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Value-production systems for block caving mines

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Abstract

Block caving mines produce the lowest grade ore in the metal mining industry and more than any other, they must begin to focus on producing 'value' rather than tonnes. Block caving involves no primary blasting or backfilling, so the first step in reducing operating cost is to improve coarse ore haulage. Batch load–haul–dump (LHD) haulage is slow and expensive; it uses six times more fuel (energy) than is required to move the ore (LHD mass is three times the payload plus return). Batch haulage leaves broken ore in active drawpoints untouched 90% of the shift and doubling the speed of the LHD only reduces this to 80%. All other industrial processes moving low-value product to the customer use the cheapest possible technique – a conveying system of some kind. A steel conveying system such as presented here can move ore 80% of the shift, at three times the speed and 20% of the energy of LHDs, around 100 times more effective (8 × 3 / 0.2) than batch haulage. The second step in improving value production is to increase the ore grade. Recent ore-sorting techniques identifying the most valuable component of the ore stream have been proven effective in surface mines.

Upgrading techniques in underground mines need a process to dispose of the reject material. Removing waste from the ore-flow system is easier in a conveying system amenable to sizing, and inline ore crushing facilitates the removal of waste from the ore stream. Boreholes and raisebore holes can elevate the crushed reject material above the haulage level for storage and disposal in mined out voids. Waste rock can be consumed in cemented backfill or in loose waste rock voids above and behind the production front.

Early removal of negative-value material (zero value, absorbing cost) from the ore-flow has to be balanced against the cost of processing zero-value material through the entire beneficiation process and tailings storage. This is especially important for shaft mines where hoisting waste rock prevents hoisting ore. Even if only 20% of the waste rock can be consumed in mine voids, the implementation underground of low-energy, low-cost, continuous, autonomous ore haulage systems shifts the cost-benefit from high-volume production to high-value production.

Keywords: *metal demand, value production, ore haulage, ore upgrading, waste rock diversion, autonomous systems, lower cut-off grade, non-mining technology, cultural change*

1 Introduction

The increase in demand for base-metal operations to supply the commodities necessary to accomplish the green transition to a low-carbon economy is significant. Bloomberg has projected the demand increase will be around five-fold for both copper and nickel and this is consistent with the needs of electric vehicles that used five time more copper than internal combustion engine (ICE) vehicles and nickel for batteries. The industry is used to a demand increase of 1–3% per annum, but this new demand growth by 2035 is the equivalent of 10–15% per annum. It is already evident, however, that a five-fold increase in supply of copper and nickel by 2035, as projected by major commodity analysts (BloombergNEF 2021), cannot be achieved by the global mining industry in its current form, since the productive capacity of the industry is projected to decline after 2024 (Figure 1) (Wood Mackenzie 2019).

The increase in demand for copper has triggered some producers to accelerate their exploration programs but since any new Tier-1 copper discovery will take at least 20 years to bring into production, this can play no role in addressing the demand increase in the next 15–20 years. This means that if a significant increase in the production of base metals is to be achieved within this time frame, it will have to come from existing mines. There is significant production in capacity currently in sub-economic copper deposits, but these will require major investments in innovation to increase productivity sufficiently to make them economically viable. The demand–supply gap projection for global nickel and cobalt supplies is very similar except there is no large pool of 'possible projects' waiting to be brought to the market.

These shortfalls cannot easily be resolved, and minor productivity improvements, typical of reactive, tactical solutions for current operational problems, will be wholly inadequate in meeting challenges of this scale and scope. These shortfalls result from over two decades of under-investment in exploration and strategic innovation in the mining industry. Exploration is a long-term problem and there are no short-term solutions. This places the burden of producing more metal by 2035 on strategic innovation – innovation ahead of operational demand. This is innovation that gets meaningful results not just to the next obvious step, but as far and as fast as possible into the future. This is the scale of innovation that is essential if there is to be any possibility of meeting future demand for the metals that can help achieve the International Panel on Climate Change (IPCC) targets on climate change. Mining has largely been on the fringe of public perception, but it is about to move to centre stage. These demand–supply gaps threaten the ability of large greenhouse gas (GHG) emitter industries such as transportation, infrastructure and manufacturing to respond to the demand for the technologies that will enable a low-carbon economy. Any criticism of the large-emitter sectors for their inability to respond to climate-driven demand for new products and services will quickly be redirected to the mining industry that failed to supply the raw materials they needed.

