Mine-to-Mill Optimization and Continuous Improvement of Lundin Mining's Chapada Operation in Brazil

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Abstract

Chapada's open pit copper–gold mine and processing plant commenced operation in 2007. As mining has progressed deeper, the ore hardness has increased, adversely impacting plant throughput. Therefore, Lundin, Hatch, and Enaex conducted a mine-to-mill optimization project to maximise throughput with existing equipment while maintaining comminution product size. The comminution circuit consists of two primary crushing lines followed by a semi-autogenous grinding (SAG)–ball mill–crusher circuit.

The project encompassed reviewing ore characterisation data, defining ore domains, reviewing drill and blast and comminution operating practices, analysing historical operating data, a drill and blast audit, measuring blast fragmentation, a comminution circuit survey, and developing site-specific mathematical models for blasting and comminution. Integrated simulations and analysis were used to determine optimized strategies for maximising production for the overall operation (mine-to-mill). This included developing blasting guidelines tailored for each domain to improve blast fragmentation and recommendations to improve comminution performance leveraging the finer feed. This involved changes to operating conditions (crushers, SAG mill, ball mills, and cyclones), liner design, and grinding media size and level.

Keywords

Mine-to-mill optimization, fragmentation, comminution, specific energy, throughput forecasting

Introduction

Lundin Mining's Chapada mine is a conventional open pit copper–gold operation 270 kilometres (km) northwest of Brasilia, Brazil, at 340 metres (m) above sea level. The copper–gold sulphide mineralization at Chapada is structurally hosted in a well-deformed and metamorphosed system, with comparable grades and ore mineralogy to porphyry/skarn copper–gold deposits in island arc settings. The copper mineralization is mainly chalcopyrite with minor amounts of bornite. Fine-grained gold is closely associated with the sulphide mineralization.

The mine and process plant have been in operation since commissioning in 2007. Since then, Chapada personnel have implemented several optimization initiatives in the mine and processing circuit. As the production pits expanded and depleted, new pits were developed and commenced operating. Consequently, previously uncharacterized harder ores started feeding the circuit, which constrained plant throughput.

In early 2020, to address the increased ore hardness, Chapada commenced a mine-to-mill optimization project with the objective of maximizing the comminution circuit throughput by using integrated operating strategies in the mine and plant. Project methodology involved detailed reviews of the ore-characterization data, mine drill and blast audits, comminution surveys, historical data analysis, and development of site-specific blast fragmentation and comminution models. Hatch and Enaex experts used these models, along with previous knowledge of the Chapada operation, to conduct simulations of the drill and blasting, as well as crushing and grinding circuits.

These simulations considered the differing ore characteristics for each ore domain at Chapada and were used to determine optimum operating strategies from mine to plant. The aim was to achieve the optimal run-of-mine (ROM) fragmentation and plant performance considering the different ore domains and their associated characteristics. Throughput was maximized by fully utilizing existing capacity and optimizing operating conditions for the finer feed from improved ROM fragmentation while maintaining the required comminution product size for flotation. The experts considered equipment specifications and potential customizations, as well as different operating conditions and circuit configurations and assessed the impact of changes to plant performance, energy efficiency, and product quality.

The project resulted in several recommendations in both the mine and plant. This included tailoring the drill and blast design and energy according to ore characteristics, to provide optimum ROM fragmentation to the comminution circuit. Recommendations were also provided to optimize the operating parameters of the crushing, grinding, and classification equipment, considering the changes in the feed, to increase throughput. Chapada has been progressively implementing these strategies and has achieved significant improvements in process performance and stability.

Chapada has also conducted further ore characterization campaigns for existing and future ores, as recommended, providing valuable information for further fine tuning of the mathematical models and continuous improvement.

Leveraging the developed and calibrated site-specific models, a throughput forecast model was also developed for the life-of-mine (LOM) to facilitate longer-term strategic planning. Ore hardness modelled semi-autogenous grinding (SAG) feed size, and ore blend information for the LOM feed are used to predict the average comminution specific energy using combinations of different methods and mathematical models. The effect of the fines generated by blasting, the contribution of different grade stockpiles feeding the circuit, and an existing pre-crushing plant were additional complexities that have been accounted for in the throughput forecast model. The model was validated using actual process data from January to June 2021. The initial model validation provided a mean relative error of 10% and 2.5% on monthly and annual basis, respectively, and further plant data from 2022, reported a monthly standard error of 7.5%, and annual error of 1.0%. This may also be improved further with additional ore characterisation testing which is ongoing.

This paper summarizes the work performed by Lundin, Hatch, and Enaex, and describes the results obtained from the integrated optimization of drill, blast, crushing, and grinding operations implemented to date. The most recent throughput forecast model results are also presented and compared with actual plant data.

Method

The mine-to-mill project at Chapada followed a structured methodology consisting of rock characterization and ore-domain definition (based on rock structure and rock strength); a review of drill and blast practices and fragmentation results; a review of comminution operations; a mine audit and plant survey; development of site-specific mathematical models; and integrated simulations and analysis.

There are many documented cases where Mine-to-Mill optimization following a structured methodology has maximized profitability (Rybinski, Ghersi, Davila, Linares, Valery, Jankovic, Valle, R., & Dikmen, 2011; Hart, Rees, Tavani, Valery, & Jankovic, 2011; Valery, Duffy, Faveere, Hayashida, Jankovic, Tabosa, & Yelkin, 2018). The Gold Fields Cerro Corona operation increased throughput by almost 15% for a hard ore type and 6% across all ore types, while the SAG specific energy was reduced by over 9% (Diaz, Mamani, Valery, Jankovic, Valle, & Duffy, 2015). At Antamina, throughput was more than doubled for certain hard ore types while also reducing the specific energy consumption (Valery, & Rybinski, 2012).

ROCK CHARACTERIZATION AND ORE DOMAIN DEFINITION

The in situ ore characteristics, particularly rock mass (structure and strength), have a significant impact on blast fragmentation, which in turn affects the performance of downstream load and haul operations and comminution circuits. In terms of fragmentation, the amount of fines (% <10 millimetres [mm]) produced in a blast is primarily influenced by the rock strength, and the coarser fractions are mostly determined by the rock structure. Therefore, to optimize ROM fragmentation for downstream processing, the blast design and intensity should be adjusted according to both the strength and structure of the rock mass. The aim is to produce a ROM size distribution that will maximise the throughput and efficiency of the subsequent crushing and grinding operations while maintaining safe blasts, mine productivity, and stable slopes in the pit.

During the mine-to-mill project, Hatch and Enaex conducted extensive characterization of the ores at Chapada in terms of rock strength and structure for the existing South, Central, and North pits. Samples were collected from a blast polygon audited during the project and sent for point load testing (PLT) in an external laboratory. PLT results can be used to estimate uniaxial compressive strength (UCS) which is an appropriate strength measurement for blast optimization. The collected ore strength data were complemented with the geotechnical rock mass rating (RMR) database of hardness testing and classification conducted by Chapada's Geology department. This included samples collected in different pits, lithologies, muck piles, and stockpiles for the existing pits. Structural measurements were also conducted for exposed mining faces near the audited polygon in the South pit. An example of an analysed structural image with joints and fractures mapped in the bench face for location P9 at Chapada is shown in Figure 1.

Based on all these data, ore domains were defined by the two main physical properties—rock strength and structure. This allows the blast designs to be tailored to ore characteristics to improve fragmentation, while minimizing operating costs and maintaining safe and efficient blasts. More blast energy is applied in harder and blockier domains, while less energy is required in softer and more fractured domains.

Ore within a domain has similar characteristics (structure and strength) and should present similar fragmentation when blasted using same parameters, including blast energy. The defined domains were named Soft Fine (SF), Medium Fine (MF), Hard Fine (HF), and Hard Coarse (HC), and are shown in Figure 2 along with the main lithological domains.

