Crushing and grinding circuit availability: Why is it important in design, and how can we increase it cost-effectively?

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Abstract

Crushing and grinding circuit availability is a critical design factor defining the installed equipment selection and the process buffers required to maintain throughput during maintenance. The comminution circuit typically accounts for a process plant's largest capital expenditure and energy use. Effective process and equipment selection and layout optimization are crucial steps when combining the objectives of cost-effective design and high circuit availability in operation. This paper outlines fit-for-purpose design principles for optimizing process flow, eliminating standby equipment and reducing buffer residence time whilst improving maintainability and operability.

Keywords

Comminution, cost-effective design, energy efficient design, circuit availability, utilisation, optimisation

Statements and Declarations

All authors are employees of Ausenco, an engineering consultancy that works with the world's leading mining and mineral processing companies. This study's analysis was completed after all client-funded work was completed.

Data from this manuscript were presented at the MINEXCHANGE 2025 SME Annual Conference & Expo, February 23-26, 2025, held in Denver, Colorado.

1. Introduction

The comminution circuit is a key component of the mineral processing flowsheet. Comminution is the process of size reduction that increases the liberation of valuable minerals from gangue minerals. It is well known that comminution is a high energy consumer in a typical mineral processing flowsheet, accounting for approximately 40% of total power consumption (Chandramohan et al., 2023). Therefore, selecting the correct flowsheet and equipment is essential to achieve the desired annual throughput at the target energy consumption.

Two broad factors drive the selection of preferred comminution flowsheet and equipment selection:

- Ore characteristics, for example, competency, hardness, feed size distribution from the mine and presence of clays
- Target throughput rate, instantaneous and life-of-mine.

The preferred flowsheet is defined by its value to the project. Optimizing 'value' is essential for long-term project success, seeking funding from investors, and building shareholder confidence. The flowsheet selection is driven by:

- The capital cost required to build the project, impacting on the overall net present value
- The operating costs, including
  - the reliability of the circuit as it impacts maintenance requirements and associated costs and
  - energy efficiency and impact on greenhouse emissions

Lane et al. (2008) and Lane and Dickie (2009) discuss the link between design, optimizing the footprint, bulk-material quantities (concrete, steel, pining, cable, etc.) and capital cost for mineral processing plants. They defined a smart and experienced team as one of the key requirements for good flowsheet design focused on adding value, not just engineering excellence or design to a pro forma arrangement.

Crushing and grinding circuits, like any other production process, are greatly affected by changes over time since they are continuous processes in which equipment is subjected to variations in feed characteristics and/or changes in equipment condition. The variations can be caused by degrading equipment performance, reducing overall plant capacity and thus decreasing product quality (Major, 2003; Bengtsson et al., 2009; Itavuo, 2009).

In flowsheet design, the impact of maintenance requirements is measured by estimating or calculating equipment availability based on the planned maintenance of critical components such as wear parts and lube systems. Major mechanical and electrical components, such as drive systems, gear components, windings, etc., are expected to last for an extended period if these components are monitored and inspected periodically as part of a preventative maintenance program.

Most primary crushing circuit designs are based on a 75% availability target, and grinding mills use, say, a 92 % availability target. The crushing circuit availability is lower due, in part, to mine requirements and truck scheduling rather than matters related to the crushing circuit. Based on the throughput requirement of the project, the flowsheet and comminution equipment are selected and process buffers, such as stockpiles, bins, and large tanks, are placed so that stable and consistent production is maintained target. The sizes of the process buffers and the selection of the comminution equipment in the flowsheet are mutually dependent. A small-capacity process buffer may require the selection of duty standby equipment. In contrast, the flowsheet may require a large-capacity process buffer when selecting duty-only comminution equipment. The optimum selection of the number of comminution equipment and the size of process buffers in the flowsheet is a function of:

- Incurred capital cost in the project – for junior mining companies, where capital is constrained. A low capital-cost flowsheet is often preferred.
- Available footprint to build the flowsheet – for space-constrained areas, the layout of the flowsheet is pertinent (e.g. Phu Kham)
- Impact on operating cost and greenhouse gas emissions (GHGe) – additional equipment in the flowsheet may incur higher operating costs and, as a result, incur higher scopes 2 and 3GHGe levels
- Commonality of spares and number of parts required to maintain all equipment in the flowsheet. Common spares minimize the need for large on-site warehousing and reduce the risk of logistics-related delay caused by unexpected circumstances (transportation risk, geopolitical, and environmental).

