CHAPTER 3.1

Mine-to-Mill Optimization

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A mining operation is essentially a series of interconnected processes, with the performance of each stage affecting the subsequent ones. Optimizing each stage in isolation can result in suboptimal performance of the overall operation. For example, isolated changes in drill-and-blast can have detrimental impacts on downstream crushing and grinding processes, which subsequently affect the downstream separation process. Therefore, it is important to analyze and optimize each process stage in the context of the whole operation.

Blasting is the first stage of comminution in most mining operations. It is a very cost-effective and energy-efficient preparation step for the subsequent crushing and grinding stages, which will then provide much finer size reduction to liberate valuable minerals for separation. An example of energy consumption and cost breakdown by comminution stage for a relatively hard ore is shown in Table 1. This illustrates the increasing cost and energy consumption of comminution stages.

Significant improvement of overall mine and plant performance can be achieved by optimizing blast fragmentation. This optimization requires utilization of appropriate levels of blasting energy according to the different types of ore but must also be tailored to the specific downstream processes, circuit flow sheet, types and sizes of comminution and classification equipment, installed power, and final product specifications.

There are many cases where the additional costs of increasing and better distributing blasting energy are more than compensated for by the improved throughput and recovery and reduction of energy consumption in downstream processing stages. For example, at the AngloGold Ashanti Iduapriem gold mine in Ghana, mine-to-mill optimization delivered finer run-of-mine (ROM) fragmentation that increased throughput by 20%–30% while reducing the 80% passing feed size (F_{80}) to leaching from 155 to 132 µm. The finer leach feed size increased gold recovery by about 0.5% (Renner et al. 2006). At the Gold Fields Cerro Corona operation, mine-to-mill optimization increased throughput by almost 15% for a particular hard ore type and 6% across all ore types while the semiautogenous grinding (SAG) specific energy was reduced by more than 9% (Diaz et al. 2015). The major changes recommended for the Cerro Corona project and the predicted impact on throughput and final grind size (P_{80}) for the ore type investigated are shown in Figure 1.

Table 1 Example of energy consumption and cost breakdown for relatively hard ore

Stage	Specific Energy, kW·h/t	Cost, US$/t
Drill-and-blast	0.1–0.25	0.1–0.25
Crushing	0.5–8	0.5–1
Grinding	10–35	2–5

Note: Data from Hatch database of industrial data.

The potential for optimized blasting fragmentation to improve downstream processing performance is well recognized within the industry. Unfortunately, this has resulted in oversimplifying the concept to the idea that increasing explosive consumption in the mine results in optimization of the entire value chain (mining and processing). This oversimplification is often referred to as mine-to-mill. However, for true holistic optimization, blast intensity is not always increased but rather adjusted to best suit the different types of ores and also the circuit configuration, equipment, and installed comminution power downstream. It is a fully integrated effort with many aspects of optimization in the mine, comminution, and separation processes.

Various mine-to-mill initiatives have been implemented over the past 20 years with varying degrees of success. The long list of well-documented successes includes the examples provided in Table 2 and many more.

However, there are also anecdotal references of failures from some operations on how "mine-to-mill did not work for us." These failures can often be attributed to several common reasons, such as the following:

- Necessary structure and integrated methodology were lacking.
- Powder factor (kilograms of explosive per ton of ore) increased indiscriminately with no real optimization

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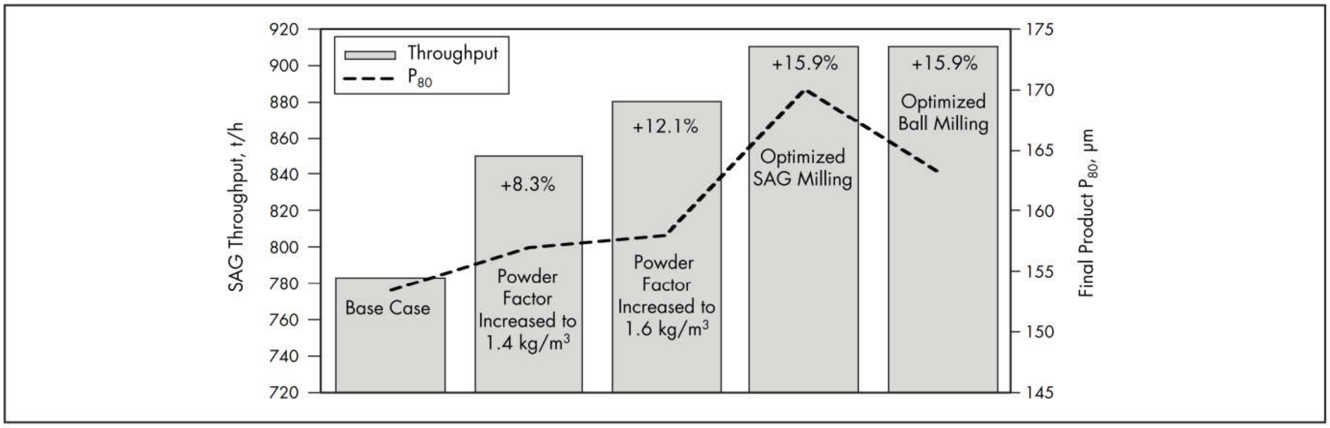


Source: Diaz et al. 2015

Figure 1 Mine-to-mill improvements at Cerro Corona

carried through the blasting and downstream processes to realize the full benefits.
- Results were not properly measured, followed through, well documented, or supported by management.
- Costs and performance were measured in isolation in the mine versus the mill instead of the overall mine and mill costs and benefits.

To be successful, mine-to-mill projects require a structured methodology supported by extensive auditing, surveys, and data analysis. Training and incorporation into site procedures, practices, and key performance indicators (KPIs) or metrics are also essential to ensure that benefits are quantified and maintained in the long term.

The objective of mine-to-mill optimization is to develop and implement integrated mining and processing strategies tailored to the operation to minimize the overall cost per ton treated and maximize company profit in a sustainable manner. The specific targets and objectives will vary for each project depending on prevailing site and economic conditions. For example, in times of high commodity prices, the main objective is often to increase production, whereas in harder economic times, the key driver is usually to reduce operating costs.

A comprehensive mine-to-mill approach recognizes that every ore body and mining operation is different, and to get the best results it is important to integrate and optimize each stage in the context of the whole operation. Understanding the ore body, and the characteristics of the ore within, allow the process to be tailored to suit the ore properties and key business drivers of the operation. Thus, the benefits from mine-to-mill will vary depending on the particular targets and objectives but can include many of the following:

- Maximization of system throughput (mine and mill), including increased excavation and loading efficiencies.
- Minimization of the overall operating cost with minimal adverse impacts, such as dilution or ore loss, structural damage, or environmental nuisance.
- Improvement of overall process stabilization (by reducing variability), resulting in superior processing performance in terms of production (throughput and recovery) and product quality (grade).
- Development of accurate throughput forecast models, because of the understanding of the impact of the ore types on blasting and processing. These models can be incorporated into the block model for mine planning and to establish optimum blending strategies for the operations. This should enable an improved revenue cutoff relationship to be determined to truly optimize blending and ore delivery strategies for maximizing revenue.
- Reduction in energy consumption and greenhouse gas emissions. At the Antamina copper–zinc mine, the fine feed from the high-energy blasts reduced the specific energy consumption by 25% (Rybinski et al. 2011).

