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High-capacity production systems for Block Caving mines

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Abstract

As the production targets for block caving mines increase, there has to be an increase in the productive capacity of the operation, without increasing cost of having more active extraction drives. The simulation analysis will show a clear limitation to the productive capacity of a system of mobile LHDs and will also show how easily a continuous extraction system can overcome this limitation. There are several possible alternatives for such a system but there are process constraints that severely limit the number of options. These include the need for continuous access to all active draw-points, the ability to manage variations in ore fragmentation, and the rapid relocation from one draw-point to another, are some of the most important. The system also has to be sufficiently flexible to cope with the kind of seismic damage that often occurs in active extraction drives. A continuous extraction system that produces over 100,000 tonnes per day requires extraction drives to produce close to 5-10,000 tonnes per day each. The capital equipment cost of such a system would be much higher than batch production equipment, but the simulation results show how the increase in productive capacity creates a more cost-effective production process, with lower labour costs and lower energy cost. The simulation results also show the impact of a high-production capacity system on the rate of development of new extraction drives. The results show that long-term future of larger, more productive Block Caving mines will rely on the development and implementation of flexible, continuous extraction systems.

1 Introduction

Most of the world's copper will continue to be produced from large, surface mining operations, but the scale and productivity of underground copper mines, such as Chuquicamata Subterránea in Chile, Grasberg in Indonesia, Oyo Tolgoi in Mongolia, and are becoming increasingly important. Given the declining discovery rate of new of large-scale near-surface deposits, block caving is the future of deep, low-grade copper production. The ability of large-tonnage underground mines to help meet the increasing demand for copper is an existential imperative, crucial to the global effort to create a low-carbon economy that can arrest the progress of climate change.

The current mine production technology platforms of LHDs and trucks for mine development and mine production, and high-volume ventilation for mine cooling have remained almost unchanged for over 30 years. When the current electric-hydraulic equipment was introduced, it was significantly more productive than the manual, pneumatic platform that it replaced. As mines have continued to become deeper, hotter and logistically more complex, the economics of these technology platforms has been overtaken by the higher costs imposed by the constraints in deep hard-rock metal mines.

The future demand for copper, as well as other base and speciality metals needed for the generation, transmission, storage and utilization of electricity needed to enable the transition to a low-carbon, highly-electric economy. The demand for the metal commodities necessary to produce the technologies that can make carbon-based technologies unattractive is increasing, but it appears that the current mine production platforms are going to be able to meet this increased demand without a significant increase in global metal prices. In terms of decreasing society's reliance on carbon-based technologies, higher metal prices will not be able to compete against fossil fuels as an inexpensive and reliable energy platform. In addition, there will be a higher cost to achieve the public's demand for more secure tailings and waste-water management system that ensures that communities and the environment are completely safe from harm in the long term.

Changing the technology platform in metal mines to a platform that allows more ore to be mined and at a lower cost is essential if electrification of the global economy is to be successful. In addition, the companies that deliver raw metals must improve their waste management practices as well as become more profitable. Given the need to impact climate crisis within the next 20 years, the rapid electrification of the economy must begin to impact GHG emissions within the next 10-15 years, the transition of the metal mining industry to be able to supply this new economy must be accomplished in the next 5-10 years. Achieving this with the next 5 years requires disruptive, transformational innovation on a scale not seen for decades.

Over the last few years, there have been several attempts to change individual technologies in metal mining operations, but these have focused on a given technology, not on the entire production system. This approach simply assembles a list of technological solutions to create a Technology Roadmap with multiple solutions that might be considered and then initiating trials to see how well or badly they perform. To date, these trials have often faltered when confronted by the real system constraints in operational settings. This empirical approach is effectively trial-and-error, eliminating what does not work rather than purposefully designing what will work.

A Systems Approach is a more direct way to consider all the natural and business constraints together, just as modern GPS Systems are more informative than traditional roadmaps. The initial focus is to define the business problem that needs to be solved, either; accelerate to first revenue, reduce capital cost or improve ROI, or all three (Figure 1). The Theory of Constraints makes it easier to define the system requirements that must be addressed before a technology that can cope with the limitations imposed by the natural constraints can be designed. The guidance from such an Mining Innovation GPS (MI-GPS) describes a mine production system that is designed to improve the utilization of capital and operating expenditures in order to effectively improve the business, as measured in terms of safety, productivity and social and environmental liabilities.