2. Description of Maintenance Parts

The selection of the comminution equipment for the duty in the selected flowsheet depends on its ability to process ore with specific ore characteristics (competence, hardness and abrasion index) at the desired throughput and the target product size distribution. A key factor in the selection of the size of the equipment to achieve the duty is the equipment availability based on the downtime for annualized throughput rates. Maintenance of crushers and grinding mills can be broken down into three types:

- Preventative – planned maintenance program to prevent catastrophic failure of the equipment
- Predictive – requires continuous equipment monitoring while in operation to prevent unplanned downtime.
- Reactive – Run to failure or 'don't fix it if it isn't broken' maintenance thinking. This type of maintenance incurs unplanned downtime, impacting production.

Table 1 and Table 2 highlight the various components of the crushers, grinding mills, classifiers and bulk handling systems that require maintenance. Wear components are parts in direct contact with the ore and slurry. The wear rate of these parts differs based on the ore type and composition (such as competency/hardness, abrasiveness, particle size distribution and moisture percentage). The operation of various equipment's mechanical, electrical, hydraulics, and safety components are similar, such as in crushers, mills, classifiers, and bulk handling systems. The expected life-of-components are based on the runtimes (i.e. hours of operation).

Table 1 – Summary of major components in crushers and grinding mills that require maintenance

	Crushers	Grinding Mills
Wear parts	Liners, mantles, concaves	Liners, pulp system, trommel screens
Mechanical	Gears, shafts, bearings, fasteners, gearboxes	
Electrical	Motors, control panels, wiring, exciters	
Hydraulics	Oil and filters, pumps, cylinders	
Safety	Guard rails, emergency stop buttons	

Table 2 – Summary of major components in process classifiers and bulk handling systems

	Classifiers (screens & hydrocyclones)	Bulk handling (conveyors, feeders, diverter gates, chutes)
Wear parts	Screen panels, pump wet ends, spigots, vortex finders	Conveyor belts, skirts, chute wear plates, diverter gates, apron feeder chains & plates
Mechanical	Gears, shafts, bearings, fasteners, gearboxes	Idlers, pulleys, gears, shafts, bearings, fasteners, gearboxes
Electrical	Motors, control panels, wiring, exciters	
Hydraulics	Oil and filters, pumps, cylinders	
Safety	Guard rails, emergency stop buttons	

In greenfield design, the wear rates of various wear parts are benchmarked using historical projects. Table 3 presents the approximate life of major components for various comminution equipment as a function of ore abrasiveness. The estimated life is based on a typical design feed size distribution and operating within the specified parameters.

Table 3 – Approximate life of major wear components

	Low abrasive ore	High abrasive ore
Crushers	3 months	1.5 months
SAG mills	8 months	4 months
Ball mills	12 months	6 months
Bulk systems (conveyors, apron feeders)	+20 years	+10 years
Bulk systems (chutes and skirts)	2 – 5 years	~ 1 – 2 years
Hydrocyclones and pumps	Cyclones <1 month; Pumps <2 months	Cyclones <0.5 months; Pumps <1 month

Most wear components should last for their estimated life if the system is designed and operated well. However, several operational factors can cause premature failure, which requires additional monitoring systems and smart design to minimize the likelihood of failure (Table 4).