These improvements can usually be achieved with minimal or no capital expenditure.

METHODOLOGY OVERVIEW

The performance in mining and mineral processing activities is governed by in situ ore properties. Therefore, a mine-to-mill optimization should start with ore characterization; then ore domains should be defined based on blasting, comminution, and metallurgical properties, and the spatial distribution of these domains mapped across the ore body. Detailed data from blasting and processing operations should be collected and analyzed for defined ore types, and used along with historical operating and benchmarking data. These data can be used to develop site-specific predictive models for each operation (blasting, comminution, separation). Together, these models indicate how the whole process will respond to different ore types and operating conditions in the mine and the plant. Simulations combined with extensive operational experience may be used to identify problems, process bottlenecks and opportunities for improvement, and then inform strategies to optimize the entire process for different ore types. The blast design should be optimized to generate optimal and consistent ROM fragmentation for all ore types, and downstream processes can be adjusted and optimized accordingly.

The models also allow prediction of throughput and recovery performance for each ore domain. By linking these with the block model and mine plan, a geometallurgical model can be created. This model can be used for forecasting, planning, and longer-term optimization purposes.

The following project structure has been successfully applied to deliver mine-to-mill outcomes:

- **Scoping:** Historical data and information are collected to identify problems, bottlenecks, and opportunities for improvement in the mine and processing plant.

Table 2 Examples of successful implementation of mine-to-mill optimization

Commodity	Operation	Country	Benefits	Reference
Coal	Hunter Valley	Australia	Decrease in fines production	—
Copper	Phu Kham	Laos	8% Production increase (simulated)	Bennett et al. 2014
Copper/gold	PT Newmont Nusa Tenggara Batu Hijau	Indonesia	10%–15% Production increase	Burger et al. 2006
Copper/gold	Cadia	Australia	15% Production increase	Hart et al. 2001
Copper/moly	Los Bronces	Chile	10%–15% Production increase (simulated)	Powell et al. 2006
Copper/zinc	Antamina	Peru	45% Production increase (+10% more in 2010); 23% less SAG specific energy	Rybinski et al. 2011; Samuel et al. 2012; Valery and Rybinski 2012
Gold	Iduapriem	Ghana	21%–32% Production increase; 0.5–1% recovery increase	Renner et al. 2006
Gold	Porgera	Papua New Guinea	15% Production increase	Lam et al. 2001
Gold	Boddington	Australia	Steady improvement in performance over time	Hart et al. 2011
Gold	Yanacocha	Peru	Reduction of ROM fragmentation and consumption of power and steel in SAG mill	Burger et al. 2011
Gold	Rio Paracatu Mineração	Brazil	Operating strategy (mine and plant) defined by ore type for circuit with new SAG mill	Tondo et al. 2006
Gold	Kalgoorlie Consolidated Gold Mines	Australia	8%–12% Production increase	Valery et al. 2001
Gold/copper	Cerro Corona	Peru	15% Production increase (hard ore); 6% production increase (overall)	Diaz et al. 2015
Iron ore	Marandoo	Australia	Increase in lump production	Valery et al. 2001

- **Ore characterization:** Measurements of rock structure, strength, and breakage characteristics are used to define how the ore will perform during blasting, crushing, and grinding. Mineralogical properties are also required to define the recovery and separation performance.
- **Benchmarking, audits, and surveys:** Audits and surveys are conducted for key processes (drill-and-blast, crushing, grinding, flotation/leaching, gravity concentration, etc.). The data collected are analyzed and can be compared with data from other mines and processing plants, allowing benchmarking against past performance and/or other operations.
- **Development of site-specific process models and simulations:** Data from benchmarking, audits, surveys, and ore characterization can be used to develop site-specific regression or predictive/mechanistic simulation models for key processes (drill-and-blast, comminution, separation). These models can be integrated to represent the main operations of the entire process. Simulations may be conducted using these models to evaluate different operating parameters for each ore type (domains) to determine alternative designs, modifications, and operating strategies to improve throughput and overall efficiency of the operation. The use of mathematical modeling and simulations is a rapid and cost-effective way to select potential optimization strategies and achieve results as opposed to expensive trial and error in the blast and plant.
- **Validation and implementation:** A detailed plan should be developed to implement the optimization strategies that have merit based on mine and plant constraints and a cost–benefit analysis. KPIs should be measured to quantify improvements and fine-tune the operating strategies.
- **Sustaining the benefits:** Recommended changes should be incorporated into managerial and site operating procedures. Training of operators and engineers is necessary to ensure that the benefits are maintained over the longer term.

ORE CHARACTERIZATION

Common ore characterization tests and measurements used in mine-to-mill optimization are shown in Table 3.

Rock structure is a measure of the natural fractures and discontinuities in the rock. It is determined by the in situ joints and fractures and can be estimated with rock quality designation (RQD), fracture frequency, and joint mapping. The energy and gases from the blasting tend to detach the rock along these natural fractures, so the rock structure generally controls the coarse end of blast fragmentation size distribution.

Rock strength is a measure of the hardness of the rock matrix and can be measured with laboratory tests such as point load index (PLI), JK drop weight test parameters (A, b, ta), and SMC drop weight index. Unconfined compressive strength is a common measure of strength and can be estimated from PLI values to reduce laboratory testing costs. Rock strength (hardness) affects the generation of fines in blasting. Rock strength is sometimes related to rock structure, but not always.

Measurement of crushability and grindability with laboratory tests such as the Bond crushability work index, equipment supplier proprietary tests, SAG power index, Bond rod mill work index, and Bond ball mill work index is important for comminution circuit evaluation and modeling.

Improved plant throughput can often be achieved by manipulating ROM fragmentation through optimization of blasting to reduce top size and increase fines. Using data that are typically available in geotechnical block models, such as RQD (for structure) and PLI (for strength), is a cost-effective and fast method to characterize ore for breakage. Examples of where this approach has been applied include the PanAust Phu Kham operation in Laos (Bennett et al. 2014) and Batu Hijau in Indonesia (Burger et al. 2006).

The range of ore properties are mapped out and ore domains defined in the example in Figure 2. The domains cover the complete range of rock properties that are present. Comminution practices (blasting, crushing, and grinding) can then be optimized for each of the ore domains.

BLAST OPTIMIZATION

Blasting is the first stage of comminution in most mining operations and should not be seen solely as a means of sufficiently reducing rock size for load-and-haul activities. The ROM size distribution has a large impact on downstream crushing, grinding and separation process efficiency, and consequently overall mine-site profitability.

Applying the appropriate intensity and better distributing the blast energy according to ore type produces a ROM size distribution that has a controlled top size and the required amount of fines. The blast intensity is not always increased; it is adjusted to best suit the different types of ores, providing a consistent and optimized fragmentation to the downstream processes.