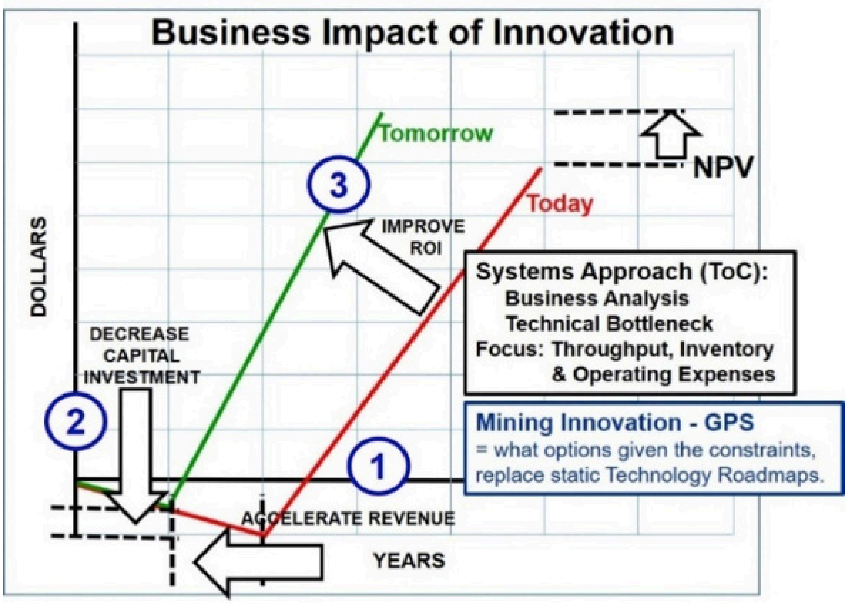

Figure 1 Business Constraints that must be addressed by any technical innovation

The greatest advantage of any GPS system over a Roadmap is the effect it has on the use of time, just as a GPS system helps anticipate traffic congestion or traffic accidents that decrease delays in arriving at the destination, by suggesting a slightly longer route. Ultimately, time is the most valuable commodity because it is irrecoverable; time spent on unsuccessful trials is lost forever. The Systems Approach, or MI-GPS, can reduce the time delay in developing the kinds of systems mines need to become fit for purpose to meet future demand.

Finally, in many mining jurisdictions the industry has great difficulty attracting new employees. The average age of miners in many jurisdictions is well over 55 and demographic projections for recruiting experienced people are not positive. Demographics will also be a driver in creating change; as full-scale autonomous systems are introduced, the nature of the work in mines will change dramatically. The speed of this transition will depend on how mines direct their use of their most valuable strategic asset – their experienced workforce – and using this asset to prolong 30-year-old production systems rather than to accelerate the implementation of new production systems, is a poor use of an invaluable and irrecoverable asset.

2 Underground mine system constraints

There are two types of constraints – fixed and variable. An example of a fixed constraint is the distribution of ore; some such as sedimentary deposits occur over a large, sub-horizontal lateral extents and others, such as most metal ores occur in sub-vertical deposits. The first ore type can use highly efficient conveyors to move ore over long lateral distances, but the second type cannot. The vertical distribution of ore and the limited lateral extent of many metal orebodies means that the location of ore sources on each level is changing frequently and eventually moves to lower levels. This means relying on relatively small, flexible and mobile equipment systems.

There are three critical variable constraints in deep hard-rock mines; high rock stresses and the resulting seismic activity, heat load from the local geothermal gradient and from mine equipment, and logistic delays in transporting supplies in to, and ore out of, mine operations. Each imposes a greater cost burden on operations as mines get deeper, and some are approaching a natural tipping point. High rock stresses have decreased the inherent stability of rock excavations and the damage to excavations caused by static or dynamic rock-mass failure requires more installed ground support, and more frequent rehabilitation to maintain the stability of access drifts (drives) for their required life. As the natural heat load released by exposed rock increases, the demand for greater volumes of ventilation increases as does the electricity cost to deliver it. Finally, the logistics of supply delivery and ore transportation becomes slower and more difficult with depth, and using a larger fleet of diesel-powered equipment units, as well as their operators and maintenance crews, increases direct costs.

Table 1 System constraints and mitigating characteristics

System constraints	Mitigating characteristics
Highly variable geotechnical conditions	Permanent access to assess and/or correct
Highly variable operating conditions	Permanent access to assess and/or correct
Zero harm requirement	Remove from hazard, provide protection
High cost to meet ventilation demand	Electric units to reduce energy demand
High ambient heat conditions	Deliver active cooling to critical systems
Low production rate capacity	High-speed, continuous ore flow
Low-quality material transportation	Up-grading; ore sorting & rock recycling
Capability to reject low-quality material	System to store/dispose of rejected material
High labour cost	Automated & autonomous systems
Automated & autonomous equipment	High-reliability, modular, rapid replacement
Limited shaft hoisting capacity	Increase vertical transportation capability

Increases in the cost of creating and maintaining new access drives, of delivering adequate ventilation quality, of delivering consumable supplies and transporting ore, combined with commodity price projections that are static or declining, result in profit margins too small to provide attractive returns on investment in deep mines.

The natural constraints that dominate deep mining operations are the sub-vertical distribution of mineralization, high rock stresses and rock temperature. The existing business constraints are that solutions must reduce the two largest cost centres in most mining operations, labour and energy, while at the same time increase the total productive capacity of the operation to meet future market demand.

2.1 Business constraints

Some 35 years ago, three aspects of all businesses were identified as the most crucial to success (Goldratt 1984), namely 'Throughput, Inventory and Operating Expenditures.' It pointed out that while all businesses have different constraints or limitations, they must all focus on the same three issues to be successful. It is striking that these three measures of business performance are almost never discussed as measure of mine performance. Although 'throughput' and 'operating expenditures' are universally understood, the meaning of 'inventory' for mines is less clear. In mining, 'inventory' is the cumulative cost of the activities that go on during a day to create the final product of the process - the pile of broken ore. In most businesses, every effort is made to move the final product to its destination as quickly and efficiently as possible. In mines, the current ore transport platform engages with the final product less than 10% of the day, and requires 4-6 times more horsepower than is required to move the product alone.

3 Design requirements to address system constraints

There are seven critical constraints on mining operations in deep, hot, high-stress mines. Large water in-flows can also be a serious constraint but are omitted here since many deep mines are very dry. The constraints that are common to all very deep har-rock mines are the following.