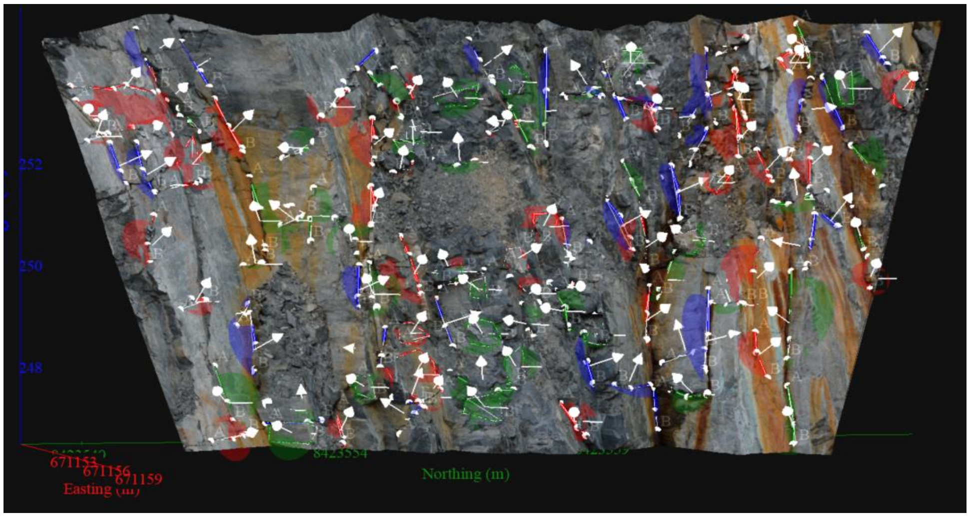
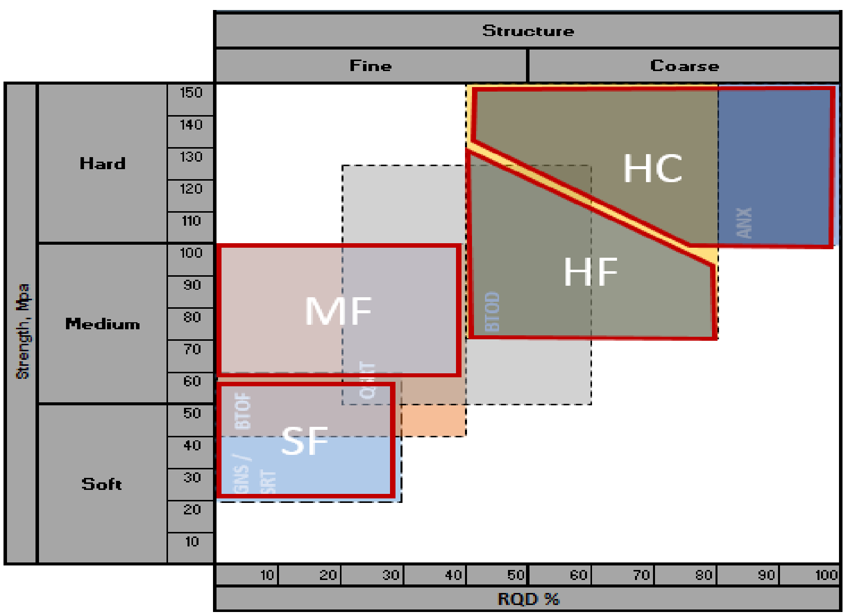


Figure 1—Example of 3D Image and Structural Analysis of Exposed Face at Chapada



Notes: Dashed-Line Boxes are labelled using Portuguese Acronyms for Lithologies: Shist Amphibolite (ANX), Foliated Biotite (BTOF), Hard Biotite (BTOD), Gneiss (GNS), Quartz Sericite (QSRT)

Figure 2—Ore Domain Definition at Chapada

Similarly, ore breakage characteristics determine the size reduction performance and power requirements of comminution circuits and are used to develop site-specific models of these processes. Historically there have been only a small number of comminution breakage tests conducted at Chapada for the main lithologies present in each pit, as summarized in Table 1. The database contained 20 tests conducted in different laboratories between 2009 and 2019, and included Abrasion Index (Ai), Bond Ball Mill Work Index (BWi), and Breakage Index (IQ). IQ is determined using a test procedure and equipment developed locally at the University of São Paulo (Chieregati & Delboni, 2002); it is similar to, but not directly comparable to the Axb parameter determined from the Drop Weight Test (DWT) by the Julius Kruttschnitt Mineral Research Centre or by the SMC test (Morrell, 2004).

Due to high ore variability, additional rock characterization was conducted during the mine-to-mill project for the audited blast polygons in the South, Central, and North pits.

Table 1—Comminution Breakage Test Summary—IQ, BWi, and Ai

Lithology	Lab 1 (2019)	Lab 2 (2018)						Lab 3 (2016)	Lab 4 (2009)	Reference
IQ										
BTO	48.74	54.70	52.60	45.10	48.90	48.70	52.40	42.90	48.70	**48.70**
BTOF	63.10	55.70	138.90	-	-	-	-	81.40	55.50	**55.70**
GNS	119.44	-	-	-	-	-	-	84.30	50.50	**67.40**
QSRT	67.63	56.90	-	-	-	-	-	-	59.30	**58.10**
BWi										
BTO	12.23	7.40	13.50	13.10	9.50	8.90	9.40	15.90	9.10	**15.90**
BTOF	13.03	13.50	15.40	-	-	-	-	12.70	11.70	**15.40**
GNS	17.39	-	-	-	-	-	-	15.70	13.90	**17.39**
QSRT	14.47	11.60	-	-	-	-	-	-	13.60	**14.47**
Ai										
BTO	-	0.139	0.137	0.215	0.151	0.143	0.155	0.191	-	**0.215**
BTOF	-	0.212	0.137	-	-	-	-	0.112	-	**0.212**
GNS	-	-	-	-	-	-	-	0.083	-	**0.083**
QSRT	-	0.183	-	-	-	-	-	-	-	**0.183**

Note: BTO = Biotite; BTOF = Foliated Biotite; GNS = Gneiss; QSRT = Quartz Sericite.

Site-specific mathematical models of the comminution circuits are required to determine the impact of improved ROM fragmentation from blast optimization and to optimize the comminution circuits for these new conditions. The comminution breakage parameter, Axb, is required for the SAG mill models.

For model development and calibration, the selected Axb parameter needs to be representative of the ore treated during the plant survey to which the model is fitted. Therefore, an appropriate Axb value was determined for the audited polygon that fed the plant during the survey. The UCS of the survey feed (determined from PLT measurement) was used to determine Axb and DWi values using correlations from the Hatch ore characterization database. The Morrell specific energy method (GMG Group, 2021) was used to check the determined ore characteristics were consistent with the power, throughput and grind size achieved during the survey. The estimated Axb was 66 and DWi was 4.24 kilowatt hours per cubic metre (kWh/m^3). Therefore, the survey ore is classified as having moderately low resistance to impact breakage. Also, despite the increasing ore hardness, the ore at Chapada is predominantly only medium hardness in terms of fine grinding in a ball mill (according to BWi).

The same correlations were used to determine comminution indices for each of the defined ore domains shown in Figure 2. The results are provided in Table 2 and were used to conduct simulations for each of the ore domains.

Table 2—Comminution Indexes for Each Ore Domain Defined

Domains	Axb
Hard Coarse	46.4
Hard Fine	56.5
Medium Fine	61.2
Soft Fine	95.1

To refine and further improve the accuracy of the site-specific comminution models it was recommended to conduct ore breakage characterisation for the different lithologies and domains (rather than relying on correlations to PLT results).

Additionally, accurate classification of rock strength and structure for each blast polygon would be critical to fully realizing the benefits of tailored blast designs. Therefore, it was also recommended that additional strength and structure data be collected on a finer spatial scale (bench scale) as mining progresses at Chapada, to improve the implementation of optimized blast designs.

Chapada has been implementing a sampling and testing program as recommended, providing updated results and correlations for the breakage parameters.

DRILL AND BLAST PRACTICES AND FRAGMENTATION RESULTS

The project team performed audits of several blasts in the Chapada mine. The information and data analysed included the polygon size and shape; hole mark-out; hole drilling and charging configurations; timing and initiation; stemming length; and as-drilled hole parameters. Ore was characterized for each of the audited blasts using rock mass structure images for in situ block size determination and PLT for strength. These were used to determine the domain for each blast, as defined above.

