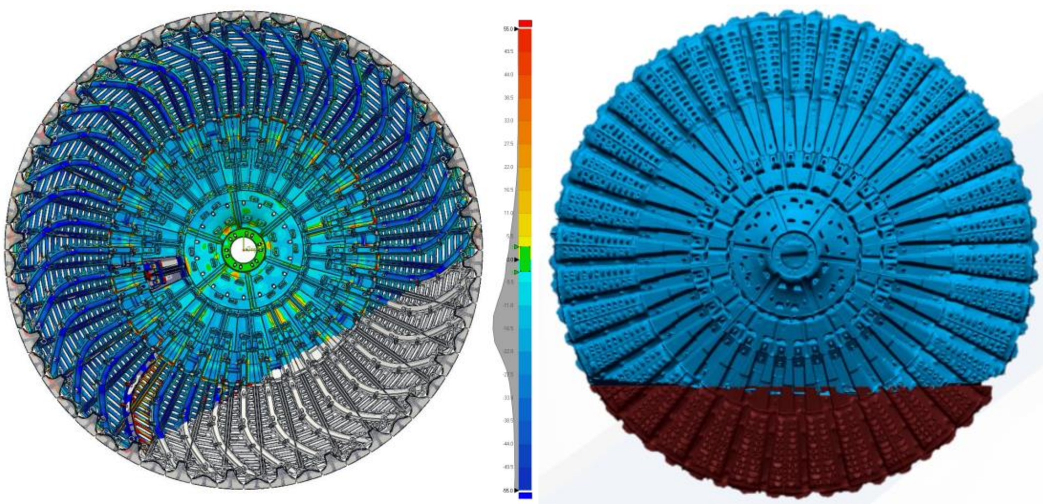

Figure 8—Comparison of Curved (Left) Versus Radial (Right) Grates and Pulp Lifters

The change from radial to curved discharge systems was implemented in grinding Line 1 (SAG 01). The performance evaluation was carried out by comparing SAG 1 against SAG 03, which kept the radial system. Based on these results, it was determined that the feed rate was higher by 1% with the curved grates in SAG 1, with a 95% confidence interval. The comparative histograms are shown in Figure 9.

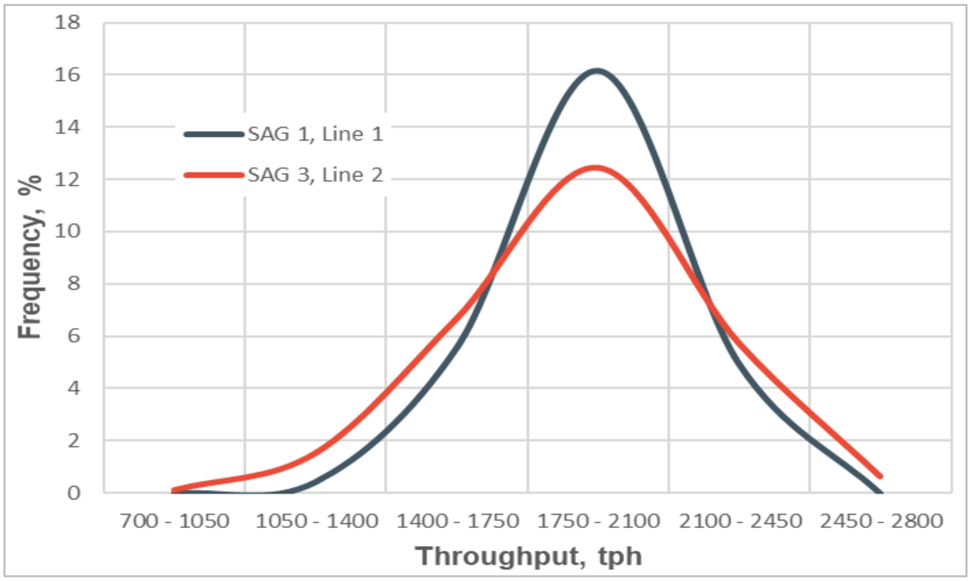

Figure 9—Comparison of Throughput Between Curved Discharge System (SAG 1) vs. Radial System (SAG 3)

New Challenges Using Machine Learning

Hudbay is also at forefront of new technologies that are currently being used in mining and minerals processing, such as machine learning. Although, this project is still in an early stage at Constancia, the primary objective of this project is the throughput forecasting for each grinding line by using machine learning algorithms. Twelve predictive models have been developed, the most relevant being the throughput and P_{80} forecast model.

The weighted mean absolute percentage error was used to calculate the accuracy of these models, which are summarized in Table 1.

Table 1—Weighted Mean Absolute Percentage Error

	Grinding Line	
Variable	**No. 1**	**No. 2**
Feed Throughput	7.33%	5.56%
P_{80}	7.97%	6.70%

Accurate throughput forecast models are valuable tools that enable an enhanced production reliability, strategic planning and maximize profit over the life-of-mine. Power-based modelling is widely adopted for comminution circuit design and can also be used for forecasting when the future ore properties are known. However, the percentage of fines (−10 mm) in the SAG feed, which has a strong influence on SAG mill throughput (Morrell & Valery, 2001) is generally not accounted for in throughput forecast models due to challenges in predicting the fraction of fines in the SAG feed. With the information of ore characteristics, additional factors can be included in the existing equations, representing another opportunity to increase the accuracy of these models—factors such as run-of-mine (ROM) fragmentation measurements (including content of fines %−10 mm), process data, and power-based and JK mathematical models developed during the optimization project conducted with Hatch (as explained later).