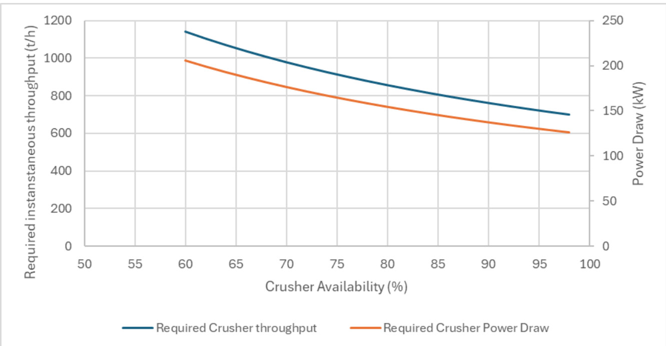
Table 4 – Cause of premature failure of wear components and recommended solutions

Equipment	Failure	Solution
Crushers	Liner and mechanical failure due to tramp metal (or media) in the ore feed	Install metal detectors and magnets on conveyors on secondary and pebble crusher systems
Mills	Liner failure caused by high media impact	Install mill acoustics and optimize liner design and process control
Hydrocyclones and pumps	Coarse media in cyclone feed	Install trommels/discharge screens or trommel magnets at the end of SAG and ball mills
Conveyors	Misalignment of conveyors and belt-tear caused by coarse-angular feed	Proper design of transfer points and install belt tracking sensors

3. Impact of Availability on Equipment Size

The impact of equipment availability on achievable throughput is significant. Figure 1 presents an example of the required instantaneous throughput by a primary jaw crusher to maintain an annualized throughput rate of 6 Mt/y and operate with the close-side setting of 120 mm.

A low-availability crusher requires a higher throughput target than a high-availability one. The corresponding power draw for the crusher changes from high to low depending on the required throughput. Thus, a crusher with low availability will need to be larger to accommodate higher throughput, which will impact the capital cost required for the project.



draw

A low-availability crusher increases the capacities of all bulk-handling equipment. Conveyors, transfer points, bins, and coarse ore stockpiles must be sized and engineered for the higher throughput and loads.

Figure 2 presents the minimum estimated coarse ore stockpile (COS) size and number of dump trucks required. Figure 3 highlights the required capital cost for the COS and reclaim system based on the crusher availability. The following assumptions were used in the calculation:

- An angle of repose of 37 degrees was used to determine the height and diameter of the COS to maintain the feed rate to the grinding circuit while the crusher is offline for maintenance
- A dozer is used to maintain consistent feed to the grinding circuit when the primary crusher is offline
- A CAT 793 dump truck with a rated payload capacity of 240 t and cycle of 15 min per dump was used as the means of haulage from the mine to the primary crusher
- Crusher dump pocket capacity has a live volume of 360 t (approximately x1.5 of one dump capacity)
- The coarse ore stockpile and reclaim systems costs are based on Ausenco's historical direct cost estimates.

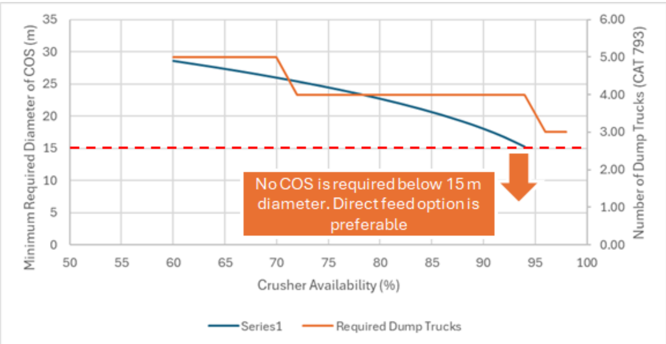


Figure 2 – Calculated coarse ore stockpile size and required number of haulage trucks