The in situ ore characteristics, drill-and-blast pattern, and properties of the explosive govern the fragmentation size distribution and energy efficiency of the blast. Detailed auditing of the blasting and processing practices may be used to develop site-specific predictive models to predict blast fragmentation resulting from different ore types and blast designs. These models can be used to assess the optimum blast conditions required for a particular ore type.

To assess, model, and improve blasting for downstream processes, it is necessary to measure the resulting fragmentation. Image analysis of resulting muck piles, sieving of belt cut samples, and online size measurement tools can be used to estimate ROM fragmentation, crusher product, and mill feed size distributions.

An example of predicted blast fragmentation resulting from simulations of different blast designs for the Gold Fields Cerro Corona operation is shown in Figure 3. The powder factor (PF) indicates the amount of explosive used per cubic meter of blasted rock, and it can be increased by using a tighter blasting pattern (shorter burden and spacing; i.e., less volume of rock per hole) or more explosive per hole. Other changes to blast design that can impact fragmentation include explosive type, blast-hole diameter and arrangement (staggered or not), burden-to-spacing ratio, stemming material type, stemming length, bench height, initiation timing, wet or dry holes, and so on.

Blast fragmentation modeling is used to determine the optimum blast design for each ore domain considering the rock structure and strength and blasting parameters as

Table 3 Ore characterization measurements

Rock Structure and Strength	Crushability and Grindability	Flotability/Separability
Fragmentation Modeling	**Comminution Modeling**	**Flotation/Separation Modeling**
• Rock quality designation	• Bond crushability work index	• Detailed assaying of head samples
• Fracture frequency	• JK drop weight test parameters (A, b, ta)	• Size-by-size assays and mineralogy
• Joint and plane mapping with Sirovision system	• SMC drop weight index	• Liberation analysis (optical microscopy, mineral liberation)
• Unconfined compressive strength	• Bond rod mill work index	• Laboratory flotation tests
• Point load index	• Bond ball mill work index	• Flotation kinetics and locked-cycle tests
• Young's modulus	• Bond impact work test	• Any other specific separation tests according to the flow sheet (e.g., gravity, magnetic, leach)
	• Grind establishment tests: SAG power index, SAGDesign test, etc.	

Adapted from Valery et al. 2013

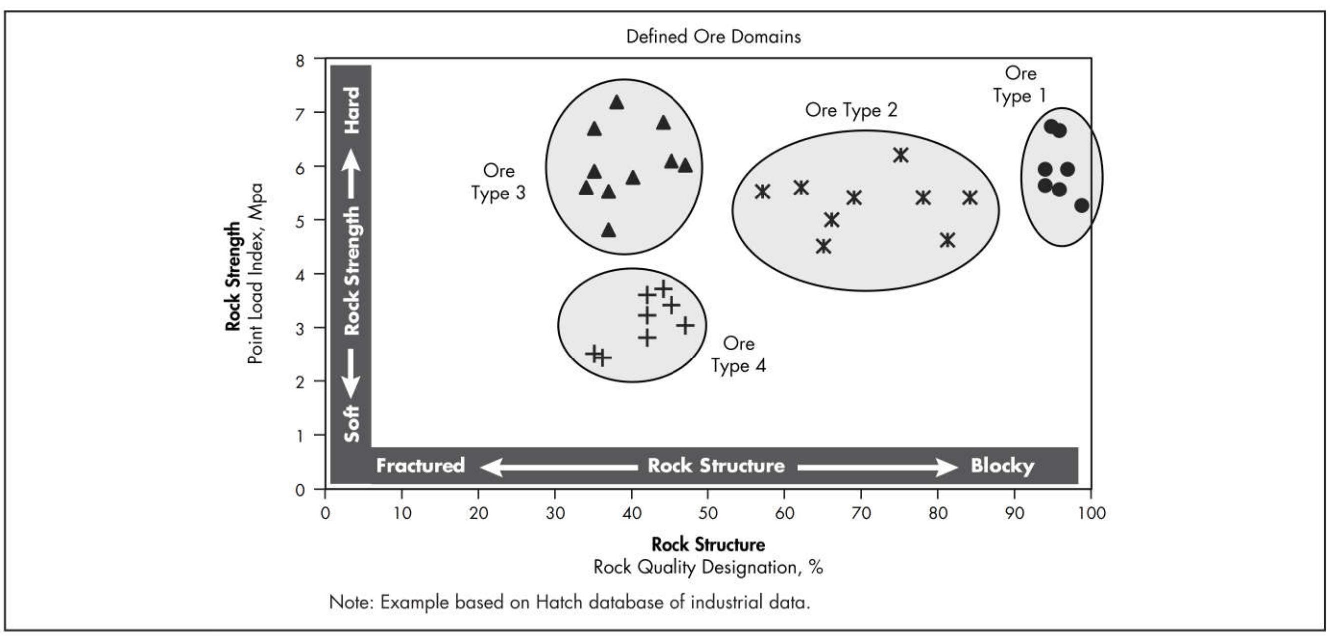
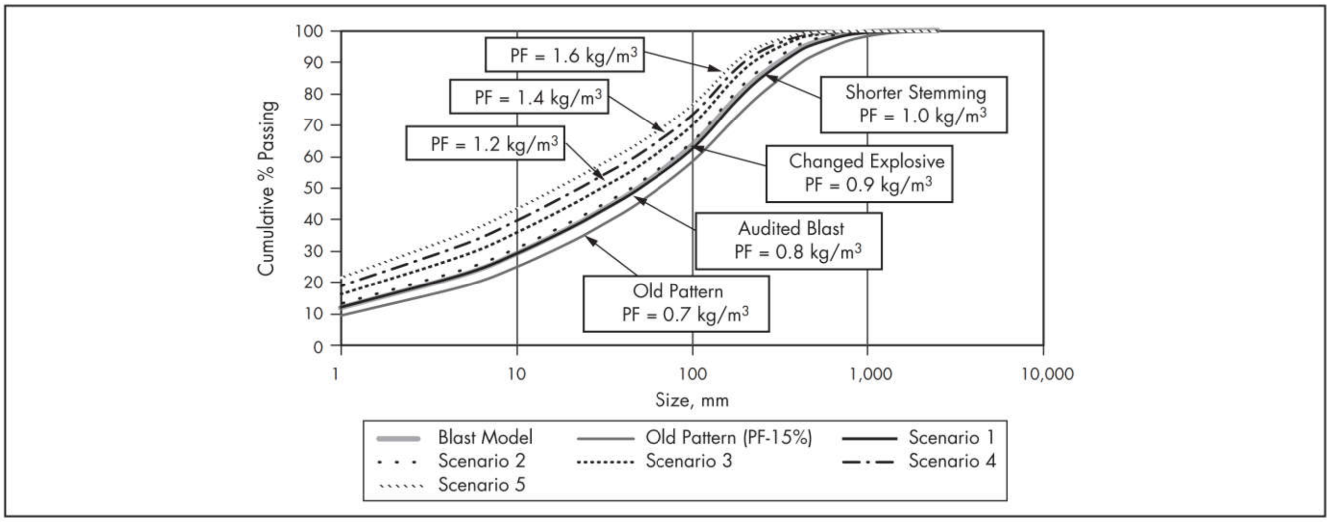
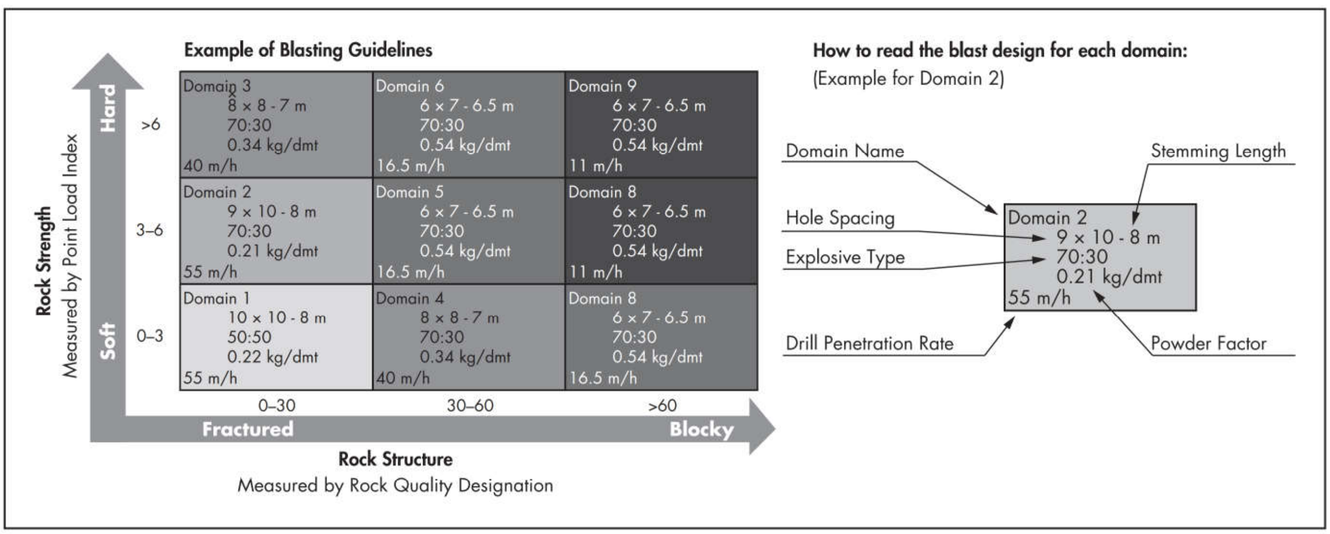