Changes in Feed Ore Characteristics

Historically, Constancia has processed predominantly supergene, skarn, and mixed ores with soft to medium hardness, but the proportion of harder hypogene ore in the feed is increasing as aforementioned. As mining advances, the harder hypogene ore is becoming the dominant ore type, which is reflected in increasing SAG Grindability Index (SGI) (similar to SPI) and Bond Work index (BWi); Figure 10 features the cumulative distributions of these hardness indices for different periods.

The hypogene ore has high resistance to impact breakage (SGI: 60–100 minutes or Drop Weight index (DWi): 5.0 to 7.5 kWh/m^3), which affects SAG milling, and also high resistance to fine grinding in ball mills (BWi from 16 to 18 kilowatt hours per tonne [kWh/t]). A comparison of previous plant surveys conducted while treating a typical feed blend (about 75% hypogene) versus a feed of 100% hypogene ore have shown a significant reduction in plant throughput (from about 1,900 to 2,000 t/h to 1,350 to 1,550 t/h), which has led to an increase in specific energy consumption (from about 7 to 8 kWh/t to 10.5 to 12 kWh/t).

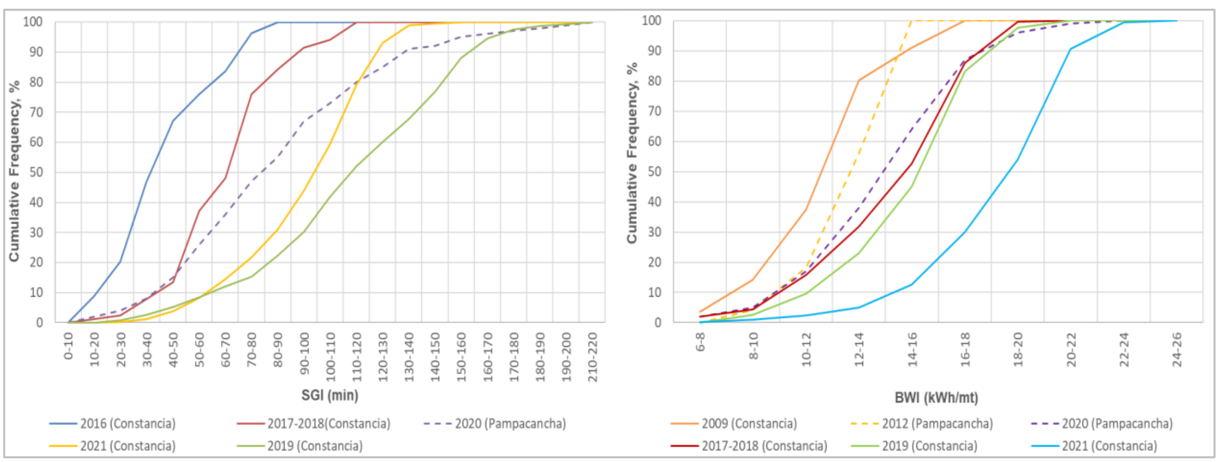

Figure 10—Cumulative Distributions of SGI and BWi Across Different Years

To demonstrate the influence of feed ore characteristics, a comparison was made between the current SAG mill specific energy and historical data from other operations with similar ore hardnesses (Figure 11). Models of the relationship between specific energy and ore hardness (Axb) are given for two feed sizes, SAG F_{80} 120 mm in grey and F_{80} 60 mm in yellow. The red rectangle represents the range of SAG operating conditions from 2021 to 2022 at Constancia, and the SAG specific energies are within a similar range to other operations with comparable hardness and feed sizes. However, when treating 100% hypogene (as indicated by March 2020 survey data), the specific energy increases significantly, as expected, due to the increased hardness of the hypogene ore.

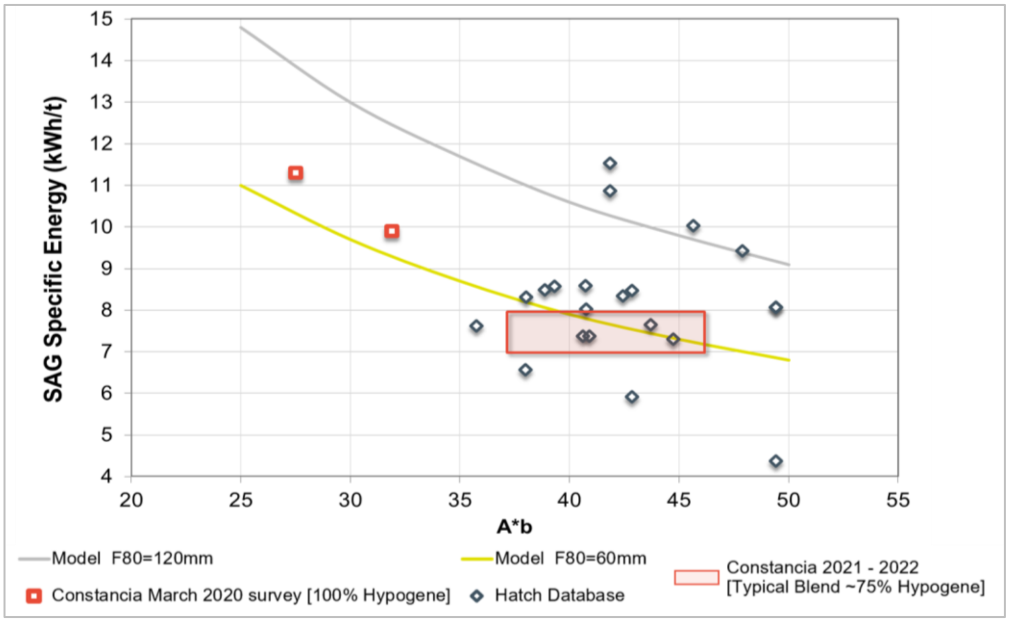

Figure 11—Benchmarking of SAG Mill Specific Energy with Similar Range of Ore Hardness from Hatch Database

Optimization of Constancia Comminution for Future Ores with Hatch

As discussed above, Hudbay has already surpassed the design throughput of the Constancia comminution circuit with implementation of many improvements, and the circuit is well operated. However, the operation is facing increasing ore hardness, which will impact throughput and energy consumption. In addition, the increase in throughput has been achieved at the expense of coarser product size to flotation. This is often a good strategy; with higher throughput more than compensating for any recovery losses associated with coarser product size. However, the trade-off between high throughput and coarser product size and flotation recovery should be investigated to determine the optimum target P_{80} to increase overall production.