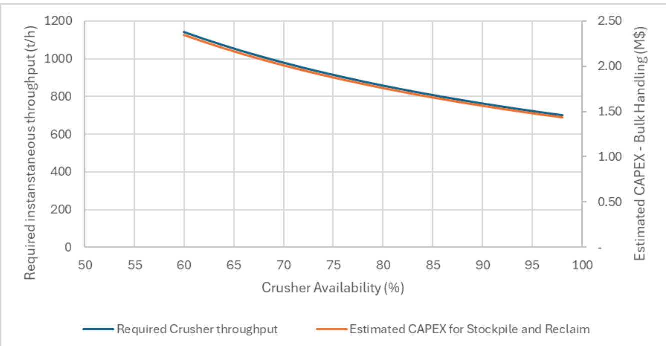


Figure 3 – Estimated coarse ore stockpile and reclaim cost based on crusher availability

As highlighted above, a drop in crusher availability (i.e. 75 to 65%) incurs significant project costs, resulting in an increased footprint for the coarse ore stockpile and an increased number of dump trucks to maintain crusher throughput. Installing coarse ore stockpiles below 15 m in diameter is not cost-effective. Due to the high primary crusher availability, incorporating a COS in the flowsheet can be avoided with a direct feed option for the grinding circuit.

4. Duty Standby vs Duty Only Process Equipment

In comminution flowsheet design, the selection of duty-only vs. duty-standby equipment is primarily driven by the maturity of the maintenance team managing the equipment and the allowance in the design to manage quick replacement of the spare parts. Figures 4 and 5 illustrate examples of duty-standby and duty-only pebble-crushing facilities and cyclone feed pumps. Table 5 presents summary comparisons between the two circuit types. The main advantage of installing duty-only equipment is essentially the simplicity and cost-effectiveness of the design.

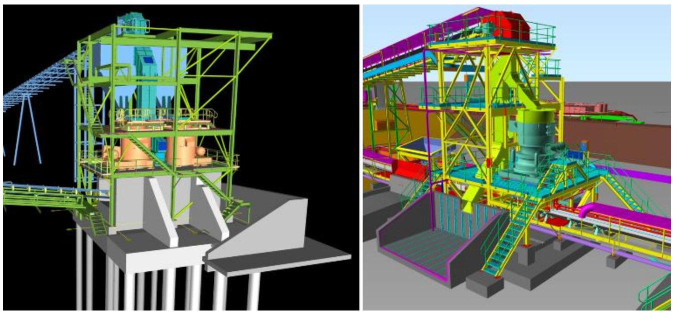


Figure 4 - Duty-standby vs duty only pebble crushing facility

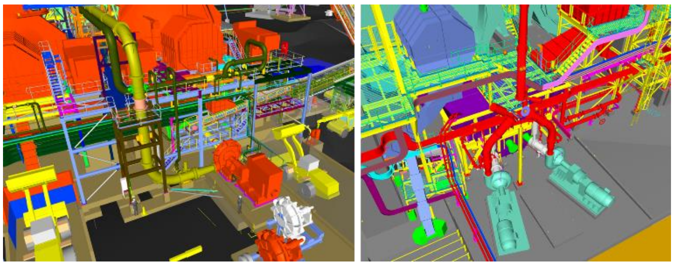


Figure 5 – Duty-standby vs duty only cyclone feed pump

A grinding circuit availability analysis was conducted for duty-standby and duty-only cyclone feed pumps (Figure 6). The net benefit of duty-standby cyclone feed pumps over duty-only feed pumps is 0.2%, an additional 20 hours of maintenance time saved in a year. The overall maintenance cost

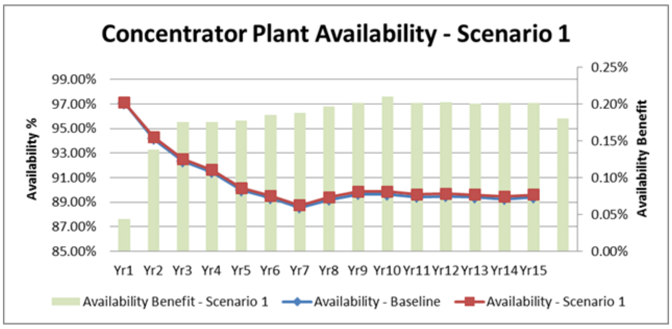


Figure 6 – Equipment availability benefit analysis on the overall grinding circuit availability (Analysis conducted by Ausenco's Asset Optimisation Team)

saving is marginal compared to capital cost saving, thus impacting the net present value.