3.1 Stability

Highly changeable and unpredictable rock-mass conditions, including seismicity and rock-bursting mitigate against the implementation of permanent or fixed infrastructure for transporting supplies and ore because it is likely to be subject to operational interruption by rock-related failures, especially close to the sources of production. The same is true for very large equipment units that require the full width and height of access drifts; rock-falls or rock-bursts that trap large equipment units make it very difficult and time-consuming to safely extricate and recover them.

3.2 Energy - ventilation

Ventilation is the largest consumer of energy with an underground mining operation. The principle goal is to remove heat from the excavations, most commonly by flow-through ventilation that removes heat and humidity, as well as dilutes and removes air-borne contaminants. All deep mining operations have a depth at which cooling ventilation cannot be delivered from surface and some form of cooling system must be introduced. For bulk mining operations, the conventional approach is to consider air chilling systems that have been introduced in high-value/low-tonnage mines such as precious metal and diamond mines. But the significant increase in the cost of ventilation is the factor that challenges the economic viability of low-value/high-tonnage mines.

3.3 Energy - transportation

The second largest consumer of energy with an underground mining operation is the transportation of ore, using the LHDs and trucks that replaced rail systems 35 years ago. Rail transport is very efficient with low operating cost with a payload: energy ratio of around 3:1 but requires the rail infrastructure cost. However, the energy consumption is related to the entire process of moving ore and includes the return trip of the vehicles. Since the mass of an LHD is roughly three times the mass of the payload the payload: energy ratio is about 1:6 for LHDs and 1:2.5 for trucks. This means that LHDs consume over 80% of the total energy of the trip and trucks consume about 60%. Since the largest consumable cost, ventilation energy, is regulated by total equipment horsepower, making mine equipment more energy-efficient should be an important target.

3.4 Rock breakage

The effectiveness of conventional drill-blast cycles has declined over the last few decades as access drifts have become larger, and continuous excavation equipment has been offered as an alternative. They are most effective in relatively low-strength, non-brittle rock and in conditions where there are few, if any, post-completion stress changes. Rock cutting machines use more energy than explosives because the physics of damaging brittle material is accomplished not by energy, but by 'work' - energy/unit time. All types of rock cutting equipment break rock in fractions of a second while modern packaged explosives deliver high energy in microseconds. Continuous excavation equipment has been very successful in long tunnels, but the equipment set-up time makes them less effective than drill-blast systems for shorter tunnels.

3.5 Access maintenance

The fundamental difference between civil tunnels for public transportation and mine access drifts is the impact of post-construction stress changes on the safety and stability of the excavations. Post-construction stress changes around civil tunnels very rarely cause any damage; but mine access drifts are often impacted by these effects because large-scale ore production activity continuously significantly alters the stress regime around these drifts. Having continuous access, to first assess then to repair minor damage, is essential in excavations immediately adjacent to the source of production where mining-induced stress changes are significant.

3.6 Automated and autonomous equipment

Efforts to automate the existing equipment platform have focused largely on removing equipment operators from production units, reducing operating cost but having little impact on fuel or maintenance cost. Autonomous units are designed from the beginning to operate with no human intervention and can be re-designed to avoid all the complex activities easily performed by human operators. New autonomous systems make it possible to re-design the process to suit simpler, modular components, with lower operating and maintenance costs.

3.7 Infrastructure design

The design of transportation equipment will impact infrastructure design. Mobile vehicles transporting material have to slow down to move through access intersections and because they are designed to match the full width of the access drifts, they operate alone. Using conveying systems to transport ore means having transfer points to change the direction of the flow of material without slowing down. Also, the speed and direction of ore transport is not connected to the movement of the vehicles themselves which makes it a leaner and more energy-efficient transportation system. Finally, for mines where the quality of the roadway is a critical component, stationary ore transportation systems eliminate the need for high-quality concrete roadways.

4 Operating solutions to address system constraints

4.1 Mine access development

Drift access development remains one of the most man-power intensive and high-risk activities in mining and one that has a significant impact on NPV. As deep mines access more orebodies that are distant from an existing shaft, driving single-heading accesses over several kilometres will become commonplace. Access development has to become safer, faster and cheaper than it is today.

Conventional sequential drill-blast activities are not efficient (Morrison 2017), but this is related to the conventional management approach rather than its inherent capability. In many mines, the four essential activities in the development cycle (removing broken rock, installing ground support, drilling face holes and charging explosives) would take around 16-17 hours to complete. But the focus on equipment utilization in multiple headings means that most headings experience several hours of no activity because of lack of availability of equipment or operators. The result is the actual operating cycle for these four activities can take 24-36 hours to complete and for 4.5 m advance, a 36 hour-cycle is an advance rate of 3 m/day. If each activity began immediately after the previous one, with centralized blasting, it would achieve only 4.5 m/day. Mine contractors can progress faster because their shift changes are more efficient, and they can blast at will.

Mechanized cutting machines offer an effective alternative, but they have limitations in deep highly stress ground conditions. Continuous excavation systems will always be additive to drill-blast capability because the void used to set up the equipment that is 10-20 m long has to be created by blasting. Secondly, bringing back large continuous mechanical excavation machines to make minor repairs to a damaged access drift is not feasible; this can best be accomplished by drill-blast technology. So, even if some mines can make beneficial use of continuous mechanical excavation they will have to rely on a drill-blast process to make occasional repairs or to establish the excavations needed to assemble the continuous excavating equipment.

Autonomous drift advance can also be accomplished by digitally controlled drill-blast equipment operating under the protection of mechanised protective canopy. Nordic Minesteel Technologies (Nordic) of North Bay, Canada, has built canopies that will achieve this and will allow for rapid human intervention if problems such as rockfalls or equipment failure occur. The main purpose of the canopies is to compress the critical path cycle-time and complete the execution of all four face-advance activities allowing a lean, quasi-continuous excavation process.