To address these challenges, Hatch Consulting & Technology was contracted to review and further optimize the Constancia comminution circuit, particularly considering the increasing ore hardness. The project objective was to determine the best operational strategies to either maximize plant throughput or achieve the best balance between maximum throughput and optimal product size using the existing assets.

The Hatch approach involves looking holistically at an operation from the mine to the processing plant. Every ore body and mining operation is different, so a detailed understanding of the ore characteristics, and the corresponding response of mining and processing operations are required to maximize throughput while minimizing costs and maintaining product quality. Therefore, the Hatch methodology is supported by extensive auditing, surveys, data analysis, mathematical modelling, and simulations.

At Hudbay Constancia, the focus was on the comminution circuit performance, and a substantial number of surveys had already been performed covering several different feed blends. Therefore, Hatch conducted a comprehensive review of the available rock characterization information, previous surveys, optimization projects and reports, historical and recent comminution production data. Using all this information, and the extensive Hatch database for benchmarking, Hatch developed and calibrated site-specific process and power-based comminution models and conducted a detailed simulation study to develop optimal operating strategies to maximize throughput while maintaining or reducing the P_{80}.

BLAST OPTIMIZATION

Blasting can be the cheapest and most energy-efficient rock breaking stage. The size distribution of the blasted material has a significant impact on the entire process, especially the throughput and energy consumption in the downstream crushing and grinding operations which, in turn, impact the performance of the subsequent separation processes.

The ROM fragmentation at Constancia was suitable for handling downstream load-and-haul and crushing equipment and acceptable (on average) for downstream operations. However, there was considerable variability ranging from P_{80} 70 to 527 mm, and fines (−10 mm) content ranging from 4% to 48% (Figure 12). This has a significant impact on SAG milling performance as observed at many operations globally (Valery & Samuel 2012; Valery et al., 2018, 2019a, 2019b; Valle & Duffy, 2014). The ideal ROM fragmentation to maximize throughput and performance will depend on the ore characteristics, and the downstream equipment and circuit arrangement. In general, for SAG mill circuits, higher throughput may be achieved when the SAG mill feed has as fine a top size as possible, the smallest possible amount of 25–75 mm intermediate size material, and the maximum amount of −10 mm fines (Valery et al., 2019a). Improving ROM fragmentation, in particular increasing fines generation, should improve performance and stability of the downstream comminution circuit at Constancia without capital expenditure.

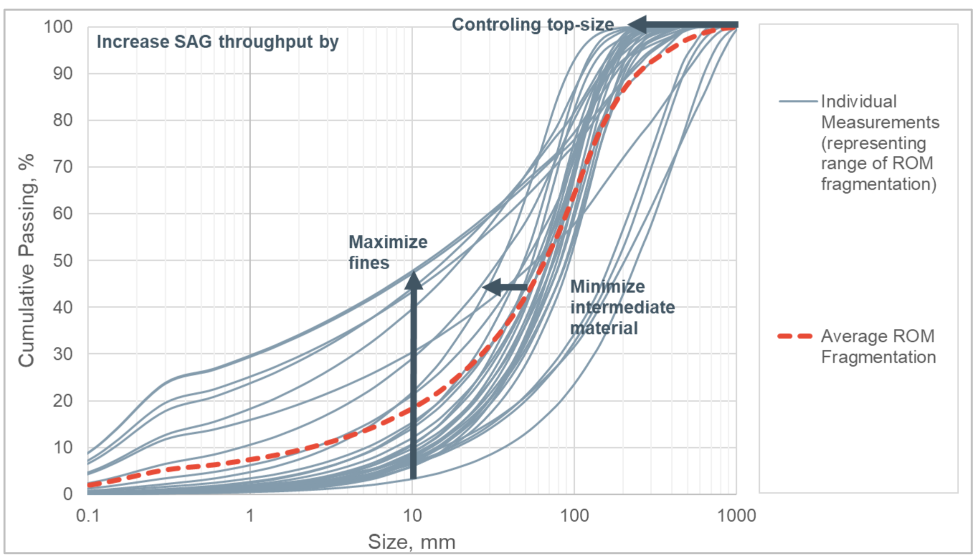

Figure 12—Measured ROM Fragmentation at Constancia

The ROM fragmentation that blasting generates is strongly influenced by in situ ore properties, in particular rock mass structure (expressed by rock quality designation [RQD]) and rock strength (expressed by unconfined compressive strength [UCS] for relevance to blast fragmentation). The fines generated in the crush zone around the blasthole are governed by rock strength, whereas the coarse particles are driven by rock structure.

The rock mass at Constancia is fractured to highly fractured, which is beneficial and contributes to the relatively fine SAG feed size. However, the UCS at Constancia is highly variable, and is increasing as mining progresses. This will reduce the fines (% −10 mm) generated in blast fragmentation, which is detrimental for plant throughput and performance.