To compensate for the marginally lower availability of duty-only cyclone feed pumps, the feed rate to the grinding circuit can be increased by 0.2%, which would incur an additional 1.2% in direct costs of all major equipment in the process plant due to resizing. A flowsheet with a duty/standby cyclone feed pump could be cost-effective. However, it can succumb to line sanding issues and inoperable valves at startup, offsetting the 0.2% availability advantage over duty-only cyclone feed pumps. Therefore, duty-standby cyclone feed pumps require proactive maintenance and operating strategies.

In flowsheet design, ease of maintenance access should be considered for duty-only pebble crushers to minimize maintenance downtime. Table 5 presents the advantages of duty only vs duty standby pebble crushers in the grinding flowsheet. For planned maintenance of duty-only pebble crushers, finer or less competent feed to the SAG mill could be scheduled in the mine plan. This would require careful integration of the mining practice with maintenance objectives to meet production targets.

Table 5 – Advantages and disadvantages of duty standby and duty-only pebble crushers

	Duty Only	Duty Standby
Advantages	• Lower capital cost • Smaller footprint requirement • Low steel and concrete quantities • Lower requirement of spares	• High availability of the facility • Lower impact on the process (i.e. no need to bias uncrushed pebbles to SAG mill) • Flexible to operate at higher throughput rates – can switch to duty-duty mode
Disadvantages	• Not flexible to operate at higher feedrates • Will impact the process during an offline period – i.e. uncrushed pebbles sent to the SAG mill	• Larger footprint (more concrete and steel) • More equipment to maintain in the flowsheet

5. Solutions to Increase the Availability of Equipment

Maintaining effective working equipment requires a combination of preventative maintenance leveraged by predictive insights gained from online monitoring (Table 6). Successful operations rely on an experienced maintenance team to continuously monitor critical assets to minimize unexpected downtime.

Several commercial online solutions are available to assess the asset's performance and provide continuous diagnostics of critical components. The data output can then be incorporated into machine learning algorithms to improve the predictability of failure, increasing the equipment's availability enabled by insight-driven maintenance planning (Chandramohan, 2023 & 2024).

Table 6 – Preventative and predictive maintenance solutions to increase equipment availability

Equipment	Preventative	Predictive
Crushers	• Conduct daily maintenance checks – lubes, closed side settings, condition of wear components • Check closed side settings of the crusher gap	• Leverage online monitoring sensors – vibration and temperatures linked with machine learning to predict asset conditions
Bulk Handling Systems	• Check belt tensions, lubes, and skirt conditions (especially at the reclaim system) • Clean up any spillage • If oversized rocks are sent through the system – check the closed side settings of crusher gaps • Check general conditions of screen panels	• Utilize online monitoring sensors, such as belt conditions, rip sensors, image analysis etc. • Utilize drones fitted with acoustics and thermal sensors to determine the conditions of idlers and pulleys and general structural integrity
Grinding Mills	• Take advantage of capturing mill internal measurements of liners and charge/media filling levels during unplanned downtime • Design the liners to suit a fixed maintenance plan (e.g. reline every six months)	• Leverage online monitoring solutions to prevent damage to mill liners (acoustics, liner load cells) • Utilize OEM-supplied condition monitoring solutions (real-time conditions of motors, drives, gears)
Hydrocyclones and pumps	• Check conditions of standby cyclones – regularly	• Utilize tramp metal detectors in cyclone feed to determine the

	switch cyclones in the cluster	required maintenance strategy. • Utilize online monitoring solutions for pump diagnostics – machine learning for condition monitoring

Besides improving maintenance strategies to increase equipment availability, OEM (original equipment manufacturer) and engineering companies are developing several smart solutions to minimize downtime during maintenance and replace worn components.