Figure 2 Example of ore domain mapping based on strength and structure



Source: Diaz et al. 2015

Figure 3 Example of blast simulation results for the Cerro Corona operation



Adapted from McCaffery et al. 2006

Figure 4 Example of blasting guidelines for the Newmont Batu Hijau operation

mentioned earlier. Blasting guidelines are specified, providing an optimized blast design for each ore domain (see example in Figure 4). Blasting according to these guidelines provides a more consistent and optimized feed size distribution to the downstream processes, increasing throughput, process stability, and efficiency. Following the guidelines also avoids excessive blasting in softer ore domains, thus reducing energy consumption and costs, and preventing the excessive production of ultrafine material that can be detrimental to some downstream processes (e.g., in heap leach operations or flotation).

To realize the full benefits of improved ROM fragmentation from changing blasting practices, optimization must be carried through the downstream processes. This may be achieved by conducting comprehensive plant surveys while the material from an audited blast is treated in the processing plant. An ore tracking system, such as radio-frequency identification (RFID) tags, can be used to track material from the audited blast into the plant. Alternatively, it may be possible to use the mine dispatch system to identify when audited material is treated in the plant or to arrange campaign material from the audited blast through the plant by direct dumping of material into primary crushing. However, it is important to also consider residence times and mixing in intermediate stockpiles such as coarse ore stockpiles.

COMMINUTION CIRCUIT OPTIMIZATION

The ROM size distribution has a significant impact on the throughput and performance of downstream processes. Finer ROM fragmentation from blasting optimization may allow the primary crusher gap to be reduced, as the finer ROM enables this change to be made without compromising crusher throughput or exceeding installed power.

The ideal ROM size distribution, which will result in maximum throughput and performance, will depend on the breakage characteristics of the ore, equipment type, and circuit arrangement as well as operating conditions. The optimum feed size requirements for autogenous grinding mill, SAG mill, or multistage crushing circuits are very different.

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.

This is shown schematically in Figure 5, and an example of the impact of feed size on SAG mill throughput (for the Antamina operation) is shown in Figure 6.

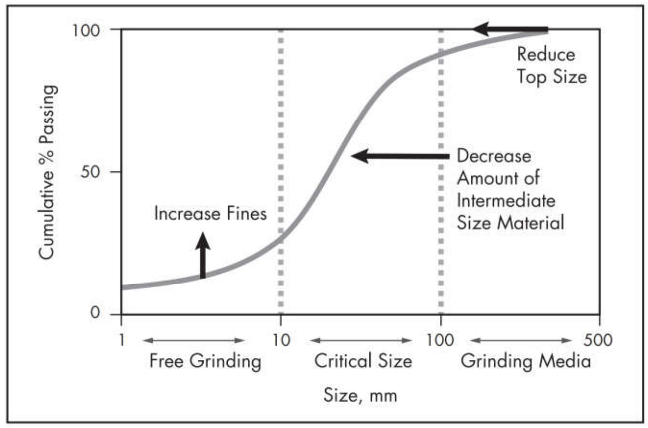
A change in comminution circuit operating strategy can often result in a reduction in power usage or an increase in circuit capacity. Comprehensive plant surveys, historical operational data, and benchmarking can be used to develop site-specific models for the comminution processes. The site-specific models allow simulation of different operating conditions, alternative circuit configurations, expansion options, and so on. This facilitates evaluation of many scenarios, avoiding trial-and-error experimentation in the processing plant, which is risky and expensive because of lost production.