4.1.1 Concurrent face activities

Conventional drill-blast equipment is small, flexible and mobile equipment units can operate concurrently when protected against all types of rock-related failures by a protective canopy (Figure 2). This allows the development cycle time to be contracted to less than 10.5 hours, making it possible to complete two standard advances of 4.5-5 m every day (9-10 m per day). We used discrete event simulations to confirm that a critical path process less than 10.5 hours could be achieved, but only if the time taken to remove broken rock from the heading was less than about one hour.

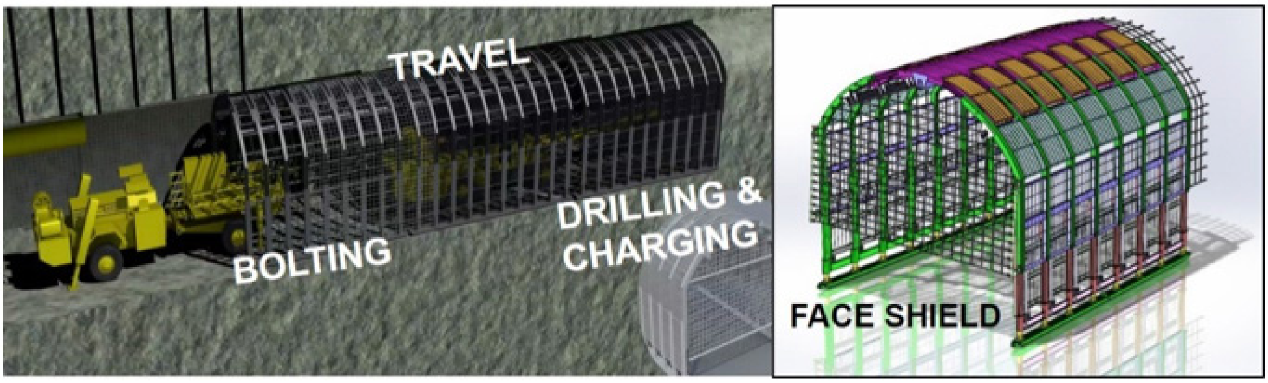

Figure 2 Schematic of three protective canopies enabling concurrent face activities

The original concept was to use three steel-frame canopies to enable drilling, charging and bolting activities in a fully manual operation, but as these activities become autonomous, some canopies can be eliminated. The two front canopies protect against rock-related damage on the walls and roof of the drift and there is a face shield on the front canopy to protect against face bursting. The captive drill unit has the time necessary to execute the blast designs created by iRing (North Bay, Canada) that will improve perimeter control and face fragmentation.

A critical activity is preparing the face holes for explosives, cleaning the holes and installing the timed initiators, tasks that are easily complete with the dexterity of human fingers but difficult to automate. Tesman Inc. (Sudbury, Ontario) has designed the equipment to achieve remotely this and is now conducting field trials. Since drill equipment has been automated for many years, we believe that within two years it will be possible to execute all of the face activities without manual intervention in the heading.

4.1.2 Rapid rock removal

The process simulations showed that increasing advance rate requires the broken rock in the heading to be removed in less than one hour. Batch activity such as a Load-Haul-Dump (LHD) unit wastes a lot of time travelling to and from the dump point, while a continuous loader can move rock at over 400 tonnes per hour (tph). Loading into an LHD or truck forces the continuous loader to stop operating while another unit arrives. The Rail-Veyor and Torex Gold Resources' Muckahi systems are recent attempts to solve this problem by relying on a rail system, either on the floor or on the roof of the drive.

An old technique that was used when drifting included installing rail transport, (Morrison 2019) used a simple loading machine to fill multiple self-discharging cars that were later pulled away by a locomotive. CEMI has had a new self-discharging system designed, called the Mascot, to solve the problem by relying on autonomous control of the units and so avoid using a rail system. CEMI has identified two commercial partners with experience of building the two essential components of the Mascot working to build the first prototypes. The narrow width of the cars allows two rows of cars to pass each other in a standard heading.

Each Mascot car receives a fixed amount of rock from the loader and will transport it autonomously to a dump point. The key is the autonomous movement of the cars that allow them to be filled rapidly and continuously by switching the discharge tray on the loader from the first row of cars to the second row (Figure 3). As soon as the rear car in the row is full it can move out of the heading. Once the front car in the first row has left the heading, a third group of empty cars can take their place in the first-row position, while the second row of cars are being filled. Once all the rock in the heading has been removed, the cars and the loader can move out of the heading and allow the canopies, followed by the face drill and bolting unit to move into the heading.