Constancia has recognized the benefit of improved blast fragmentation and has already increased PF with increasing ore hardness. However, this optimization can be taken even further, for greater benefit, by adjusting blast designs for different ore domains, which are defined based on rock structure and strength. Higher blasting intensity is applied in harder and blockier domains to improve ROM fragmentation and increase throughput of downstream comminution circuits, while less energy is required in more fractured and softer domains to reduce costs and maintain productivity in the mine. The Hatch blast fragmentation model is sensitive to the major parameters known to affect blasting performance (e.g., rock mass strength and structure, and blast design parameters such as burden and spacing). Thus, once calibrated, the model can be used to determine optimum blast designs for each ore domain, to improve ROM fragmentation for downstream processes while minimizing cost and maintaining productivity in the mine.

The focus of the project at Hudbay was on performance of the comminution circuit, and blasting was not included in the initial project scope. However, preliminary modelling and simulations indicated scope for improvement through optimizing blasting to improve ROM fragmentation.

COMMINUTION OPTIMIZATION

Analysis and review of the Constancia comminution circuit was conducted using process historical data from June 2021 to July 2022, and survey data with typical feed blend and 100% hypogene ore; it also included a review of internal components of main equipment and grinding media. The main findings of this analysis are summarized below.

Assessment of Plant Operating Data

The primary crusher was slightly underutilized, with power draws ranging from 200 to 400 kW for 75% of the time, compared to the rated power of 1000 kW. This is explained mostly by the predominantly relatively fine ROM PSD, which represents an opportunity to reduce the gap setting. However, it is crucial to reduce the current fragmentation variability observed and accommodate current liner geometry to prevent any volumetric constraints. Thus, this should be done in combination with the recommended blast optimization.

The SAG mills were generally treating around 1,900 to 2,000 dry t/h per line. Typically, the mills were drawing very high power, more than the original rated power of 16 MW. However, Hudbay made some motor improvements, allowing the mills to draw up to 16.5 MW (Figure 13). The SAG mills speed typically varies between 75% and 77% of critical speed, which is in line with typical operating speeds observed in the industry.

The SAG mill feed size is relatively fine, and the absence of coarse rocks to act as grinding media means most of the breakage energy must be imparted by the ball charge. In such a scenario, the recommended mode of operation of the SAG mill is to maximize ball charge while reducing the total charge and operate like a large ball mill. This maximizes the ball breakage events, and therefore improves SAG mill throughput.

SAG power curves for ball charges from 12% to 18% were estimated using the Morrell mill power model for a SAG mill speed of 75% critical (Figure 14). The ball charge was estimated to be around 12% to 15% and could be increased up to 16% to 17% with total load reducing to about 20% at maximum power of 16.5 MW to optimize conditions for the fine SAG feed size.

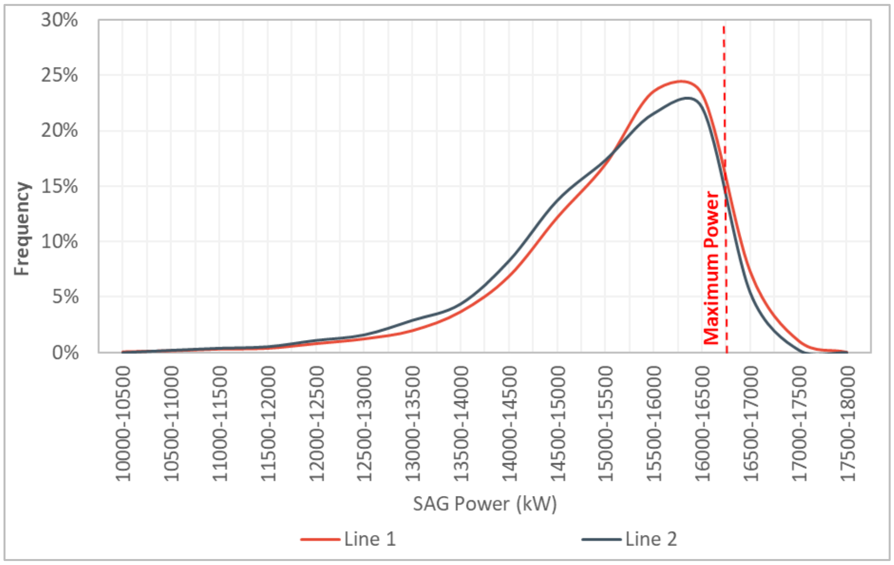

Figure 13—Histogram of Constancia SAG Mill Power Draw (January 2021 to July 2022)