Trend and variability analysis of historical operating data, power calculations, and benchmarking with similar operations can also be used to determine the bottlenecks and constraints in the current circuit and identify opportunities for improvement. For example, consideration should be given to the following:

- Availability and utilization
- Power draw, utilization of installed power
- Gap measurement and feed conditions (choke feeding) for crushers
- Pressure, roll speed, gap for high-pressure grinding rolls (HPGRs)
- Media size, ball load, charge and lifter/liner design for tumbling mills
- Trommel aperture and design
- Pebble crushing
- Media size in stirred mills
- Transfer size between various comminution equipment
- Recirculating loads
- Screen aperture, open area and loading
- Cyclone size, internals and feed density, and so on

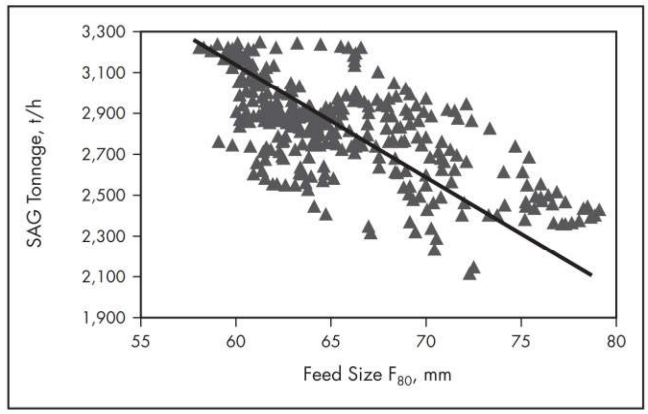
However, the constraints and limitations are not always associated with major pieces of equipment but can also include ancillary or material transport issues such as pumping and conveying limitations, and water or power constraints.

Comminution flow sheets using technologies such as HPGRs and stirred mills are becoming more common because of growing challenges with regard to supply and cost of grinding media, energy, and water. The holistic mine-to-mill approach is equally relevant for different technologies and flow-sheet arrangements, and requires detailed understanding of the ore characteristics and processes. While mine-to-mill optimization has been more widely applied (and benefits documented) for operations with SAG mills, there are several examples with HPGR circuits. The Newmont Boddington gold mine (with HPGR circuit) in Australia is a good example of the significant impact a focused mine-to-mill program can have on multistage crushing plant efficiency and operating costs (Hart et al. 2011).



Adapted from Valery et al. 2015

Figure 5 Ideal SAG mill feed size distribution



Source: Rybinski et al. 2011

Figure 6 Example of the impact of feed size on SAG throughput for the Antamina operation

Comminution is the most energy-intensive part of mineral production (typically accounting for more than half of the total energy consumption in the processing plant), and energy consumption increases as particle size decreases. Therefore, particle size should only be reduced as much as required for effective separation. The relationship between final grind size and separation performance should be understood to find the optimum trade-off between grind size (throughput and energy consumption) and recovery.

FLOTATION CIRCUIT OPTIMIZATION

In many mine-to-mill projects, for brownfield (existing) operations, the grinding circuit capacity is limited. Without significant capital investment for additional equipment, increasing throughput can result in coarsening of the grinding circuit product size, even with optimization of the circuit. Depending on the ore characteristics and liberation, this can have a detrimental effect on metal recovery in the flotation circuit. (Although in some cases the reduction of ultrafine material can have a positive effect on flotation recovery.)

Comminution and flotation circuits have traditionally been surveyed, analyzed, and optimized separately. This often results in less-than-optimal outcomes because of the complex interactions between the two processes. Flotation recovery is a strong function of the valuable mineral particle size distribution in the flotation feed. The highest recoveries are achieved for intermediate-sized particles, with lower recovery of ultrafines because of poor flotation kinetics, and lower recovery for the coarser particles because of poorer liberation and settling. Thus, to optimize flotation recovery and grade, it is usually best to grind to a fine size. This requirement needs to be balanced by the cost of grinding finer and the revenue that results from an increase in grinding throughput, which often results in a coarsening of the flotation feed. The flotation circuit can be adjusted and optimized for coarser feed if necessary, often making greater use of regrinding capacity where available.

There is a cost related to grinding to a fine size. Power usage increases as the grind size decreases, and the tonnage able to be processed by a grinding circuit can be limited by a grind size target. The overall objective should be to optimize profitability of the entire operation. It is therefore important to understand the relationship between grind size and the flotation grade–recovery performance. One possible technique, described by Bazin et al. (1994), uses simple relationships, calibrated with data routinely measured by an operation, to predict flotation recovery as a function of grind size.

This enables optimization of the comminution and flotation operations with respect to the overall operation by finding the optimum trade-off between grind size (throughput) and flotation recovery. In some cases, the effect of increased throughput outweighs the lost recovery to provide an overall increase in metal production and profitability. A good example is documented by Runge et al. (2014) for the Barrick Osborne copper–gold operation in Australia. An economic trade-off demonstrated that while higher flotation recovery could be achieved with lower throughput and finer grind size, the operation generated more revenue per hour by operating at higher throughput despite the lower flotation recovery because of higher metal production per hour and lower costs. See Figure 7.

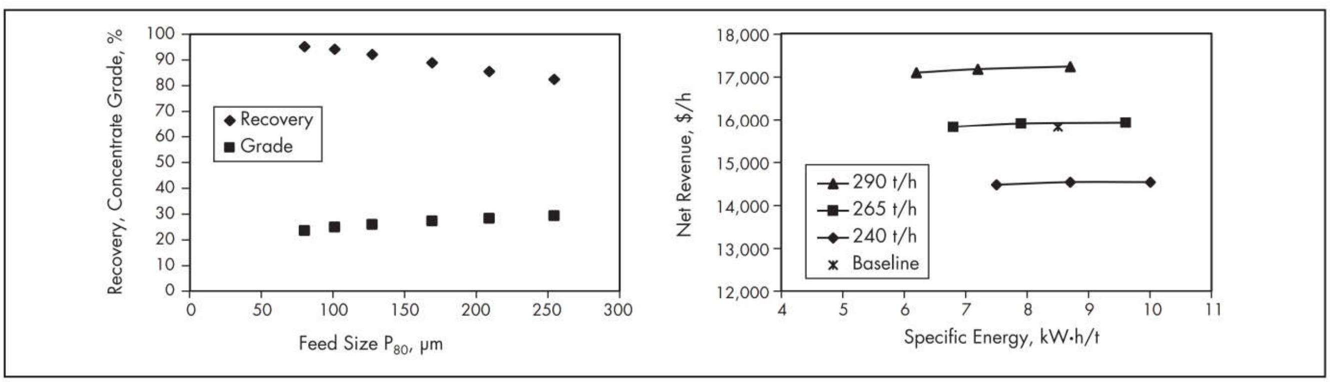
Besides the integration between comminution and flotation circuits, in a mine-to-mill optimization study, the flotation circuit itself can be evaluated and optimized. This involves studying the flotation circuit to identify opportunities for improving circuit metallurgical performance (grades and recoveries). The scale of the flotation optimization exercise can range from a simple Bazin-type analysis to determine optimum grind size to a comprehensive circuit evaluation including surveys, cell characterization measurements, batch flotation testing, liberation analysis, mass balancing, model development, and simulations. Flotation parameters such as bubble size, bubble load, superficial gas rate, gas holdup, bubble surface area flux, carrying capacity, lip loading, residence time, froth stability, froth transportation, and froth depth can be measured or estimated to identify possible avenues for improving cell and bank performance. This information, along with detailed surveys, historical operating data, and flotation kinetics can be used in modeling and simulation to evaluate and optimize flotation circuits. These analysis techniques are used to

- Determine characteristics of the valuable mineral not recovered (e.g., size and degree of liberation) and the reason they are not being recovered (e.g., insufficient circuit residence time, poor selectivity, insufficient grinding, poor liberation, insufficient reagent, oxidation surface coatings);
- Ascertain optimum circuit configuration;
- Determine optimum feed and regrind particle size;
- Establish strategies for optimizing cell operation (e.g., froth management, air profiling); and
- Quantify downstream flotation circuit benefits associated with changes to comminution circuits (e.g., tonnage rate, grind size).