For example, different maintenance approaches can reduce downtime for cyclone feed pumps. Weir Minerals has estimated the time taken to replace the worn components in the slurry pump based on the type of maintenance strategy (Table 7). Shifting the maintenance strategy from in-situ to bare shaft assembly can reduce the downtime by 8 hours. The maintenance cost incurred is higher for the bare shaft than the in-situ strategy, as a complete pump assembly is required for replacement. Compared to production lost time, the trade-off for a new pump assembly is insignificant as production lost time significantly impacts the overall project net present value (NPV).

Table 7 – Cyclone feed pump maintenance strategies (Weir Minerals, 2024)

Strategy	Approach	Maintenance time (hours)
In-situ	• Each worn components are replaced/exchanged on the spot when the pump is offline	16
Clamshell	• The entire wet-end / clamshell is replaced instead of replacing each worn component	12
Bare shaft	• Similar to the clamshell, the entire pump (including the wet ends) is replaced with a spare. The worn pump is then refurbished at the warehouse.	8

High-wear components in bulk handling, such as transfer points and chutes, can be replaced with refurbished sections or rotable spares. To accommodate 'ease of lift', all sections of the rotable component must be engineered to suit the type of crane used for maintenance. Due to the 90-degree transfer point to the SAG mill feed chute in Phu Kham, a deflector liner plate requires frequent replacement (Figure 7).

Figure 7 – Phu Kham's near 90-degree transfer head chute for the SAG mill feed

Rotable chute designs are incorporated to minimize downtime during the replacement of the deflector plate. Access to the Phu Kham's SAG mill feed chute is by the overhead tower crane, which is permanently used for condensed Phu Kham process plant footprint.

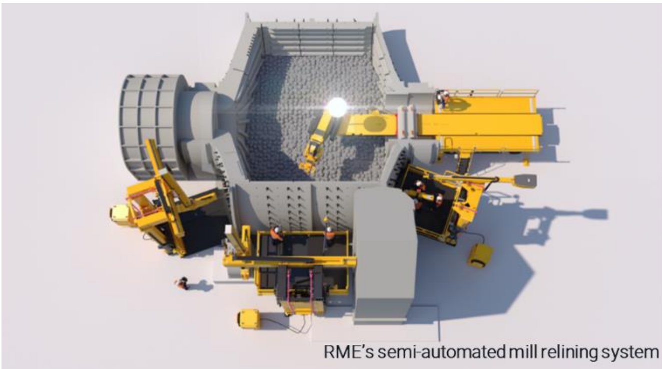


Figure 8 – Russel Mineral Equipment's semi-automated mill relining system (Global Mining Review, 2023)

In grinding mills, optimizing the number of liner components and sequencing the change-out using automation can reduce the relining time of the SAG and ball mills. Russell Mining Equipment (RME) has been developing relining automation solutions to increase the maintenance crew's safety and reduce the relining time (Gwynn-Jones et al., 2024).

Figure 8 presents the key features of RME's semi-automated mill relining solution. The solution comprises of:

- INSIDEOUT Placement – automated technology improves safety by removing personnel from the mill during liner placement
- INSIDEOUT Removal - automated technology improves safety by removing personnel from the mill during liner removal
- THUNDERBOLT SKYWAY – automated liner bolt removal and placement technology

- RUSSELL 7 AutoMotion MRM – semi-automated mill relining machine, allowing flexibility and adaptability for a range of motion inside the mill

Enabled by automation, RME's solution has decreased relining times by approximately 20 per cent, significantly improving the mill's availability (Figure 9).