ROM fragmentation was measured using image analysis from multiple sources, including post-blast muck piles, and from trucks while dumping into primary crushers during the survey of the audited polygon. Examples of original and delineated images using Split-Desktop image analysis software (Version 4) are shown in Figure 3 (Left) and the resulting individual fragmentation curves (from all truck and muck pile images) are also shown in Figure 3 (Right). The results demonstrate a large degree of variation in ROM fragmentation. The average values of the main size parameters for the ROM fragmentation of the audited polygons are described in Table 3.

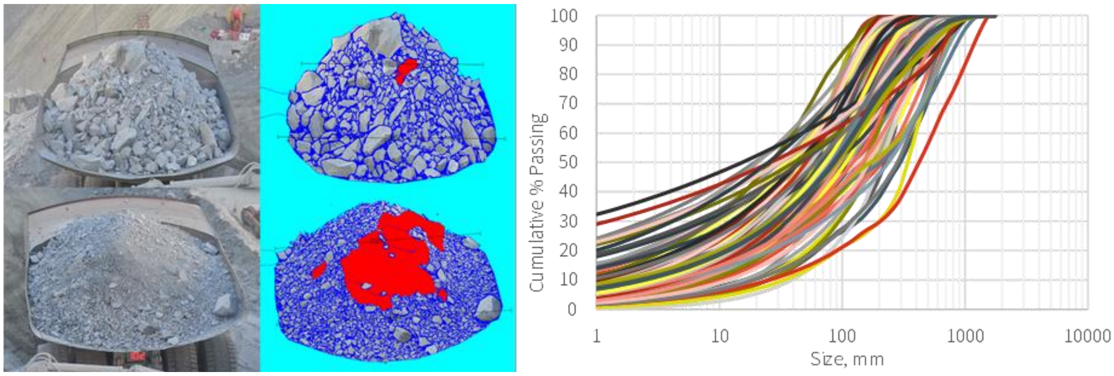


Figure 3—Examples of Fragmentation Image Analysis

Table 3—Mean ROM PSD Fragmentation Values

Parameter	Muck Pile PSD	Truck PSD	ROM PSD
P_{20}	13 mm	10 mm	12 mm
P_{50}	82 mm	89 mm	85 mm
P_{80}	230 mm	305 mm	260 mm
−10 mm	17.6%	20.0%	18.8%

Note: P_{20} etc. = % passing; PSD = particle-size distribution.

These key fragmentation output parameters and the estimated ROM curve, together with the drill and blast design details collected during the blast audits were used to calibrate the blast fragmentation model. This is used, along with the calibrated comminution model, to conduct simulations of blasting and comminution to determine optimized blast designs and adjust downstream comminution circuits accordingly to maximize production and minimize overall costs (mine and plant).

CRUSHING AND GRINDING OPERATIONS

The comminution circuit has two parallel crushing lines, one with a jaw crusher and grizzly and the other with an in-pit gyratory crusher (IPC) feeding a grizzly and an MMD Sizer. The products from the two crushing lines are sent to a coarse stockpile via independent conveyor belts. The stockpiled material feeds the grinding circuit, which consists of a SAG–ball mill–crusher (SABC) circuit. The circuit differs slightly from a standard SABC flowsheet, with the SAG circuit product classified in its own cyclone cluster. The undersize from those cyclones reports to the ball mill, which operates in closed circuit with a separate cyclone cluster. The combined overflow of the two cyclone clusters reports to flotation. The flowsheet is shown in Figure 4.

An analysis of historical operating data was used to determine the typical range of operating variables and trends over time for use in the mathematical modelling phase. The analysis of the historical data allowed for the definition of baseline performance and uncovered a number of easy to implement “quick-win” opportunities.

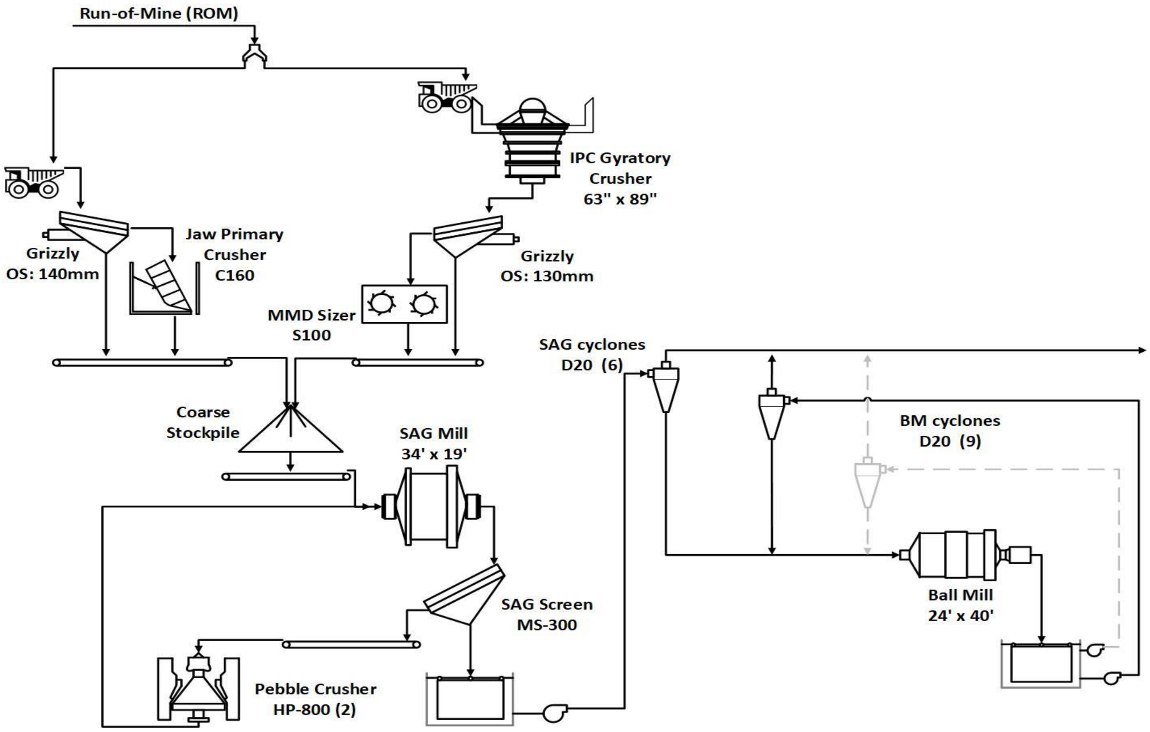


Figure 4—Simplified Flowsheet of the Chapada Comminution Circuit

MINE-TO-MILL AUDIT AND SURVEY

A full comminution survey was conducted in February 2020 while treating material from the audited blast polygons. The ore was characterized for each of the audited blast polygons, and also for additional samples taken from feed material for the comminution survey. This enabled comminution performance to be linked with the current blasting conditions, rock mass characteristics, and explosives properties, and the associated fragmentation results and also allowed the development and calibration of site-specific mathematical models for each unit operation (blasting, primary crushing, SAG milling, screening, pebble crushing, ball milling, and classification). The ore characterisation results indicated the ore from audits and the survey was from the HF ore domain, which is considered a hard rock domain for site conditions. Thus, the feed rate during the plant survey was limited to 2,390 t/h.

As part of the survey, a belt cut sample was collected from SAG feed for particle-size distribution (PSD) analysis. Crash-stops and grind-outs were also carried out in the SAG and ball mills. Charge measurements were taken, and the condition of the lifters and liners and ball size distributions were reviewed. In the SAG mill, the extent of pegging and peening of the grates, the capacity of the pulp lifters, and the presence of slurry pooling were also investigated. Figure 5 shows photos of some of these activities required to develop and calibrate robust comminution models.

Figure 5—SAG Feed Belt Cut Sampling and Measurements Taken During the SAG Mill Crash-Stop

MATHEMATICAL MODELLING AND MINE-TO-MILL INTEGRATED SIMULATIONS

Mathematical models of all unit operations were calibrated using data analysis, rock characterisation, and audit and survey results, in conjunction with in-house modelling tools for blast fragmentation and JKSimMet model fitting and simulation software for comminution operations. The calibrated site-specific models allowed integrated simulations to be conducted with a holistic approach from mine to plant to develop optimized strategies considering the different ore domains and associated range of ore characteristics at Chapada.