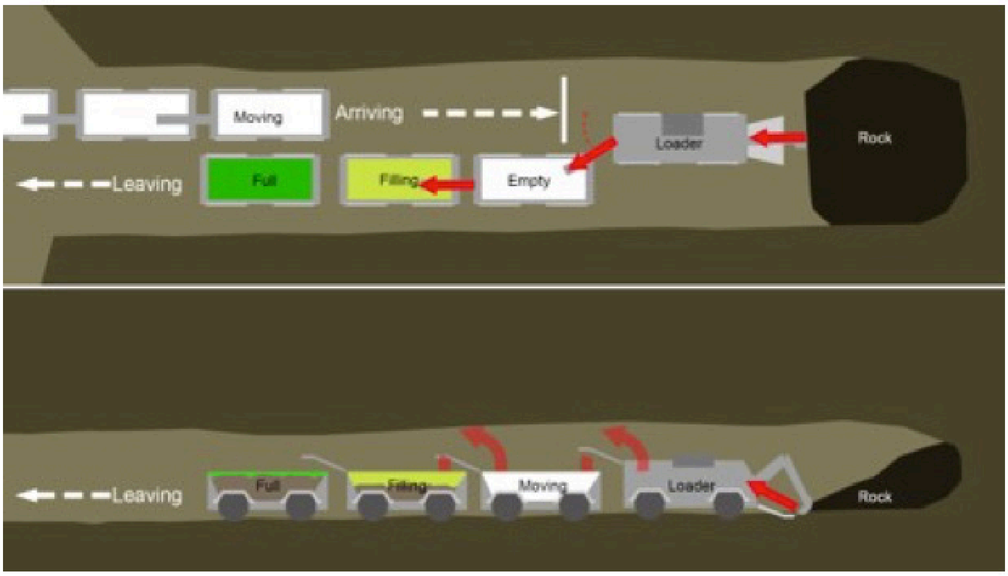

Figure 3 Sequence of Mascot car moves to accelerate rock removal

The concurrent face activities take around 8 hours to complete and during this time the fully loaded Mascot cars can travel to the dump point and return to their parked position near the face ready for the next cycle. They can do this under battery power, hauled by other vehicles, or by connecting to a trolley assist system. Once the blast is ready for initiation, the face equipment can then travel past the parked

Mascot cars to a location where they can be maintained and re-supplied. The canopies can be withdrawn to a safe distance away from the face, moving autonomously or moved by the loader where they are nested inside each other. After the blast, the continuous loader can re-enter the heading autonomously, with or without the canopies, followed by the Mascot cars, to begin the next cycle by removing broken rock. In this leaned process it is the utilization of the face, not the workforce or equipment, that is maximized since it is the most expensive component of the system.

The canopy and Mascot systems rely on digital equipment control to offer the real possibility of a completely autonomous drill-blast development process. This can achieve two cycles per day, advancing a 5- to 6-metre square heading in poor ground conditions at about 10 metres per day, using a process that allows all equipment maintenance and re-supply to be completed off-cycle. We believe the opportunity exists to optimize this process further, making it possible to achieve three 4m-long advances, to achieve an advance rate of 12m/day.

4.2 High-capacity production

The limitation on the ore transfer rate by LHD or truck is revealed by a simple analysis of the transfer cycle time. An LHD might spend 30 seconds on loading ore and another 30 seconds discharging or at the ore-pass, while spending 1-2 minutes traveling to and from the draw-point, for a total cycle of 3-5 minutes. For simplicity, a 10-tonne load is transferred at a rate of 120-200 tph. Since the LHDs are designed to fill the access drives, only one vehicle can access the ore pile at any time, so that the 30-second loading activity ensures the ore pile remains untouched by any unit 80-90% of the time. A continuous loading system would be removing ore 80-90% of the time, at a rate of 400 tph. Given the high cost of creating the ore pile, which is the value of 'production inventory', the business objective should be to move the ore to its destination, by any means, as fast as possible. The objective is to maximize the utilization of the ore pile, rather than maximize the utilization of the equipment or workforce.

A variation of the Mascot cars has been designed as a rapid ore transfer system. In this case, these units have no storage capacity, so the Mascot is simply a mobile section of walled chain conveyor under autonomous control. Once the units are aligned with each other behind a continuous loader, the ore is transported by the series Mascots directly to the ore-pass at the same speed as the transfer rate of the continuous loader, say 400 tph. The Mascots are positioned along one wall of the crosscut that accesses the ore draw-points, allowing utility vehicles unrestricted travel along the crosscut or extraction drive. A transfer device, called a Brig, is used at the intersection of the cross-cut and the footwall drive, or main haulage drive, to allow utility traffic to pass along the main haulage drive or to turn into the cross-cut access, without interrupting the flow of ore. The Brig units can also be combined to allow equipment to access two adjacent draw-points in a single cross-cut access, again without interrupting the flow of ore to the main haulage drive. This means that if a draw-point becomes un-usable because of oversize or a hang-up, the loader can relocate to the second source of ore, while the problem (large over-size or a hang-up) in the first draw-point is resolved. Moderate over-size that is too large to be loaded, can be mitigated by a hydraulic chisel behind the bucket on the arm of the loader.

The conventional continuous loader design is sufficient for the low production rates common in many open-stoping operations. For higher throughput mines, such as block caving operations, there is an alternative design for the loader making it capable of a loading rate of 1,000tph, with more powerful Mascots and Brigs configured to match this production rate. In the case of extraction drives in a block caving operation, the Mascot System would allow 1,000 tph for each extraction drive, producing 1,200 tonnes per day (tpd).

A larger version of the Mascot, called a Dragoon, would operate in the main peripheral access drive, or external or peripheral drives, positioned along the outside wall of the drive opposite the extraction drive entrances. The Dragoon has to receive the flow of ore from 1-3 extraction drives producing up to 1200 tph and the Mascots and Brigs can direct the flow of ore in both directions along the extraction drives, to two peripheral drives (north and south). This maximizes ore flow while limiting the demand any one set of Dragoons. The Dragoons feed ore directly into the ore-passes that deliver ore to the Main Haulage

Level below. The transfer rate of the Dragoons defines the number of extraction drives that can discharge ore into them, and also determines the number and spacing of the peripheral ore passes. The higher the transfer capacity of the Dragoons, the fewer the number of passes and the greater distance between them.