ENSURING EFFECTIVE CHANGE MANAGEMENT TO SUSTAIN BENEFITS

The mining industry typically experiences a high turnover rate of employees, particularly at many remote operations. As a result, the benefits from mine-to-mill optimization (or any other improvement initiative) can be short-lived if the changes are not effectively embedded into systems, site operating practices, and procedures. Even in locations where turnover is not high, the changes may not be sustained if the operating staff does not understand the reasons for the changes or where measures of personnel performance are not aligned with the mine-to-mill objectives.

Therefore, to sustain the benefits in the longer term, it is important to debrief site operating personnel and management on the outcomes of mine-to-mill optimization, and the reasons for changes and benefits. The results need to be properly measured, documented, and supported by management. Furthermore, the changes need to be incorporated into managerial and site operating systems, procedures, and ongoing training of operators and engineers. In many cases



Source: Runge et al. 2014, reprinted with permission from the Australasian Institute of Mining and Metallurgy

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Figure 7 Example of economic trade-off between throughput/grind size and flotation recovery

where mine-to-mill has been particularly successful, regular meetings have been established involving both mining and processing personnel. These mine-to-mill meetings ensure an ongoing integrated effort to maximize the profitability of the overall operation.

Integration of mine and processing databases, including block models, mine dispatch systems, mine plans, and processing plant distributed control systems (DCSs), will certainly facilitate effective implementation and management of mine-to-mill optimization strategies. These systems provide the quantification of key operational and business drivers to allow informed decisions that maximize the profitability of the overall operation. Common centralized mine and processing plant operation and control centers will also play a major role in ensuring effective communication and aligned focus on common goals.

It is also important that KPIs or other measures of performance are adjusted to reflect the mine-to-mill strategies. Metrics and KPIs help to focus people and measure success; however, if inappropriately used, they can detract from broader operational goals. For example, if the performance of the mining department is measured only on cost and tons mined, better performance could be achieved by decreasing blasting intensity, but this would result in coarser fragmentation and lower throughput in downstream processing. To prevent this, KPIs and rewards or bonus payments for mining and processing plant personnel should be aligned and focus on profitability of the entire operation. As well stated by Eliyahu Goldratt (1990), "Tell me how you measure me and I will tell you how I behave."

MINE-TO-MILL OPTIMIZATION CASE STUDY: ANTAMINA

Numerous case studies demonstrate successful implementation and sustained benefits from mine-to-mill optimization for a wide variety of operations around the world. One such case study, Antamina, is discussed briefly here and in more detail by Rybinski et al. (2011), Samuel et al. (2012), and Valery and Rybinski (2012).

Compañía Minera Antamina is a polymetallic mining complex situated in the central Peruvian Andes around 4,300 m above sea level. Antamina produces copper and zinc concentrates as primary products, and represents one of the main complexes of the Peruvian mining industry.

The advent of harder ores presented a problem for the operation, significantly reducing plant throughput. A comprehensive review was conducted of existing operations at the mine and in the comminution circuits. Ore sources were characterized into ore domains based on rock structure and strength. Blast audits were conducted, and the blasted material was tracked from the mine through the process using RFID tags. Process surveys were conducted while treating the ore from audited blasts, allowing the performance in comminution circuits to be linked to the ore characteristics and blast fragmentation measured during the audited blasts. Historical data and current operating practices were also reviewed.

The collected data were used to develop mathematical models of the drilling-and-blasting, crushing, and milling operations. The resulting site-specific models were linked and simulations were conducted to identify optimum operating strategies for the overall process. Conditions such as different blast designs, primary crusher setting, SAG mill grate design, SAG mill ball charge level, ball mill operating conditions, changes in classification with hydrocyclones, and use and operation of recycle/pebble crushers were all considered and evaluated in the simulations. The proposed strategies were discussed and analyzed in detail with site technical staff.

The optimal and most cost-effective integrated operating strategy for the entire process (mine and plant) was then implemented, significantly increasing throughput. After the initial success, further investigation of higher-intensity blasts produced even finer ROM fragmentation and subsequently finer feed to the SAG mill. Additional optimization of the crusher, SAG, and ball mill circuits was conducted to achieve maximum throughput and best overall performance. The additional blasting energy was more than compensated for by the large energy savings in the crushing and grinding processes, thus minimizing the specific energy consumption of the entire operation. The sustained throughput benefits and energy savings achieved at Antamina are demonstrated in Figure 8.

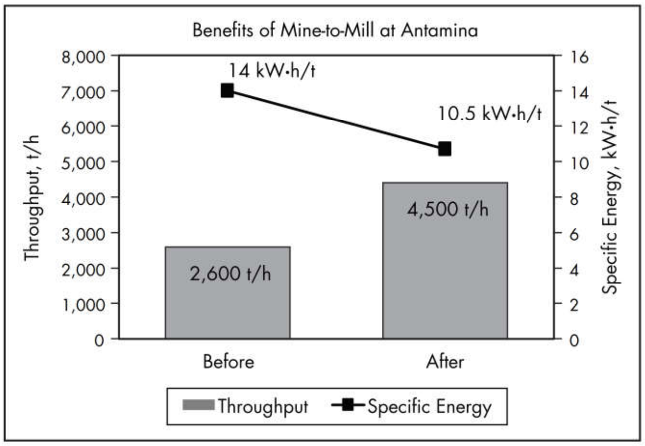
At the beginning of the project, the operation achieved a throughput of 2,600 t/h with a specific energy consumption of 14 kW·h/t. At the end of the project, throughput of 4,500 t/h was achieved and maintained with a specific energy of 10.5 kW·h/t. This represents a significant increase in resource efficiency by reducing the total environmental impact of metal concentrate production with an energy savings of 25% for Antamina.

GEOMETALLURGICAL MODELING: OPTIMIZING MINE-TO-MILL OVER LIFE-OF-MINE

Mine-to-mill optimization should not only be considered in the short term. To remain viable and competitive in the face of increased challenges in extracting valuable minerals, the mining industry requires methodologies and tools to mitigate risks and to ensure the highest operational profitability throughout the life-of-mine (LOM). To maintain high profitability in the long term, it is crucial to be able to accurately predict the future performance of the process as well as the interaction with mining practices. This requires an accurate understanding of how each stage of the operation behaves for different ore characteristics as well as a detailed knowledge of the relevant ore characteristics and their distribution throughout the ore body.