Blast Fragmentation

The ROM fragmentation at Chapada was highly variable prior to this project. One primary project goal was to optimize ROM fragmentation with respect to both mining and downstream processing operations. To achieve this goal, a robust and reliable method of predicting blast fragmentation is required so the effect of changing various practices can be determined. Hatch has developed a blast fragmentation model that considers all the major parameters known to affect blasting performance (e.g., rock mass strength and structure, blast design parameters such as burden and spacing, and explosives properties). The blast fragmentation model has been used extensively in Hatch projects and validated at numerous sites around the world. Therefore, this fragmentation model was calibrated according to rock characteristics and operating conditions at Chapada, and used to run simulations with different scenarios.

Comminution

The models of the crushing circuit—including the jaw crusher, MMD Sizer (and associated grizzlies), and the IPC—were calibrated based on analysis of the historical data, equipment specifications, and the survey results. The key model parameters were fitted to the crusher product survey PSDs. The predicted PSDs from the fitted model showed good agreement with the measured survey PSDs. The survey PSDs were measured using a combination of image analysis (for the coarse end) and laboratory sieving and sizing results (for the finer fractions that cannot be accurately measured by image analysis).

In the grinding circuit, models were fitted for each unit and combined into an overall model of the Chapada grinding circuit, as shown in Figure 6. These models were able to replicate the survey operating conditions satisfactorily, with the level of accuracy sufficient to conduct the integrated mine-to-mill optimization simulations.

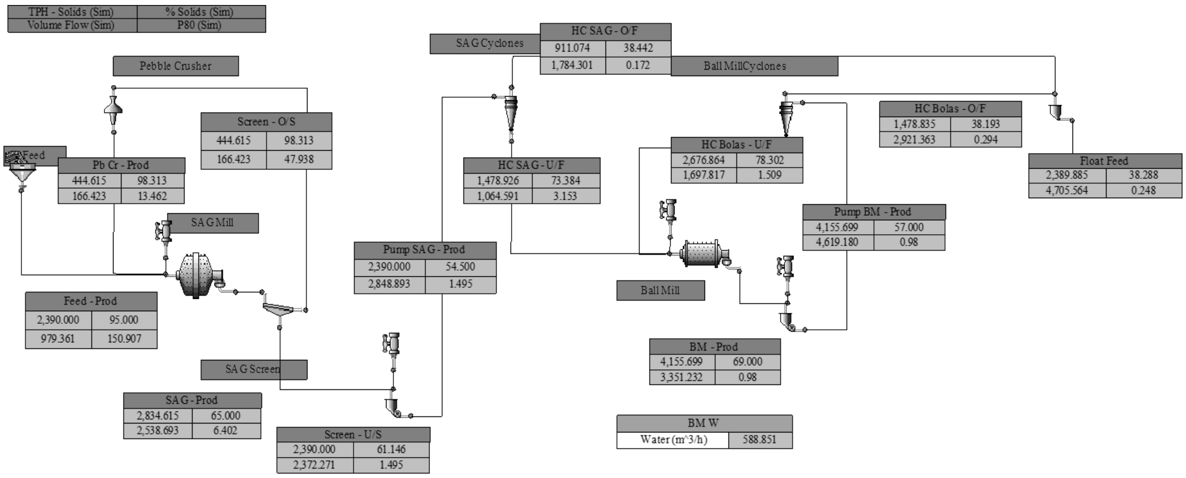


Figure 6—Site-Specific JKSimMet Model of the Chapada Grinding Circuit Model

Integrated Simulations

Simulations were conducted to investigate the effect of altering blast design parameters, specifically burden, spacing, stemming, and sub-drill, as well as comparing explosives properties (namely straight emulsion versus high energy explosive) on ROM fragmentation. This was conducted for each ore domain to determine the optimum blast design for that domain. The result is a set of blasting guidelines which consists of an optimized blast design for each domain. Blasting according to these guidelines ensures that an appropriate level of energy is applied according to the rock characteristics. Higher blast energy is applied in harder and blockier areas of the deposit to ensure adequate fragmentation and efficient operation of downstream processes, while less energy is required in more fractured and softer domains. Simulations were carried out using both 171 and 241 mm drill-hole diameters for each domain.

The modelled ROM PSD for the base case and for the optimized blast design for each ore domain using 171 mm drill holes are shown in Figure 7. In all domains, the blasting guidelines produce finer ROM fragmentation, including more fines (−10 mm), less intermediate material, and controlled top size which will benefit load and haul productivity and downstream comminution circuit performance. The change in ROM fragmentation is greatest in the hard domains, particularly the HC domain, which will have the greatest benefits in the comminution circuit, where the increased hardness will also impact the comminution circuit performance.

Optimizing ROM fragmentation can provide significant improvements in downstream operations; however, it is also very important to consider the viability of the underlying changes to the drill and blast design, and to evaluate the effect these changes will have on other operational variables. Therefore, checks were conducted to confirm that the available drilling capacity was sufficient for the proposed guidelines, and additional evaluations carried out to assess the effect on explosives consumption, material movement, load and haul productivity, and blast vibration and wall control.

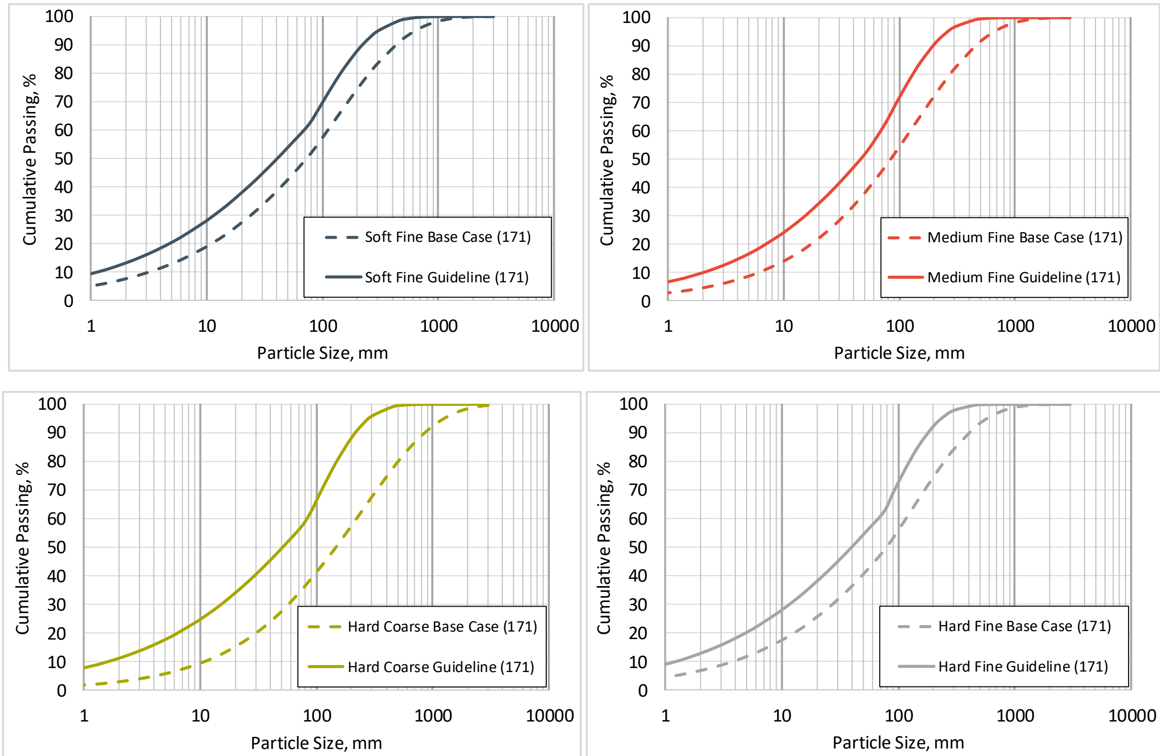


Figure 7—Base Case PSD vs. Optimized PSD from Guidelines for each Ore Domain (Hole Diameter 171 mm)

Integrated simulations between the optimized ROM fragmentation and the comminution operations were conducted to evaluate the impact of the recommended blasting guidelines on crushing and grinding operations, and to leverage the benefits of combined strategies in both the mine and the plant. Evaluations were conducted to assess potential improvement opportunities in the comminution circuit considering the upstream changes in blasting. Examples of changes that were considered include: cavity profiles and operating gaps in the primary crushers; MMD Sizer circuit configuration; ball charge level and make-up ball size in both mills, SAG mill liners and pulp lifters designs, ball mill trommel configuration, and cyclone internals. These changes were evaluated based on their impact on plant throughput and copper rougher recovery.