Essentially, the Brigs and Dragoons are minor variations on the design of the Mascot which is the core unit of the Mascot Mining System. It has been designed to maximize ore throughput using simple, robust designs using variable electric drives that operate autonomously. This system has a higher capital cost than current LHD systems but offers a much higher ore transfer rate. The balance to be achieved between equipment cost and mine productivity and profitability is addressed in Section 5.

4.3 Mine ventilation

In very deep mining operations, it will be prohibitively expensive to provide ambient cooling ventilation in every excavation and in many deep mines this is already a very challenging requirement. The conventional heat removal system will not be sufficient and one feasible alternative is the release of fresh compressed air created by a Hydraulic Air Compressor (HAC), a technique is about to undergo a trial in a mine in Northern Ontario. An extension of this approach is to rely on the staged decompression of a liquid nitrogen-oxygen mixture to deliver cooling to the ventilation system. Such a system makes the best possible use of off-peak power and provides storage for excess, off-peak, power from alternative power systems such as solar or wind generation.

Given the high ambient heat flow in very deep excavations, it will become prohibitively expensive to remove this heat from the excavations by conventional methods and delivering active cooling in temporary 'critical areas' will be essential. The critical areas will be equipment components that that must be cooled, as well as people. In a largely autonomous operation with very few people underground, it will be much more cost-effective to keep people cool in vehicles and suits than to cool all mine excavations. Underground personnel can be protected from all possible hazards by Comprehensive Personal Protective Equipment (CPPE) that goes beyond protection against head, hand and foot injuries and vision and hearing impairment, to include protection against the inhalation of all air-borne particulates and contaminants. Most of the time underground personnel will be in cooled utility vehicles with a normal air atmosphere around 25 degrees centigrade.

Utility and Supply vehicles could be motivated by electric motors supplied powered batteries that are recharged during operation by a turbine driven by a jet of air from a liquid-air cylinders. This jet of decompressing synthetic air is also the 'exhaust air' that cools the vehicle and the surrounding atmosphere. All-electric production equipment, such as drill units and bolting units in drift development will operate in the same way, so that air and water lines will no long be required; all equipment units will bring air and water with them and be re-supplied as necessary.

In order to minimize humidity, face and production drilling will not use water for dust suppression; cooling and flushing of drill holes could be achieved by decompressed liquid air or nitrogen, so long as the drill dust is captured at the collar of the hole and stored in a canister for later disposal. The same will be true for dust created by blasting, with a venturi dust-capture system on the continuous loaders used for ore and rock removal.

In future, when autonomous equipment systems are well established, and the adequacy of CPPE systems are well accepted, it may be possible to consider a variable liquid oxygen-nitrogen mixtures (Va-L-O-N-X) that will provide an ambient atmosphere with higher nitrogen content than normal., suppressing the risk of fire. A mixture of 15% oxygen and 85% Nitrogen is equivalent to the atmosphere in the cities at around 3,400 m above sea- level (e.g. Arequipa, Peru). Producing liquid air on surface and delivering it in containment vessels of different sizes, makes cooling ventilation accessible where required. All equipment units will carry a compressed air supply and very small personal air tanks will provide short-period supply, replaced frequently. The personal supply would be used only when staff are outside the vehicles in a CPPE suit. All vehicles would be supplied with a normal air supply and staff will rarely be required to operate outside the vehicle, and only for very short periods of time.

4.4 Autonomous vehicle control

In the closed system of underground mining operations, autonomous vehicles can be readily adopted since there will be no erratic pedestrians or weather variations that make the safety of autonomous vehicles problematic. The few people underground will travel in autonomous vehicles that will be constantly communicating with the production equipment within range, determining which vehicles wait and which proceed according to a set of priority protocols. People will submit their destination to the utility vehicle computer and it will transport them there autonomously while it communicates with the nearby autonomous vehicles in order to ensure the smooth flow of ore and a safe arrival at the destination. People will not be able to leave their transport vehicle if there are other production vehicles moving around within range, or if CPPE, such as a helmet, is not properly engaged. The use of an emergence over-ride to exit the utility or supply vehicle will trigger the shut-down of the nearby autonomous production vehicles.

5 High-capacity production systems

At some stage in their development, all deep underground mines will have to introduce autonomous, high-capacity production systems to remain profitable, and to achieve this, they will have to draw on innovations being developed outside the traditional mining technology silo – from innovations in multiple sectors of the economy. The two mining methods that dominate metal production are open-stope blasting with backfill for very strong rock-masses, and various forms of block caving without backfill in auto-fragmenting rock-masses. The main difference between these two methods is multi-level activity with blasting and backfilling, and single-horizon auto-fragmented haulage-extraction levels without backfill.

5.1 Open Stoping

Open-stoping mines with very strong rock-masses, have to incur the cost of production blasting and backfill and will have to find other ways to remain cost-competitive with lower-cost mines. The best way to achieve this is to move introduce top-down bulk extraction sequences which accelerates the time to first production by up to two years, and the cost of developing to lower levels of the orebody before production begins. This has a larger effect on NPV that the additional cost of high-quality paste backfill that is required to achieve top-down mining. It also makes it possible to extract low, or no grade material, and storing this in un-filled stope at higher levels. Ore-sorting is only feasible in underground mines if there is a cost-effective way of managing the reject material. In open-stoping mines the reject material can be consumed in the backfill if there is an equipment system designed to accomplish this. One option is to transport the coarse ore to the top of the orebody, crush it and divide it into an up-graded product and a reject product. The reject material is delivered to an adjacent storage stope for inclusion in backfill, while the upgraded product is conveyed to the hoisting system. The reject material in the storage stopes can be crushed in the draw-point of the storage-stope and combined with the cemented backfill. Thus, low- or no-grade material is not conveyed to the surface hoisting system, minimizing expenditure on no-value material and creating more hoisting capacity for up-graded ore, increasing the value of the throughput.