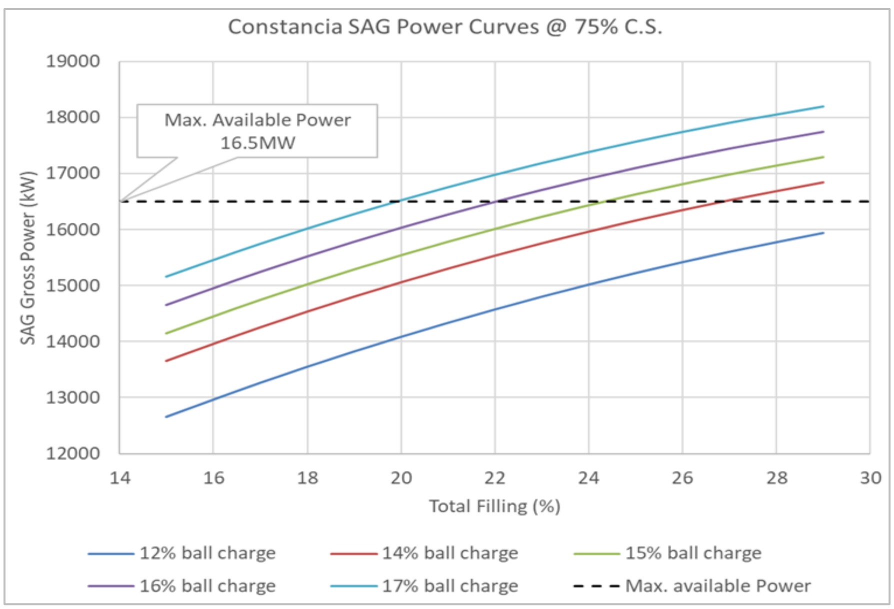

Figure 14—SAG Mill Power Curves as a Function of Ball Charge and Total Load

The ball mills were also operating at maximum power draw due to motor improvements. The ball mills draw very high power, with both mills operating above 90% of the total available power (Figure 15). However, the Line 1 ball mill is drawing higher power than Line 2 ball mill. Both mills were operating with a wide variation in power draw, which could be a result of variation of ball charge levels, given that the ball mills, unlike SAG mills, are operated with fixed speed drive of 75% critical.

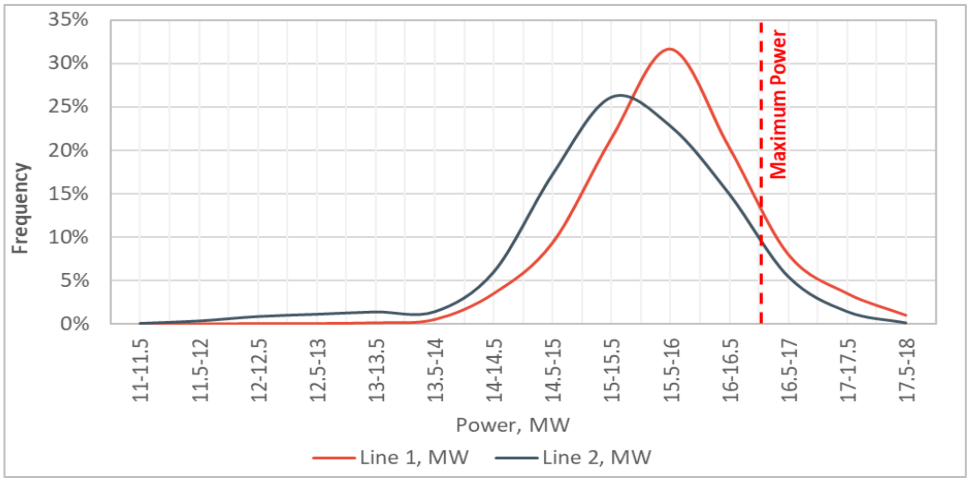

Figure 15—Histogram of Ball Mill Power Draw (Jan 2021 to Jul 2022)

Liner Review and Ball Size Analysis

From the review of the liner design and configuration it was determined that, for the current conditions and SAG feed size, there is an opportunity to further optimize the liner design. The shell lifter profiles shown in Figure 16 (Left) represents the shape of the majority of lifters; however, there are some departures from this design as shown in Figure 16 (Right), where the lifter is almost square, which may affect outermost ball trajectories especially when liners are new. Vendors usually tend to make these changes to compensate for the lack of steel around the bolt holes for the lifters; however, the inclusion of variable lifter profiles also produces different outermost trajectories, as shown in Figure 17.

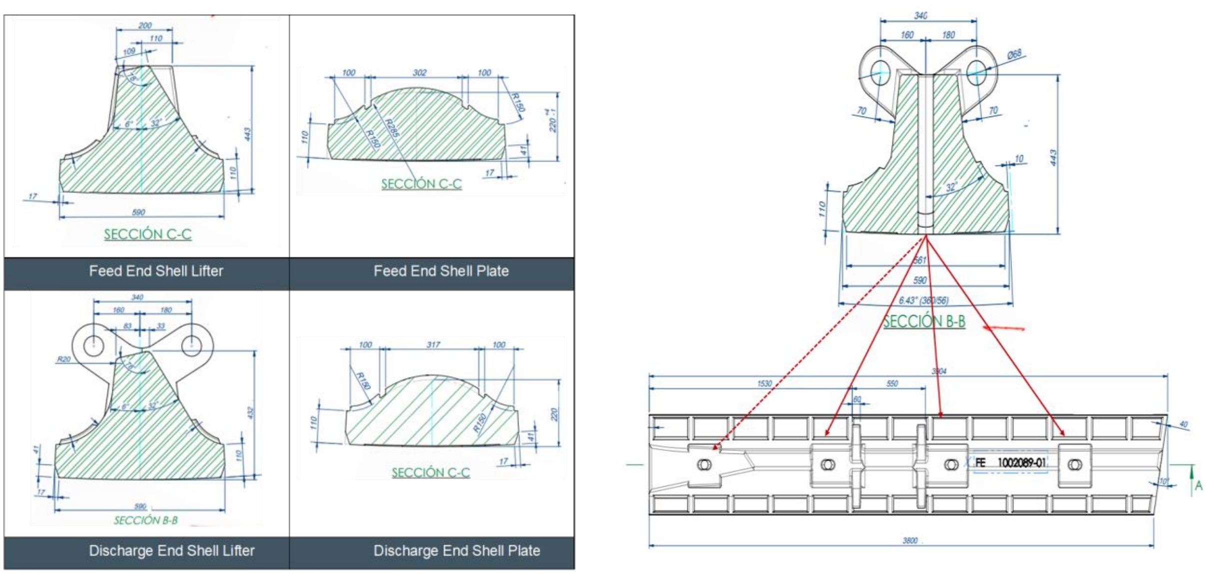

Figure 16—Summary of Cross Section Profiles of Nominal Lifter and Shell Liner Design (Left) and Shell Lifter Design at Bolt Hole (Right)