Simulation Results

The integrated simulations indicated that plant throughput could be increased by 13% to 22% while maintaining the final comminution product size (flotation feed size) below the target of P_{80} 280 µm. The increase can be achieved with very limited capital expenditure. Figure 8 summarizes the cumulative benefits expected from applying the combined strategies in both the mine and the comminution circuit.

The site-specific calibrated models of the comminution circuit developed from the survey data (Figure 6) were used to estimate the impact of optimisation recommendations on plant throughput and grinding circuit product P_{80}. Each ore domain (SF, MF, HF, and HC) was simulated independently to estimate the range of throughputs expected, as illustrated by the grey bars in Figure 8. The resulting P_{80} estimated from the simulations is shown by the red dotted line.

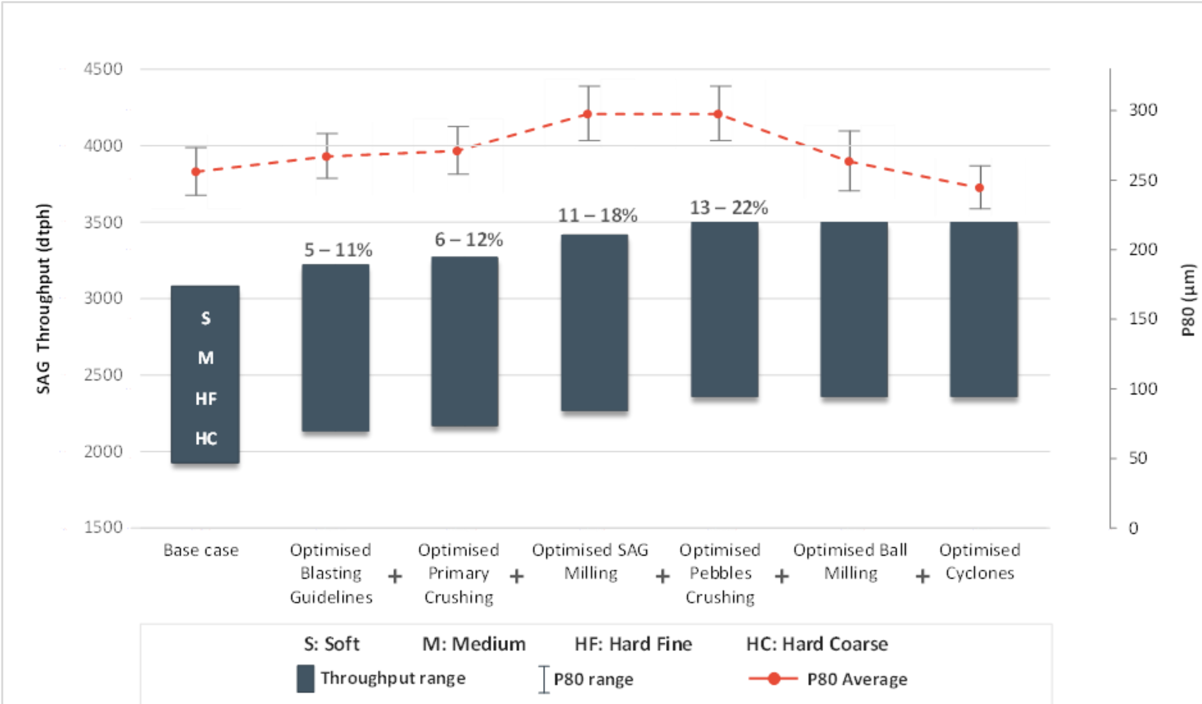


Figure 8—Mine-to-Mill Summary of Benefits (dtph = Dry Tonnes Per Hour)

RECOMMENDATION N°1: IMPROVE ROM FRAGMENTATION AND INCREASE FINES IN THE SAG FEED

The objective of the blasting guidelines is to maximise the production of fines (−10 mm) in the SAG feed while decreasing the SAG F_{80} and reducing the amount of material in the critical size-fraction (pebbles), as illustrated in Figure 7. The optimised ROM fragmentation was run through the primary crusher models, and the combined crusher product was used in the grinding circuit models to predict the increase in throughput that can be achieved when using the optimised blasting guidelines. The improved fragmentation of the SAG feed and increased fines content from implementing the blasting guidelines would increase the plant throughput across all the ore domains and reduce SAG mill specific energy. The expected increase in throughput ranges from 5% to 11%, with the greatest benefits in the harder domains. However, the product will also become coarser, which can be mitigated by ball mill and cyclone optimisation.

RECOMMENDATION N°2: REDUCE PRIMARY CRUSHER OPERATING GAP

The IPC power utilization has been historically low compared to the installed power of 1000 kW, indicating an opportunity to utilise more of the available power to achieve improved size reduction in IPC. Previous attempts to operate the crusher at a smaller gap resulted in difficult operation, with crusher blockage and reduced throughput. This may have been caused by the coarse and blocky ROM fragmentation during this time. Blast modelling suggests that applying the optimized blast guidelines will significantly reduce the amount of coarse material to be crushed by the primary crusher and enable sustained operation with a smaller gap in the IPC. After blasting guidelines are implemented, it is recommended to reduce the closed-side setting (CSS) of the IPC to 4.5 inches instead of 5.5 inches, and also reduce the CSS of the jaw crusher from 5.5 to 4 inches. Crusher volumetric capacity calculations (using crusher vendor tools, calculations, and catalogues) confirmed there would be no constraints on the volumetric capacity or power of the IPC and jaw crusher for the recommended finer CSS settings when treating finer ROM from blasting guidelines.

Primary crusher models were used to predict the SAG feed size distribution with reduced CSS in both crushers (when treating finer ROM from blasting). This was carried through the grinding models and demonstrated an expected increase of 1% to 2% in SAG mill throughput.

RECOMMENDATION N°3: INCREASE BALL CHARGE IN THE SAG MILL

There is an opportunity to reduce SAG mill ball size and increase ball charge in the SAG mill. For soft to medium hardness ores, such as those at Chapada, the use of balls 5 inches in diameter is widely accepted for SAG operations and should result in better performance than the 6 inch diameter balls used at the time. While 6-inch balls would be beneficial to provide high energy impact required to break down very hard and blocky material, 5-inch balls provide more contact surface area than 6-inch balls (for a constant ball charge), and therefore more area for grinding action. The SAG mill grind-out inspection and power model simulations estimated that the mill is generally operated with a ball charge of 13% and a total charge of about 30%. Operating with a higher ball charge of 16% and lower total filling of 26–28% was advised. Mill power calculations indicated that these conditions would give similar SAG mill power. However, a higher ball-to-rock ratio will provide more grinding action and increased grinding rates, leading to higher throughput when treating the finer SAG mill feed size. Simulations indicated that replacing the 6-inch balls with 5-inch balls, as well as increasing the ball load from 13% to 16%, could increase throughput by a further 4% to 5%.

RECOMMENDATION N°4: REDUCE PEBBLE CRUSHER CLOSED-SIDE SETTING

Historical data analysis revealed that there was more than enough pebble crushing capacity available with the two HP800 pebble crushers. Pebble flow rate would likely increase with the increasing throughput resulting from the recommended changes to blasting and crushing, as confirmed by simulations. However, operating the SAG mill with a higher ball charge of smaller balls will reduce pebble production, because the smaller balls and higher ball-to-rock ratio will crush the pebble-sized material more efficiently. Overall, simulations indicated that it is unlikely that the pebble crushing capacity would be exceeded with the implementation of blasting, crushing, and SAG milling recommendations above.