The concept of geometallurgy integrates the disciplines of geology, mining, and metallurgy with the aim of developing proactive operating strategies as a function of the ore variability. Geometallurgical modeling requires a detailed understanding of the relevant ore characteristics, and models of how these will affect the performance of the blasting, crushing, grinding, and separation stages in terms of throughput, recovery, and product grade. This technique provides a link between the performance of the process, or efficiency of the extraction, and the physical properties of the ore. It facilitates throughput forecasting and allows strategic planning and optimization for different ore types to maximize the profitability of the operation in the long term.

The mine's existing block models can be used as the framework for developing geometallurgical models. The process starts with the mine-to-mill methodology described earlier in this chapter. The site-specific predictive models generated for blasting, comminution, and separation allow prediction of throughput and recovery performance for each ore domain and, when combined with the mine plan, enable a production forecast for the LOM. This can be used for long-term planning and to identify potential bottlenecks, process



Source: Duffy 2012

Figure 8 Increased throughput and energy savings achieved at Antamina

constraints, and opportunities for improvement. For example, this was well executed at the PanAust Phu Kham operation as discussed by Bennett et al. (2014). Geometallurgical modeling and production forecasting determined that the harder ore later in the mine life would prevent production targets from being met for several years. This facilitated projects and planning to account for the harder ore and process constraints.

FUTURE TRENDS OF MINE-TO-MILL OPTIMIZATION

As high-grade and easily accessible mineral deposits are exhausted, new mineral deposits are expected to be low grade, more complex, and difficult to extract. In addition, the mining industry is facing growing challenges associated with the cost and supply of energy, limited water resources, and more stringent legislative requirements. Therefore, the search for more economical and sustainable technologies and practices is becoming increasingly important.

Many strategies for improving sustainability of mining operations are not new but rather involve novel application of existing technologies and tailored solutions based on understanding of the process and ore. Existing technologies from other industries can be used, or technologies can be applied in new ways to maximize efficiency. Also, understanding the impact of each process step on preceding and subsequent stages allows optimization of the entire process.

Mining operations need to be more efficient to remain economically viable but also to meet environmental targets. Improving the resource efficiency increases the economic return of the project and can make the difference between a project being viable or not.

Duffy et al. (2015) proposed that a more resource- and eco-efficient mining process of the future may incorporate the following methods.

- High-intensity selective blasting (HISB) improves blast fragmentation and reduces the energy requirement of downstream comminution.
- In-pit crushing and conveying (IPCC) is a more efficient method of transporting ore and waste than conventional truck-and-shovel operation, and can eliminate the use of diesel.
- Elevated high-angle conveying (HAC) facilitates removal of material from deep pits via the shortest route for IPCC solutions.
- Preconcentration using screening and/or bulk ore sorting could be implemented to discard barren material, consequently reducing haulage and downstream processing requirements per ton of product.
- Alternative energy-efficient and dry technologies such as HPGRs, vertical roller mills (VRMs), and air classifiers may be included in new comminution circuits.
- Partial or full replacement of hydrocyclones with fine screens may be used to improve the efficiency of existing wet grinding circuits.
- Coarse particle flotation can significantly reduce the energy consumed in the previous grinding stages.
- Filtration and dry stacking of tailings can be implemented to reduce water consumption, with a much higher recovery of water than can be achieved from a traditional tailings dam, and reduce reclamation and closure costs.

Each of these concepts is described in more detail in the following sections.

High-Intensity Selective Blasting

HISB involves further increasing and better distributing the energy of blasting, and using advanced initiation systems to provide a more selective blast. The result is improved fragmentation, reducing the energy requirement of downstream comminution. Blasting energy may exceed double the current levels. It may require significant changes in current drill-and-blast practices and possibly adaptation of drilling equipment to allow several blast holes to be drilled simultaneously with a single rig. The result is ROM fragmentation with a controlled top size and more fines, as illustrated in Figure 9. The ROM top size could be decreased to less than 400 mm compared to traditional ROM top sizes of about 1–1.5 m. The improved fragmentation significantly decreases the energy requirements in downstream comminution circuits. Benefits include maximization of system throughput (mine and mill), increased excavation and loading efficiencies, better overall process stabilization, and minimization of the overall operating cost. HISB also improves the viability of IPCC because of the reduced top size.

In-Pit Crushing and Conveying

IPCC is the use of fully mobile, semimobile, or fixed in-pit crushers with a conveyor system to remove material from the pit. IPCC can eliminate the use of diesel and is more efficient than conventional truck-and-shovel operation. The economics of belt conveying are particularly attractive in large-volume operations, since conventional truck haulage costs increase dramatically with pit enlargement.

The main advantages of IPCC are low operating costs, reduced supply requirements, high capacity, reduction in greenhouse gas emissions, and improved safety. Operating costs are typically 20%–60% lower than a truck-and-shovel system, with a fully mobile IPCC system the most frugal (Foley 2012). The benefits depend on the site conditions; however, studies have indicated operating cost reductions of between US$0.18/t and US$0.25/t compared with conventional truck-and-shovel operations (Cooper 2008). In addition, studies by Norgate and Haque (2010) and Koehler (2010) have indicated potential reductions in greenhouse gas emissions of 100,000–150,000 t CO_2/yr.

However, IPCC requires careful evaluation of geological, technical, and economic factors specific to the operation. IPCC needs to be factored into the mine design, which is generally more complex and less flexible than truck-and-shovel operations, and has longer delivery and development time. HAC is an effective system to implement IPCC in operations with steep pit walls, removing the material via the shortest route. The capital cost is higher for IPCC but is typically paid back within four or five years.

Preconcentration

The aim of preconcentration is to discard barren material early in the process, decreasing the amount of material that needs to be treated in downstream processes. This significantly reduces the energy and water consumption and operating cost per ton of product. Resource efficiency is improved by extending resource utilization (upgrading below cutoff grade material) and/or increasing production rates per ton of ore treated.

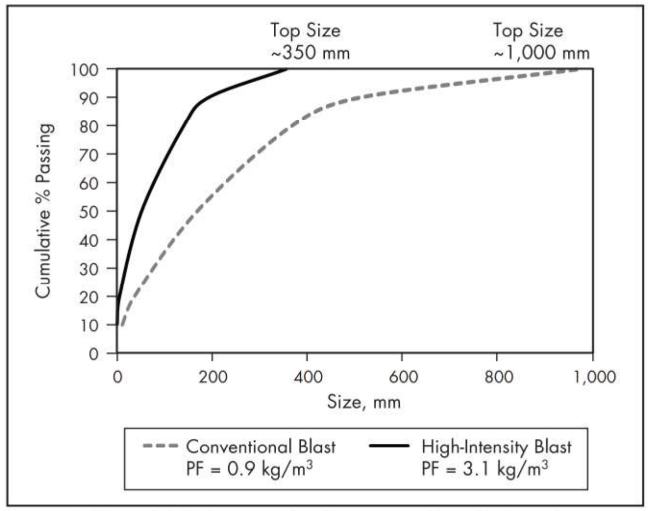
For some ores, preconcentration can be achieved by screening, as valuable minerals are often softer or more friable than gangue and therefore are concentrated in fine size fractions after initial breakage stages. There is evidence of this for several ores, including massive sulfide, base metal, gold, and some platinum ores (Bamber 2008; Bowman and Bearman 2014; Van der Berg and Cooke 2004). Screening has reasonably high capacity, low costs, and low technical risk.