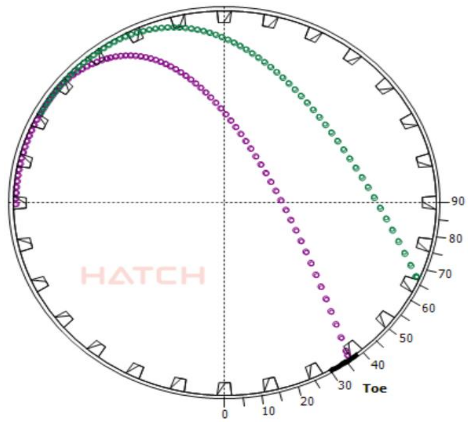

Figure 17—Shell Trajectory Comparison for Nominal Lifter (Purple) and at Bolt Hole (Green)

When the lifter is new, most of the outer charge is expected to strike the toe (purple line); however, with a square lifter the outermost trajectory is likely to be much more aggressive (green line), which in turn causes much more ball-on-liner collisions, and therefore higher steel wear rates and reduced milling efficiency. Thus, design modifications are recommended to produce a consistent liner profile and trajectory. Additional modifications are also recommended, as the operation of the SAG mill is adjusted to be more like a large ball mill. This will require a less aggressive profile to maximize grinding efficiency in this mode of operation and avoid damaging liners.

With respect to grinding media, ores at Constancia are slightly abrasive. Measured ball size distribution in both SAG mills featured well graded and similar profiles (Figure 18), with no signs of balls segregation or broken balls. Nevertheless, some deformation was observed (although not severe), which can be a secondary effect of the aggressive liners profile at bolt hole.

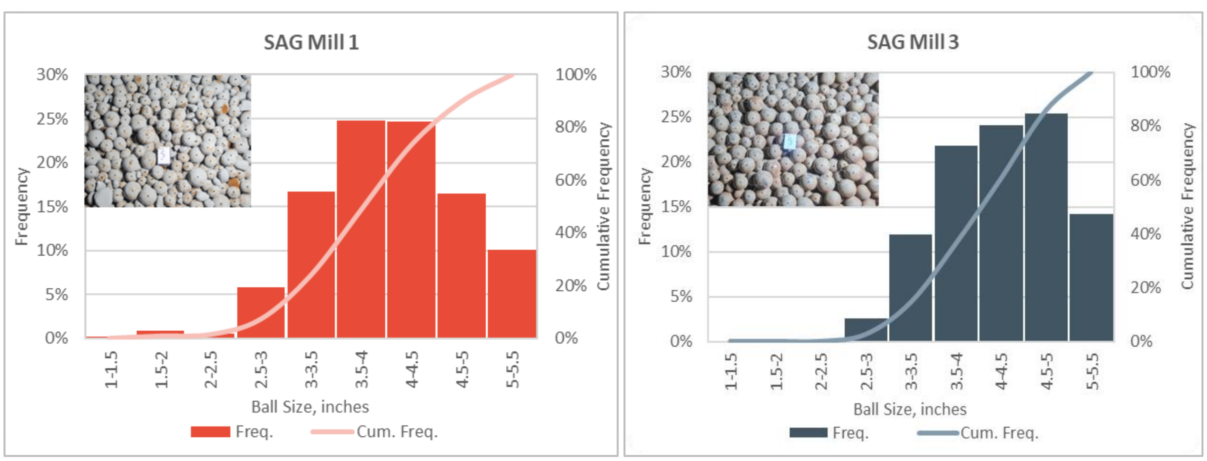

Figure 18—SAG Mill Ball Size Distribution from Image Analysis

Comminution Surveys with Typical Blend and 100% Hypogene

To understand the impact of the increasing proportion of harder hypogene ore, and to develop mitigating strategies, Hatch reviewed historical comminution circuit surveys provided by Hudbay, and compared surveys treating typical feed blend (73%–78% hypogene) against to surveys treating 100% hypogene ore. The comparison included two surveys conducted in 2020 while processing 100% hypogene ore. A summary comparison of key variables (throughput, power draw, specific energy, and circuit product P_{80} size) for each survey for Line 1 is shown in Figure 19. Similar trends were observed for Line 2.

The comparison revealed that processing 100% hypogene ore resulted in reduced throughput and increased SAG specific energy consumption (kWh/t) compared to the typical feed blend, likely due to the greater proportion of harder hypogene ore. Ball mill specific energy also increased; however, the product size decreased. This is because the ball mill has sufficient power to grind the ore finer due to the reduction in throughput.