Operating the pebble crushers with the smallest gap possible offers the possibility of further increasing SAG throughput. The fine short-head chamber should allow for a decrease in closed-side setting (CSS) to 10 mm. According to the simulations, reducing the pebble crusher CSS from 13 to 10 mm would allow a further increase of 2%-4% in SAG mill throughput. The crusher volumetric loading will also increase, for a CSS of 10 mm, and Metso's Bruno crushing software calculations indicated that it was still within the capacity of the HP800 crushers.

RECOMMENDATION N°5: INCREASE BALL CHARGE AND REDUCE MEDIA SIZE IN THE BALL MILL

Simulations indicate that changes in blasting, primary crushing, and SAG milling are likely to result in coarser grinding circuit product P_{80}, as shown in Figure 8. This is expected, as the product from the SAG milling circuit will become coarser. However, there are opportunities to decrease the grinding product size by reducing the grinding media size and increasing the ball charge in the ball mill.

The Morrell mill power draw model (Morrell, 1996) was used to estimate what ball charge would be required to maximise ball power, which was found to be 32% ball charge. However, to operate safely with this charge, a ball retaining-ring would be necessary.

At the time, large, worn SAG balls (with 3.5 to 4 inch diameter) were recycled and used in the ball mill ball charge. The ball mill charge consisted of about 30% of worn SAG balls mixed with 70% of new balls with 2.5 inch diameter. The large oval shaped balls recycled from the SAG mill may negatively affect grinding rates and increase ball mill circuit product size. The grinding efficiency could be improved by using only smaller balls, thereby increasing the surface area of the steel media in the ball mill charge. The optimal media size was assessed using Azzaroni's (1980) methodology. The formula was used to confirm an optimal make-up ball size of 2.5 inches (63.5 mm). Therefore, it was recommended to stop recycling the worn SAG mill balls while treating the current medium hardness ores (with respect to fine grinding in a ball mill). If ore hardness increases substantially, the ideal make-up ball size may need to be re-evaluated.

Simulations were conducted to estimate the opportunity of using make-up balls of only 2.5 inches and increasing ball charge to 32%. The simulations indicated this is expected to result in a product P_{80} about 30 µm finer feeding the flotation circuit for a similar recirculating load.

RECOMMENDATION N°6: IMPROVE CONSISTENCY BETWEEN SAG AND BALL MILL CYCLONE PRODUCT SIZES

The data collected during surveys, and review of the historical data revealed that SAG cyclones were producing a significantly finer product than the ball mill cyclones. It was concluded that this difference can be reduced to provide a more homogeneous and narrower PSD to feed the flotation circuit. Flotation recovery is optimal for intermediate particle sizes and decreases for both coarser and finer particles. A narrow size distribution maximizes the amount of material in the intermediate fractions, which have the highest flotation recovery. The P_{80} of the SAG cyclone overflow was about 180 µm for an overall product P_{80} 280 µm. Targeting a coarser P_{80} from the SAG cyclones would reduce the tonnage reporting to the ball milling circuit. This, in conjunction with other changes to the ball mill circuit, would produce a finer cyclone overflow from the ball mill circuit.

Simulations were conducted to investigate changes to the SAG mill and ball mill cyclone configurations and operating conditions. The objective was to produce more consistent product size from the two circuits, and a finer overall grinding circuit product. The simulations indicated that increasing vortex finder size of the SAG cyclones would produce a coarser cut size and reduce the load on the ball mill circuit. There was also room to increase ball mill cyclone pressure, which was low. The feed percent-solids of the ball mill cyclones was reduced, which resulted in higher operating pressure, higher recirculating load, and finer classification. Overall, the overall combined cyclone product was reduced by about 13 µm.

Implementation of Recommendations

Chapada commenced implementing the recommendations in a coordinated and paced manner in August 2020. Table 4 summarizes the recommendations issued, the expected benefits, and the status of implementation, as of February 2023.

Table 4—Summary of the Mine-to-Mill Site-Specific Recommendations

Opportunity	Actions	Benefits	Status of Implementation
Improve ROM fragmentation and increase fines content in the SAG feed.	Implement drill and blast guidelines tailored to ore domains	Increase in throughput ranging from 4.5% (soft) to 10.8% (hard coarse)	Done. Implemented 30% in January 2021, 60% in January 2022 and 100% in January 2023.
Reducing primary crusher gaps with finer ROM fragmentation.	Jaw crusher CSS: 4 inch IPC CSS: 4.5 inch	1% to 2% increase in throughput.	Done. Implemented in October 2021.
Increase SAG mill ball charge and use 5-inch balls.	Operate with 16% ball charge (5-inch balls), with 26%-28% total charge.	4% to 5% increase in throughput.	Partially implemented in May 2021, SAG operates at 15.5% charge, ball diameter is still 6 inches.
Reduce pebble crusher gap to maximise power utilisation.	Check with equipment supplier to reduce crusher gap to 10 mm.	+2.4% in throughput.	Done. Implemented in January 2021.
Increase power utilisation in the ball mill and reduce grinding media top size.	Increase ball charge up to 32%. Do not use worn SAG mill balls in the ball mill.	Improve grinding efficiency in the ball mill and reduce circuit product size by 30 µm.	Done. Implemented in May 2021, 32% ball charge and lower recycle of balls from SAG mill.
Coarsen SAG cyclone overflow P_{80} and reduce Ball mill cyclone overflow P_{80}.	Increase vortex finder of the SAG cyclones. Reduce ball mill cyclone feed %solids (<60% solids) and increase pressure in ball mill cyclones.	Reduce the difference between SAG cyclone overflow P_{80} and ball mill cyclones P_{80}. Finer and more homogeneous product to flotation.	Done. Implemented in September 2020, cyclone cluster changed, and pressure increased.
Reinstall curved pulp lifters.	Review design of the curved pulp lifter before the next mill reline.	Improve slurry and pebbles discharge from the mill.	Done. Implemented in August 2020.
Optimise shell lifter design for unidirectional rotation and Maraca mill and conditions	Review and modelling of unidirectional liner design.	Improve liner life and optimise media and particle trajectories.	Done. Implemented in August 2020.
Reinstall ball mill trommel.	Review design and reinstall ball mill trommel.	Efficient removal of scats from the grinding circuit, improved grinding efficiency.	Under review.
Replace the existing MMD Sizer with one designed for a secondary crushing duty.	Review design and evaluate opportunity to further reduce SAG mill feed size.	Reduce SAG Feed F_{80} from 119 to 75 mm.	Under review.

With partial implementation of the recommendations carried out so far and despite increasing ore hardness, some gains have already been obtained (as reflected in Figure 9). Comparison of the periods pre- and post- mine-to-mill project shows a throughput increase around 5%. The box plots on the right side of Figure 9 summarize the throughput data populations for both periods. Further gains are expected when Chapada implements the remaining changes and recommendations, which have a cumulative effect when fully implemented.