5.2 Block Caving

Block caving mines rely on auto-fragmentation of low-grade ore and so avoid the cost of production blasting and backfilling. Since they typically extract a low-grade product, their profitability depends on the cost of high-volume transportation of ore. For many years, productivity rates of 50,000 tpd have been successful but increasing to much larger production targets over 100,000 tpd has been problematic. Given the limited ore transfer rates achievable by LHDs, the number of active extraction drives has significantly increased the number of active extraction drives, each with two LHDs operating in each drive at any one time.

The time necessary to bring new extraction drives into production also have limitations. This is not just the advance rates for access development drives in highly stressed ground, but the creation of draw-points and draw-cones and the placement of high-quality concrete floors in the extraction drives, necessary to maintain the performance of the LHD fleet. The most durable ore-passes are those located on the periphery of the orebody, where the host rock is often much stronger than the orebody. Some mines have used mid-drive ore-passes to reduce the LHD travel time and increase the ore transfer rate, but these cause other operational problems.

To make very large-tonnage caving mines operate effectively, it is not sufficient to simply increase the drill-blast access advance rate to around 10 m/day, there has also to be an increase in the rate of moving ore out of the extraction drives. Figure 4 shows the results of a discrete event simulation (Shelswell et al. 2018) that compares the capacity of an LHD batch ore production system and a continuous ore production system (CPS) using only 10 extraction drives. The results show that for this limited number of extraction drives, the daily production rate for an LHD system feeding peripheral ore-passes to both the north and south peripheral drives is limited to around 70,000 tpd. The continuous ore transport system can produce over 100,000 tpd, moving 1,000 tph, for 10 hours per day from 10 extraction drives. For the LHD production systems that were able to produce only 40,000 tpd or 70,000 tpd, the simulation was also able to show how many drives such a system would need to meet the target production level of 100,000 tpd - 33 drives and 28 drives respectively.

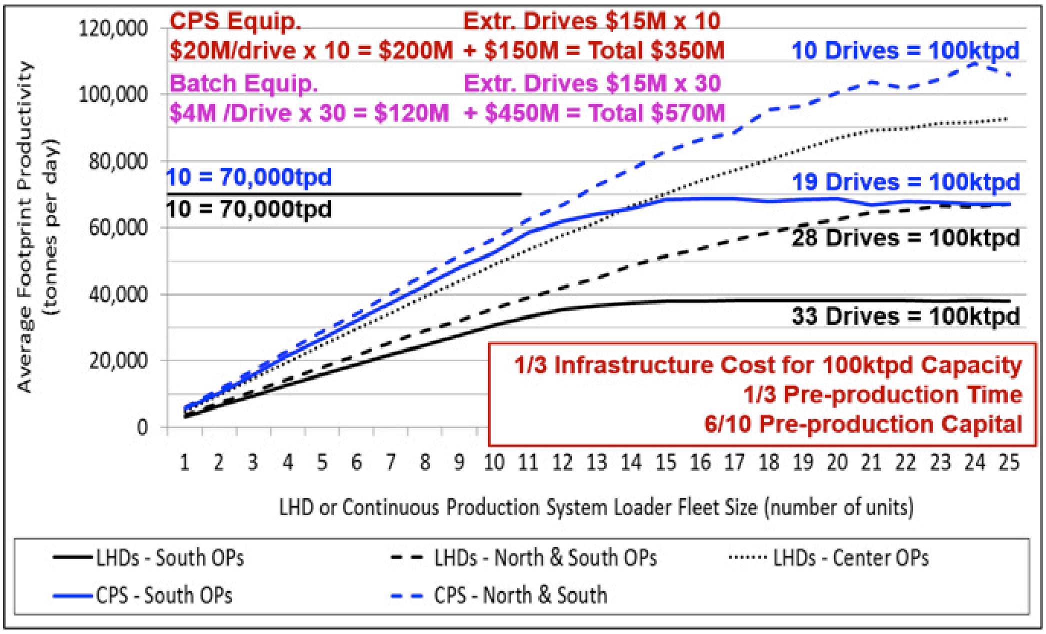

Figure 4 Simulation comparison of batch and continuous production systems

The comparison of the LHD and continuous systems feeding one or two sets of peripheral ore-passes shows that the batch system needs three times as many drives (around 30) to achieve the target tonnage. This implies a three-fold increase in operating cost to achieve this target and will likely encounter an operating limit caused by the number of LHDs exceeding the mine's ventilation capacity.

A more recent discrete event simulation by SRK Consulting also compared the operating costs of the batch LHD systems and the continuous ore transfer system. The simulation suggested that the labour cost of the continuous autonomous system will drop to around 22% of the batch process and the energy demand will drop to around 63%. Since the largest operating cost is labour, an estimate of the overall operating cost of a continuous autonomous production system is around 35% of the current batch production system.

As a result of reducing the production equipment horsepower to 63% of the current demand, there is an opportunity to reduce the ventilation cost. The energy consumption of underground equipment often defines the regulated ventilation requirement, which is the largest operating cost after labour. Reducing the total energy demand for equipment also reduces the cost of the mine ventilation, and the transition from diesel equipment to direct electric power reduces the GHG footprint of the operation.