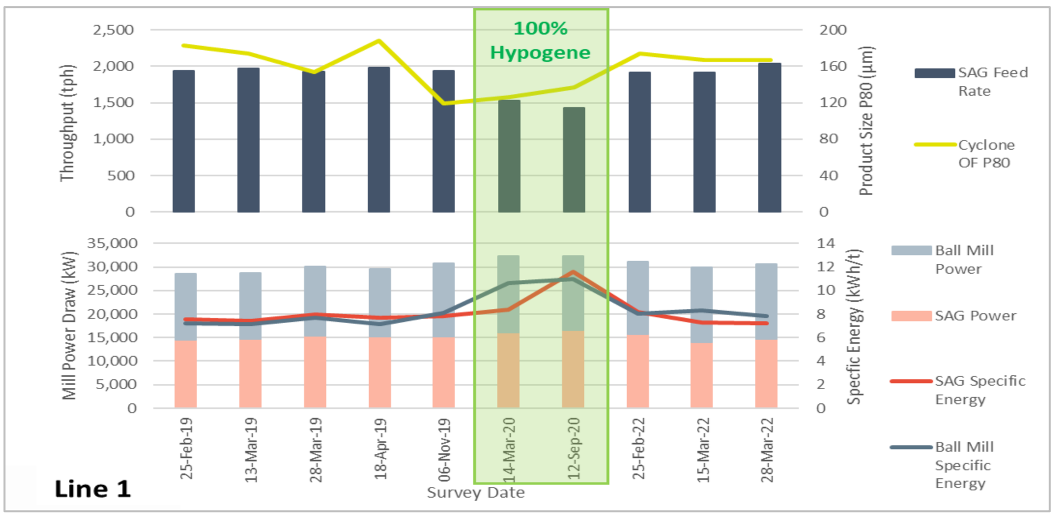

Figure 19—Survey Summary for Line 1

Process Modelling

Site-specific process models were developed for both the typical feed blend and 100% hypogene ore. These models allow simulations to determine the impact of the harder ore, evaluate possible circuit changes and determine optimum operating strategies.

The models were developed using all available information, including ore properties, operating data, previous plant models, and historical survey results. These were used in conjunction with complementary measurements of current fragmentation and ore characteristics to calibrate the mathematical process models using JKSimMet.

The first step was to perform a mass balance to confirm the data validity and calculate any missing streams. The data provided achieved a good reconciliation and were considered suitable for model development.

Comminution process models require both machine parameters (dimensions and operating conditions) and ore physical characteristics such as ore hardness (DWi or Axb, BWi) and specific gravity. Since most of the comminution properties were expressed in terms of SPI, Hatch established a site-specific correlation for these ores to convert them into DWi (kWh/m³) breakage parameters according to Equation 1, thus enabling their use in both Morrell's power model and JKSimMet simulations.

$$DWi = 0.16\ (SPI)^{0.84} \qquad \text{Eq. 1}$$

Model parameters (fitted parameters) are then used to calibrate the models to the survey conditions. Models were calibrated for each piece of equipment, then combined in an overall comminution circuit model. These fitted parameters either remain fixed in all subsequent simulations or are scaled by the underlying models in response to changes in the machine or ore parameters.

Overall, the fitted (calibrated) model correlates well with the available survey and historical operating data. The fitted model represents a best estimate of the steady-state conditions of the circuit at the grind size observed during the survey.

In addition to the site-specific calibrated process models, Hatch compares with and uses Morrell's global mining standard approach for determining comminution circuit specific energy (GMG, 2021), which has been validated by a database of over 100 different circuits and ore types. The required specific energy of the comminution circuits and equipment are predicted using the results from laboratory tests (SMC test and BWi) on representative ore samples. The predicted specific energies from both the site-specific process model and Morrell calculations aligned well with the SAG and ball mill actual specific energies (Table 2).

A comparison of the typical feed blend with 100% hypogene ore reveals a significant difference in both SAG and ball mill specific energy. The proportion of hypogene ore in the typical feed blend is only marginally lower, ranging from 73% to 78%, when compared to 100% hypogene ore. However, this results in an increase in ore hardness from an Axb value of 40 for the typical feed blend to 30–32 for 100% hypogene ore. Given that the SAG feed size in both cases are similar, the main driver for the increase in specific energy is the change in ore hardness.

Overall, the site-specific comminution circuit model aligns well with the survey data and Morrell's energy-size calculations, and are therefore, considered suitable for simulations and evaluation of improvement opportunities. The models were used along with historical operating data trends, power-based modelling, benchmarking, and operating experience to conduct simulations and identify strategies to improve performance, particularly when treating harder hypogene ores.

Table 2—Comparison of specific energy calculations

					SAG Mill Specific Energy (kWh/t)			Ball Mill Specific Energy (kWh/t)		
Blend	**Process Line**	**Axb**	**BWi (kWh/t)**	**F_{80} (mm)**	**Actual**	**Process Model**	**Morrell**	**Actual**	**Process Model**	**Morrell**
Typical Feed	Line 1	40	17.0	56	7.6	7.6	7.6	7.5	7.5	7.4
	Line 2	40	17.0	67	7.8	7.8	7.8	7.2	7.3	7.6
100% Hypogene	Line 1	31.9	18.7	73	9.9	9.8	10.3	10.0	10.0	10.5
	Line 2	30.5	18.4	68	11.1	11.0	10.5	10.1	10.2	10.8

Results

SIMULATION RESULTS

Analysis of historical operating data and survey data has shown the Constancia SAG mills and ball mills are drawing very close to maximum rated power. The ball mill circuit recirculating loads are relatively high, and the cyclones have increased capacity using ABC devices, as mentioned previously. These factors indicate that the grinding circuits are well operated and are at or very near maximum capacity. However, some opportunities for further optimization were identified, especially for harder ores, and the expected benefits from simulations are summarized in Figure 20.