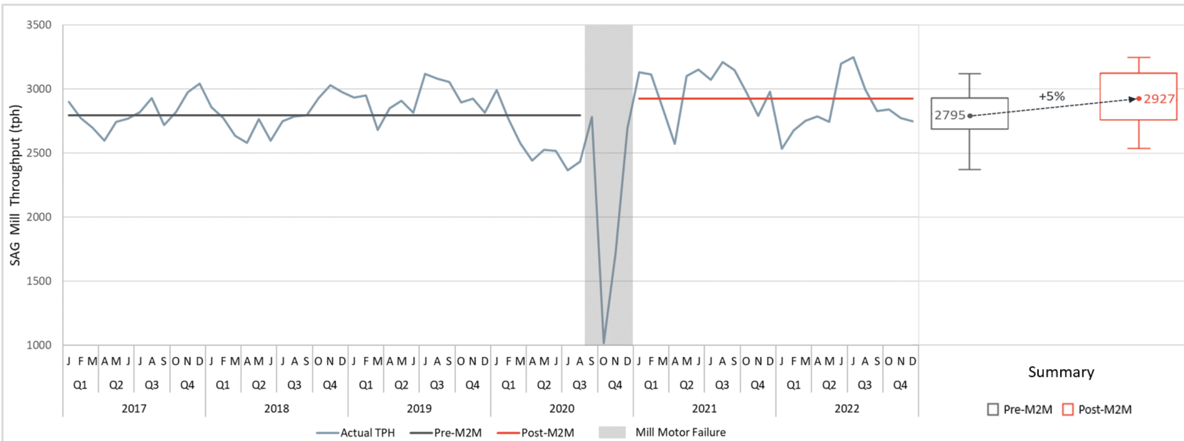


Figure 9—Comparison of Plant Throughput Between Pre- and Post-Mine-to-Mill Periods with Partial Implementation

Throughput Forecast Model

The site-specific mathematical models developed in the mine-to-mill project have also been used as the basis for developing a throughput forecast model for the LOM. These models were used in combination with the mine production plan and additional ore characterization data to forecast plant throughput according to different ore properties, feed blends, drill and blast practices, circuit configurations, and target product size. The model enables forecasting and planning to improve production reliability and assist with strategic LOM optimization.

Historical and current ore characterization testwork data were analyzed and compiled to develop the database of ore characteristics which is the source of information for each domain in the throughput forecast model. This testwork included data provided by external consultants and laboratories in addition to PLT conducted by the Chapada Geology department. More recently, a testing campaign was conducted including DWT and BWi tests. In late 2020, Chapada also commenced on-site testing of drill core samples with a hardness index tester (HIT) to collect hardness variability data within each domain and across various pit locations and requested Hatch to use these data for throughput forecasting. The HIT device can be used to estimate Axb and BWi using a relatively small sample (Kojovic, Bergeron, & Leetmaa, 2019). Based on the limited number of paired tests available at the time, a reasonable correlation was achieved between the Axb estimated by HIT with the Axb determined from DWT; however, there were some discrepancies particularly for softer domains and samples (with Axb of less than 30). HIT results were used in calibrating the throughput forecast model, as this will be the measurement method used to estimate the hardness values in the future mine planning. However, the correlation between the Axb estimated by HIT with that measured by either DWT or SMC test should always be confirmed for different ore types.

Hatch also analysed the recent data and information on the drill and blast, ore characterization, and blend proportion for the lithologies. These were used to calculate weighted average blend of lithologies and corresponding blasting powder factors, and to correlate with the actual feed size to the plant.

At the time, the blasting guidelines provided as part of the mine-to-mill recommendations project were partially implemented, with overall increases in powder factor for the harder and blockier ores. The resulting outcomes were similar to those predicted by the simulations, demonstrating the effectiveness of the mine-to-mill strategy proposed and models developed. Chapada began implementing a two-year plan to further increase the powder factor up to the levels recommended during the mine-to-mill project, which is now complete. The associated increase in costs (due to increased drilling requirements and explosives consumption) is offset by the increase in plant throughput and reduced specific energy consumption in the comminution circuit, which results in increased profitability.

To develop the throughput forecast model for Chapada, Hatch has applied a combination of Morrell power-based and mechanistic models, using the hardness and breakage properties to predict a weighted average comminution specific energy for each ore domain. The effect of content of fines (% −10 mm) generated during blast fragmentation was also included. The model is used to estimate the throughput according to the mine plan, based on the feed blend of ore domains coming from the mine, the low-grade and high-grade stockpiles, as well as the contribution of the pre-crushing circuit. The outputs of the model are the average instantaneous throughput and the yearly capacity; it also indicates when the circuit becomes SAG or Ball mill limited. Figure 10 shows the throughput forecast model concept diagram, which in turn provides the calculation steps diagrammatically.

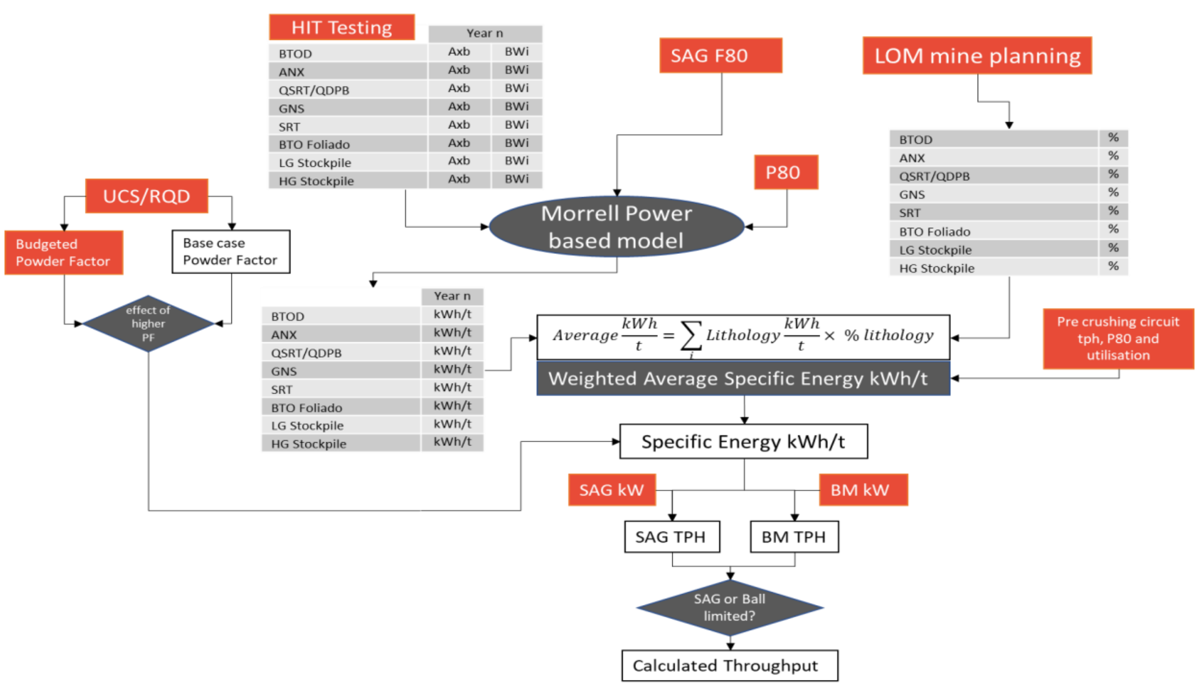


Figure 10—Concept Diagram of the Chapada Throughput Forecast Model

Model validation consisted of comparing the throughput forecast model predictions with actual process throughput at various time scales (daily, weekly, monthly, annually) in 2020 and 2021. Appropriate filtering was applied to the plant operating data to exclude shutdowns and periods of maintenance activities.

It should be noted that the September to December 2020 operating period with SAG mill only (single-stage SAG) was excluded from the validation data, as this does not represent the normal SABC mode of operation. During March to September 2020, Chapada changed the SAG mill liner design and pulp-lifter configuration. An older design of the SAG mill internals was installed in the mill during that period, with bidirectional mill liners and radial pulp-lifter (instead of curved pulp-lifter). The throughput forecast modelling methodology does not take these changes into consideration. This is due to the input parameters being limited to ore characteristics, feed size, and product sizes, and the prediction of specific energy consumption being based on the models developed for typical operating configurations, like the mill internals surveyed during the mine-to-mill project. While the changes to SAG mill internals can affect productivity, the model prediction of throughput was still acceptable during this period. These production data were therefore not excluded from the model validation.

The data analysis showed that the blend hardness increased during this time, as illustrated in Figure 11, by an increase in DWi values. This coincides with the period containing a higher proportion of hard material in the feed blend. The harder blend properties resulted in a reduction in throughput during this time, as illustrated in Figure 12.