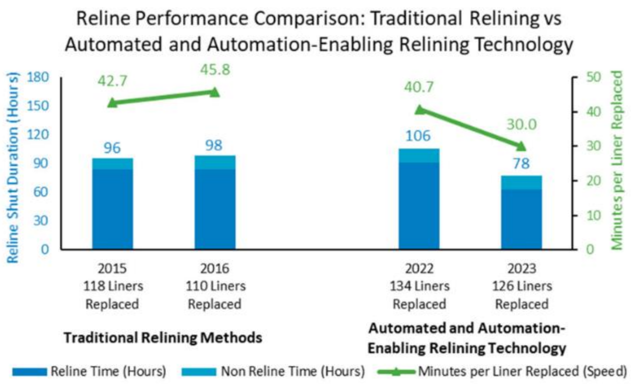


Figure 9 – Performance benefit comparing traditional relining methods to automated and automation enabling technology methods (Gwynn-Jones et al., 2024)

6. Conclusions

The availability of crushing and grinding equipment is a critical design factor for equipment sizing and flowsheet selection. Most primary crushing circuits use an availability factor of 75 per cent, and grinding circuits use 92 per cent, based on the processing of average ore types (circa, Axb = 50, BWI = 15 kWh/t) and fixed relining schedules of the wear components. The availability of the crushing and grinding equipment is sensitive to the type of maintenance strategy used by the site team. In well-operated and well-maintained mine sites, higher availability can be achieved through preventative and predictive maintenance strategies. Reactive maintenance strategies significantly impact the overall circuit availability, resulting in higher throughput rates to maintain annual production targets.

Selecting low-available equipment in the flowsheet incurs higher operating and capital costs in the project. The low-available crushing circuits also incur higher haulage costs and increase the size of the bulk handling equipment.

There are advantages and disadvantages to selecting duty-only equipment over duty standby in the process flowsheet. Duty-only equipment has a lower footprint, requiring less steel and concrete used in the construction. Ausenco's asset optimisation team's analysis on the maintenance downtime impact for a well-run maintenance program for duty-only cyclone feed pumps shows only marginal impact, incurring a 0.2% lower availability when compared to similar duty standby equipment. For crushing equipment and circuits, such as pebble recycle crushers in SAG and ball mill flowsheets, the impact of duty-only equipment on grinding circuit performance can be minimized by coordinating the plan maintenance with ore supply from mining – i.e. feeding the SAG mill with a lower competent feed during pebble crusher maintenance.

Several solutions are available to increase crushing and grinding equipment availability through smart maintenance practices and design considerations.

Switching from an in-situ to a bare shaft assembly maintenance strategy for cyclone feed pumps can save significant maintenance downtime. However, a completely new bare shaft assembly has a higher maintenance cost than an in-situ one.

Automation is a key enabler in minimizing downtime during planned maintenance programs. RME's semi-automated mill relining system can reduce maintenance time by 20 per cent while improving overall crew safety.

Critical spares of major equipment should be stocked as part of a proactive maintenance strategy to minimize extended downtime during unplanned maintenance.

Ultimately, successful mining operations with higher crushing and grinding circuit availability take a proactive approach to maintenance, leveraging predictive technology, smart engineering designs for quick equipment access, and, when possible, automation to minimize worker hazards.

Acknowledgements

The authors acknowledge the following personnel and companies in support of writing this paper:

- Weir Minerals Australia on the discussions regarding pump designs to improve equipment availability
- Maarten van de Vijfeijken from ABB for providing examples of online monitoring solutions
- Jon Garnaut from Ausenco's Asset Optimisation Team on providing data analysis on duty standby vs. only cyclone feed pumps
- Pablo Zuniga for cost analysis of bulk handling equipment
- Peter Litzow, Ausenco's Technical Manager of Bulk Handling, for discussions on crushing circuit availability
- And Ausenco management for the approval and publication of the paper at the MINEXCHANGE 2025 Conference.

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