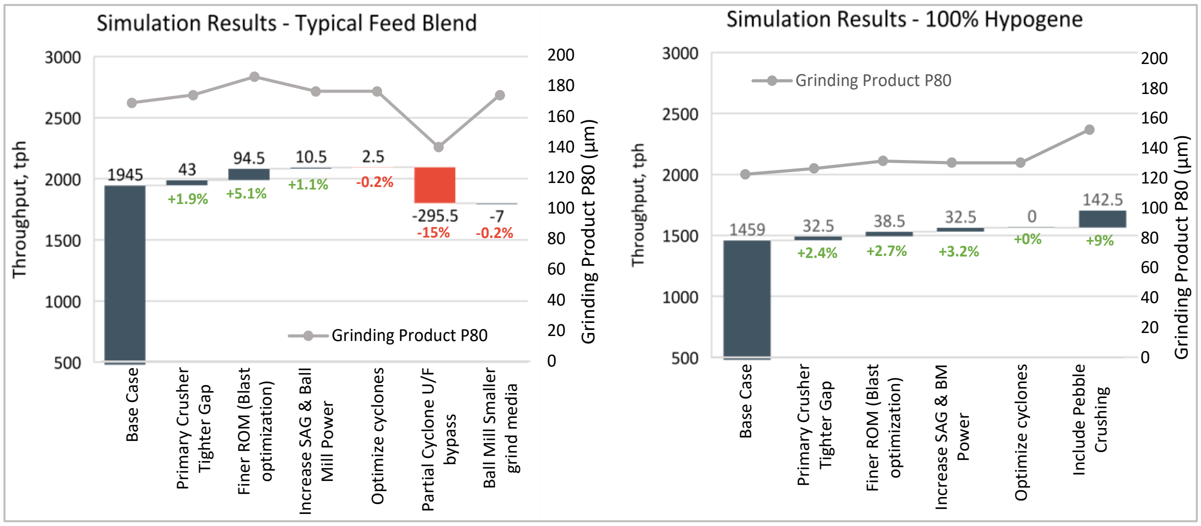

Figure 20—Simulation results

While only a preliminary analysis of blast optimization was conducted, it has shown great potential to increase throughput at Constancia. This is especially significant when combined with primary crusher optimization through further tightening of crushing gap and modification of liner geometry. SAG mill feed size has a considerable impact on throughput and efficiency, particularly for harder ores, such as those observed in many operations globally. The primary crusher at Constancia is currently operating with a reasonably tight gap of approximately 5.5 inches. However, finer ROM fragmentation resulting from blast optimization can often allow for operation with a tighter closed-side setting (CSS) without compromising the primary crusher volumetric capacity, and there is available crusher power.

Constancia SAG mills and ball mills are drawing very close to maximum rated power, and the ball mill circuit recirculating loads are relatively high. Therefore, while there is only limited scope for increasing power, some additional throughput gains may be achievable by further maximizing both SAG and ball mill power draw up to 16.5 MW by reducing current fluctuation of media charge level. The benefits would be most significant for the harder hypogene ore.

Overall, implementing all proposed optimization strategies, including blast optimization, tightening the primary crusher CSS, and increasing SAG and ball mill charge levels and power, could lead to a potential 6%–8% increase in comminution circuit throughput without incurring in any additional capital expenditure. However, it is important to note that increasing throughput may result in a coarser product size, which can negatively impact flotation recovery. Preliminary analysis indicates that, on average, rougher copper recovery drops by around 0.3% for every 10 µm increase in P_{80}.

It may be possible to mitigate the coarsening of product size by maximizing ball mill power. This would require the ball mills to consistently operate at approximately 33%–34% ball charge. Also, optimizing the cyclones through adjusting the smaller spigot and cyclone operating conditions may improve classification efficiency and reduce cut size. Simulations also indicate that a minor improvement in product size may be achieved by using a smaller media size of 65 mm for ball milling. However, in practice it may not be possible to observe the differences.

There is facility in the Constancia grinding circuit to partially split the cyclone underflow from the ball mill circuit back to the SAG mill. Typically, this presents an opportunity to use available motor power in the SAG mill and remove some grinding requirements from the ball mill circuit. However, the SAG mill power is already very well utilized, making this strategy less attractive. Simulations indicate this would reduce product size, but at the expense of lower throughput.

Pebble crushing is very effective when treating hard ores, so the installation of pebble crushing was evaluated to determine the potential to increase throughput when treating 100% hypogene ore. Simulation indicates that an additional 9% increase in throughput could potentially be achieved, provided the crushing circuit is sized and selected appropriately for the required duty. This increase in throughput for 100% hypogene ore can be achieved without exceeding the target product size of 160 µm. This is a good strategy for tackling harder feed, and it is currently scheduled for commissioning in 2024.

Hudbay Constancia is in the process of implementing the changes and recommendations delivered from this study to mitigate the impact of increasing ore hardness and maximize plant performance.

Conclusions

Hudbay achieved commercial production at Constancia rapidly, and through several improvements implemented in the plant and in the mine now consistently operates above the design throughput of 76,000 t/d. However, this comes at the expense of coarser product cut size to flotation. This is often a good strategy as higher throughputs may more than compensate for recovery losses related to the coarser product size.

Hudbay is also tackling increasing ore hardness at Constancia pit, which is negatively impacting the plant throughput. Historically, Constancia has processed predominantly supergene, skarn, and mixed ores with soft to medium hardness. As mining progresses, the dominant ore type is the harder hypogene ore, which has high resistance to impact breakage (DWi: 5.0–7.5 kWh/m^3) as well as high BWi, affecting both SAG and ball milling.

Hatch conducted a detailed review of ore characteristics, ROM fragmentation, historical plant operating data, and previous plant surveys and studies. Site-specific mathematical models were developed, and simulations conducted to determine the best operating strategies to increase throughput with increasing ore hardness, while maintaining or reducing the product size and its variation.

The Constancia operation is already very well operated. However, several opportunities for further improvement were identified to maximize plant throughput by combining new operating strategies in the mine, primary crushing, SAG milling, ball milling, and cyclones. Once fully implemented, this should enable a throughput increase of between 6% and 8% while maintaining the product size close the product target. The project also confirmed the benefit (expected ~9% throughput increase) of installing pebble crushing to tackle the harder ore, and implementation of this and the other recommendations are underway.

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