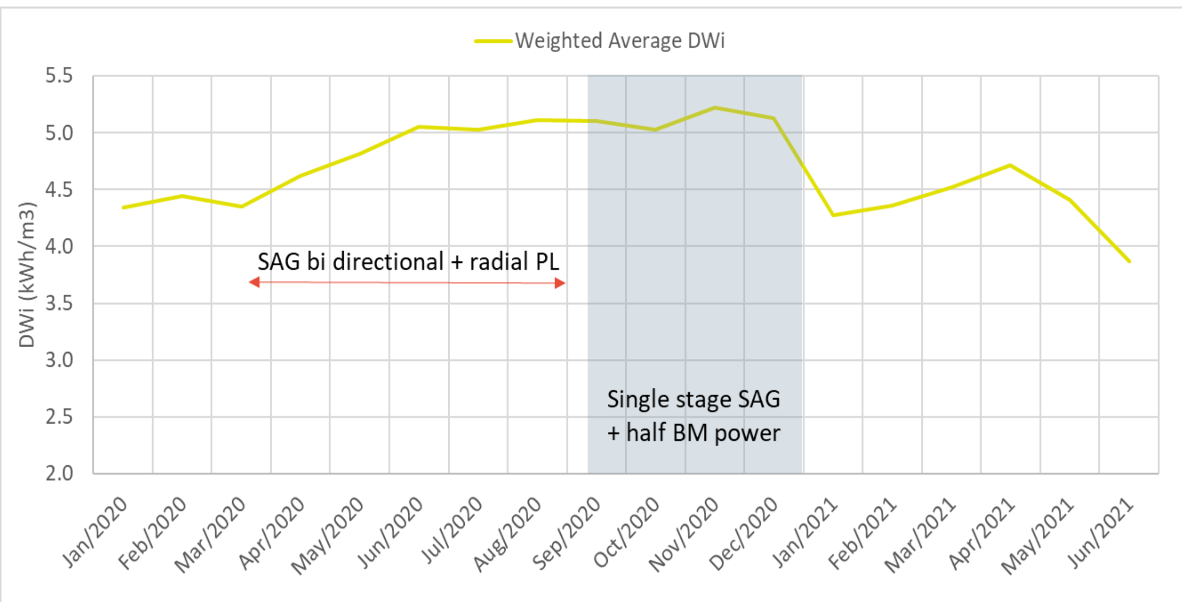


Figure 11—Variation in Calculated DWi (Weighted Average DWi Based on Blending Proportion)

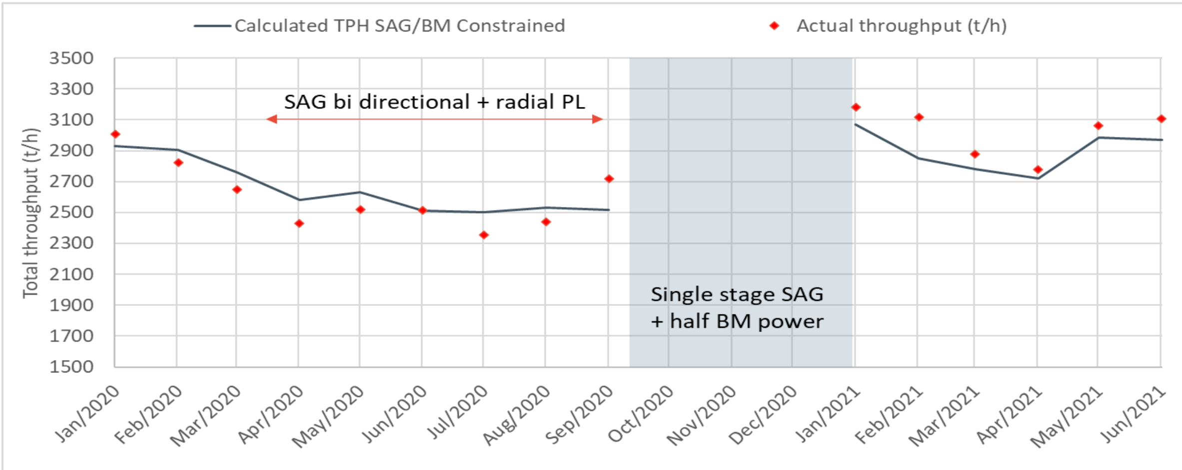


Figure 12—Throughput Forecast Model Validation against Actual Plant Throughput

The estimated model throughput is compared with the actual plant throughput, and the standard error of the model is calculated based on the number of observations at different time scales (Table 5). The relative standard error (%) was compared to the average throughput with a confidence interval of 90%. The model is predicting quite well on a yearly basis (error of 2.5% for 2020 and 1.95% for 2021) and in an acceptable range on a monthly basis (±10%) for the same years. With updated plant information from 2022, the model monthly standard error was 7.5%, and annual error 1.0%, as shown in Figure 13 and Table 6.

Table 5—Model Prediction Error in Daily, Weekly, and Monthly Basis (2020–2021 period)

90% Prediction Interval		Daily Error	Weekly Error	Monthly Error
Throughput Model Standard Error	± t/h	485	339	297
	±%	16.2	12.5	9.9

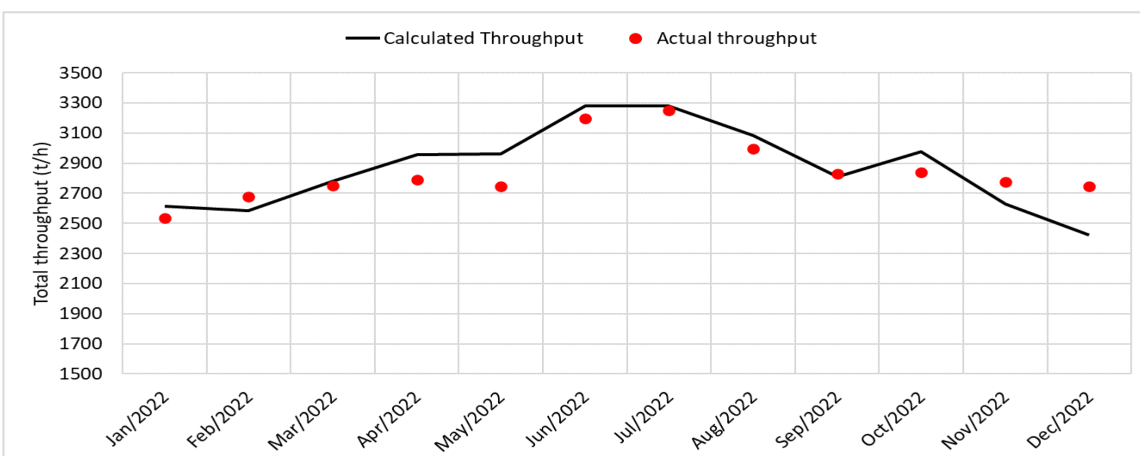


Figure 13—Model Prediction Error for 2022

Table 6—Model Prediction Error on Annual Basis

90% Prediction Interval		2020	2021	2022	Average
Throughput Model Standard Error	± t/h	66	59	29	51
	±%	2.5	1.95	1.0	1.8

Conclusions

The presence of harder ores at Chapada was significantly reducing plant throughput. It is expected that the proportion of harder ore will continue to increase as mining extends deeper into the pits. To address this issue, a mine-to-mill project commenced at Chapada between December 2019 and July 2020. Opportunities for improvement were identified in ore characterization, drill and blast and comminution circuit operation and are expected to increase the plant throughput by 13%–22%, while maintaining final grinding product size.

Chapada has been progressively implementing the recommended changes, prioritising these according to ease of implementation and potential benefits, achieving approximately 75% implementation to date. Despite partial implementation and increasing ore hardness, higher throughputs (average gain of about 5%) are being consistently achieved without coarsening the grinding product P_{80}. Further gains are expected when the remainder of the recommendations are fully implemented, which will deliver a cumulative effect.

This case study demonstrates that through structured application of the mine-to-mill approach—and the development and implementation of pragmatic, integrated operating strategies which it entails—existing equipment can be exploited to its fullest extent, providing significant operational improvements with little or no capital expenditure.

The models developed during the mine-to-mill optimisation project were used in combination with Chapada's mine plan and additional ore characterisation data to forecast plant throughput according to different ore properties, feed blends, drill and blast practices, circuit configurations, and target product size. The model predicts the plant behaviour quite well, which enables forecasting and planning to improve production reliability and assist with strategic LOM optimisation.

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