Finally, a higher ore transfer rate from the extraction drives has implications for the normal draw rate of 300mm per day. This is the accepted limit for a conventional caving operation because the operation has to ensure a uniform draw rate along the length of the production front. Increasing the draw is desirable only if it is uniform along the production front and this is difficult to accomplish with an extended front and multiple extraction drives. By significantly increasing the ore transfer rate per extraction drive, the angle of the production front becomes more obtuse and the length of the production front becomes shorter. The continuous ore transfer system and shorter production front means it is possible to maintain a uniform draw along the front at a higher rate of draw than is possible with a conventional batch production system.

5.3 Balancing infrastructure and operating cost

The equipment cost of a continuous autonomous production system is much higher than that to the batch process; in simple terms the two LHDs in each extraction drive would cost $4M while the suite of Mascot units would cost $20 M. However, the cost of creating a 400 m long extraction drive, excluding the cost of the concrete roadways, is around $15 M. A production target of 100,000 tpd can be achieved using 10 extraction drives with an equipment cost of $200 M and an infrastructure cost of $150 M (Figure 4). The same production target can be achieved by a batch system with $120 M of equipment and $450 M of infrastructure cost. The combination of infrastructure and equipment cost to achieve a production target of 100,000 tpd, is about $350 M for the continuous system and $570 M for the batch LHD system. If the total cost of installing concrete floors in the extraction drives is $1 M each, the cost differential between the two alternatives increases to around $250 M.

There is a time delay in completing 30 extraction drives than creating 10 extraction drives, including the need for high-quality concrete floors. Since a continuous autonomous ore transportation system, such as the Mascot System, can move ore without moving the vehicles there is no need for high-quality concrete floors. The material movement in the Mascot system will require steel wear-plates rather than concrete roadways, but these are integral to the equipment, increasing operating cost but not delaying extraction drives coming into production.

Finally, the nature of the continuous autonomous system means it is possible to scale-up capacity by increasing the number of active drives, with relatively small increases in operating costs. Increasing the number of active drives in a batch production system attracts a very larger increase in the operating cost burden, especially the increase in ventilation demand. In contrast, bringing 15 extraction drives into production at 12,000 tpd allows the continuous autonomous system to deliver a production rate of 180,000 tpd, maintain a higher uniform draw rate, and can achieve this in half the time required for a batch production system that produces 100,000 tpd.

6 Conclusion

There have been many trials of different technologies to improve the performance of mining operations, but few have resulted in strategic successes. We believe that simply selecting a possible technology from a list is not as effective as assessing the business needs of the operation, and then addressing the operation's system constraints with new technologies designed for that purpose. The business case for a new technological innovation has to take into account all the factors that limit the performance of the operation and the Theory of Constraints is a valuable tool for prioritizing the innovation strategy. Specific constraints can be matched to characteristics that will address them and these should be the design criteria for the technological solutions that are capable of improving the performance of deep metal mining operations.

This approach has led to the design of a system of canopies to accelerate access development and a continuous, autonomous ore transfer system that could replace the conventional batch LHD ore transfer system. The adoption of these technologies has been slow, despite the lack of superior alternatives. The production simulations used in both cases indicate how a routine advance rate of 10 m/day was possible in seismically active, jointed rock mass conditions, and how a block caving operation in these conditions could achieve a production rate of 12,000 tpd per extraction drive. It showed that the additional capital cost of the continuous equipment is more than offset by the lower infrastructure cost to achieve daily production target of 100,000 tpd. The result is a continuous production system at a capital cost of around 60% of the current system, and a reduction in operating cost to around 35% of the LHD batch process.

These simulations indicate that the implementation of continuous autonomous production systems offer a profitable future for ultra-deep, high-volume, low-cost mines. Given the need for higher copper production from low-grade, underground production sources, the future success of these operations depends on completing the transition to autonomous, high-capacity production systems that are capable of operating continuously within the natural constraints imposed on them by deep underground conditions.

Building deep underground mines requires an increasing amount of capital and they have to achieve higher productivity and lower operating costs to provide an adequate return on investment. The increasing burden of the constraints imposed on underground mines are such that technology platforms that have been in place for over 30 years will not be able to achieve the productivity levels sufficient to provide an adequate return on investment. Without up-dated production systems, only an increase in commodity prices can ensure deep mines are profitable. Since metal-price projections do not show reliable price increases, mines will have to implement new technologies that will reduce expenditures on labour and energy.

However, implementing innovation in the mining industry is far more critical than simply achieving an adequate return on investment. The performance of the mining industry is critical to meeting the higher demand for metals at lower cost that is essential if the transition to a low-carbon economy, required to arrest the progress of climate change, is be successful. The pace of change in the mining industry has languished for decades but it is the now urgent demand to meet the challenge climate change that provides the greater imperative for achieving strategic innovation in the mining industry.

If the metal mining industry is to meet all the demands of the future; cost-competitive metal production, greater volume of metal production to meet the demands of global electrification, and superior waste management strategies that protect communities and the environment from harm, making strategic changes to the operating practices of the mining industry is vitally important. The individual technological changes discussed here present only one possible 'Progressive Approach' to the transformation of the mining industry, but it relies on the industry embracing the technological developments being made in other sectors of the economy. Regardless of the success of one technology or another, making a fundamental change in its approach to innovation is essential if the mining industry is ever to achieve its higher purpose of meeting the needs of a globally sustainable society.

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