Where the grade-by-size relationship does not allow effective separation, it may be possible to achieve an upgrade using a sensor to measure a difference between the valuable and waste material. A variety of sensors are available that measure different ore properties, the most common being photometric, electromagnetic, radiometric, and X-ray. The current technology measures and separates individual particles and thus is throughput limited. To be practical in preconcentration applications for large-scale mining operations, sensor-based sorting must be applied to bulk quantities of ore (e.g., on a truck tray or batches of ore on a fully loaded conveyor belt). Most of the existing sensor technologies are currently not suitable for bulk ore sorting because they are either too slow or insufficiently penetrating. However, it may be possible to adapt existing sensors or develop new sensors suitable for bulk quantities of ore. Bulk ore sorting may incorporate more than one type of sensor. It also needs a control system to make an accept-or-reject decision and a diversion system to separate the "batches" of valuable material from the waste. Ore sorting benefits from the natural heterogeneity of deposits and should be implemented as early in the process as possible, at the mine, immediately after loading, or integrated with the IPCC (where the variability is greatest) to maximize the benefits.

Energy-Efficient Comminution Circuits and Technologies

Comminution is the most energy-intensive part of mineral processing operations, consuming more than half of the energy in the mineral processing plant.

New comminution circuits may include alternative technologies to tumbling mills such as HPGRs, VRMs, and stirred mills. These are recognized to be more efficient than conventional tumbling mills. HPGRs and VRMs have the added advantage of being dry processes, thus reducing water losses. They also use no grinding media, which reduces operating costs and embodied energy, and may in some cases improve



Source: Duffy et al. 2015, reprinted with permission from the Australasian Institute of Mining and Metallurgy

Figure 9 Effect of high-intensity blasting on ROM fragmentation

flotation performance by reducing galvanic interactions on particle surfaces. Both HPGRs and VRMs have shown energy and other process benefits in pilot-scale testing of hard ores. Novel flow-sheet arrangements such as HPGRs followed by stirred mills may significantly reduce the energy consumed in comminution (Valery and Jankovic 2002).

In existing operations, a typical grinding circuit arrangement uses a ball mill(s) in closed circuit with hydrocyclones. Full or partial replacement of hydrocyclones with fine screens may improve both process and energy efficiencies. A circuit closed with screens is expected to have 15%–20% higher capacity at significantly lower circulating load because of higher classification efficiency (Jankovic and Valery 2012). Two-stage classification with cyclones followed by screens may be able to achieve higher efficiency with less screening capacity. A conservative economic evaluation suggests that replacing cyclones with fine screens could be justified at energy costs of around $US160/MW·h or higher for some operations. Benefits are even greater when the valuable mineral is higher density than the gangue; for example, capacity may be increased by as much as 50% for magnetite ores (Nunna et al. 2014). However, further development is necessary to tailor fine screening to the very large throughputs encountered in most grinding circuits.

Coarse Particle Flotation

Grinding energy increases exponentially as particle size decreases. Therefore, if flotation of coarse particles could be enhanced, the energy consumed in the preceding grinding stages could be significantly reduced by delivering a coarser product to flotation. Typically, flotation recovery decreases for particles coarser than about 0.1 mm. However, if flotation could be performed effectively at 0.3 mm rather than 0.1 mm, the potential energy savings in grinding would be around 30%–50%. A coarse rougher flotation stage could reject barren material prior to regrinding and subsequent cleaning flotation of a much smaller amount of material to achieve the required product quality.

Coarse particle flotation may be enhanced by using alternative technology, such as the fluidized bed froth flotation cell.

This technology uses a teeter bed to maximize coarse particle attachment and shallow froth depths to reduce fallback.

Alternatively, coarse particle flotation in conventional flotation cells may be improved through modifications of cell design and operating philosophy. This may include split conditioning of reagents, manipulating the turbulence regime, optimizing bubble size, increasing froth stability, and minimizing froth residence times (Tabosa et al. 2013).

Water Recovery Optimization

The mining industry typically consumes 0.6–1.0 m^3 of water for each ton of ore processed by flotation (Brown 2003; Norgate and Lovel 2006; Wiertz 2009). Most water is lost from tailings dams in evaporation, entrapment, and seepage. Plants typically recycle water; however, site water balances have revealed that as much as 70% of the water discharged into a conventional tailings dam can be lost.

Dry stacking of filtered tailings is becoming increasingly common, especially in locations with limited water supply or high seismic activity (where risk of dam failure is high). Significantly higher water recovery can be achieved compared to a traditional tailings dam. Additionally, reclamation and closure costs are significantly reduced because of smaller footprint, easier construction, and the possibility to rehabilitate progressively. Currently, there are only a few applications of dry stacking of tailings because of the high cost associated with filtering. However, it is expected that within 10 years, legislation will prohibit the deposition of wet tailings in some countries.

The dry tailings system at the Gindalbie Metals Karara iron ore mine, installed in November 2012, is the first of its type in Australia. Filtered tailings are conveyed and stacked rather than pumped to the tailings storage facility. The system has a capacity of 2,850 t/h and a total conveying distance of 3.3 km. Water consumption is reduced by about one third, providing significant environmental benefits in the arid project location (Read 2012). However, operational issues with the tailings dewatering system have limited the plant's ability to produce at nameplate capacity for sustained periods. Partial reengineering is required to achieve design moisture content in the final tailings product, thereby allowing the tailings filtration circuit to operate at design throughput (Read 2012). This emphasizes one of the main challenges in implementing tailings filtration and dry stacking, which is ensuring correct selection and sizing of technology based on the nature of the tailings.

CONCLUSION

Mine-to-mill optimization has proven to be extremely successful when implemented using a structured methodology and supported by extensive data collection and analysis. Significant increases in throughput and reduction in energy consumption and costs have been achieved for numerous operations worldwide and across various commodities. Some notable recent examples include the Gold Fields Cerro Corona operation, Compañía Minera Antamina operation, and PanAust Phu Kham operation.

The mine-to-mill benefits are sustained in the long term when the outcomes are incorporated into site practices, procedures, and training. Integration of mine and processing databases, including block models, mine dispatch systems, mine plans, and processing plant DCSs, also facilitates effective implementation and management of mine-to-mill optimization strategies.

The production, efficiency, and cost benefits of mine-to-mill optimization will become more critical in the future as the mining industry faces growing challenges with decreasing feed grades, increasing cost pressures, issues with energy and water supply, and stricter legislation. Mining operations will need to operate more efficiently to meet environmental targets and to remain economically viable.

Mine-to-mill optimization is equally applicable for greenfield projects as it is for existing operations. This provides an opportunity to make a fresh start and develop something smarter and more efficient. Novel application of existing or adapted technologies and tailored solutions based on understanding of the process interactions and ore types provides an opportunity to develop solutions that are more efficient and profitable for the overall operation.

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