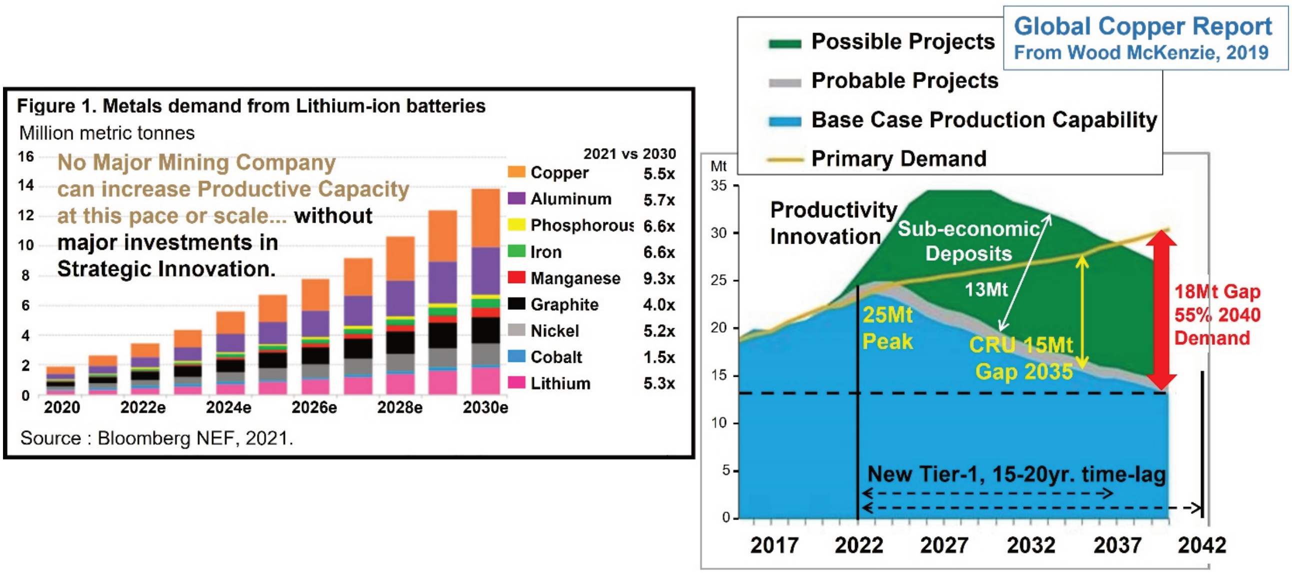

Figure 1 Global copper demand increase and global copper supply decline

Most base-metal mines are surface operations and while this method will continue to dominate copper production for the foreseeable future. Meanwhile, underground copper production is becoming increasingly critical to filling the supply gap, and the most productive underground mines are block and sublevel caving operations. These mines are particularly important as new surface mines can take decades to bring into production and they simply cannot extract deeper ore, no matter how high the price of copper. The transition of surface mines to continuous, autonomous ore haulage out of the pit is essential for increasing the rate of production, and this will require more inline crushing and waste diversion to upgrade the ore stream so that it can conform to the mill capacity.

Block caving mines are required to extract very low-grade material and over 99% of the material produced is waste rock. Traditionally, mines have transported all material to surface for processing and this continues to be convenient in most cases because diverting some waste rock out of the material transportation system requires a diversion system to relocate it for storage and disposal. The high cost of conventional material transport in underground mines, dominated by LHDs and trucks, has mitigated against the use of waste diversion techniques but the combination of higher production costs and lower grades will make these operations unprofitable unless they can find ways to produce higher value at lower cost.

For shaft-access mines the other barrier to change is the limitation of the hoisting system and so long as the material transportation system meets the shaft capacity, nothing more can be achieved. Some shaft mines (Onaping Mine in Canada, 1983 and Mina Grande in Brazil, 1999) have experimented with techniques such as hydraulic hoisting in pipelines, but these were unable to exceed conventional hoisting systems or had excessive wear problems and so were discarded as an option. However, these systems can now be re-considered as a means of augmenting conventional hoisting capacity rather than replacing it. Using hydraulic, pneumatic or dense-medium hoisting could bring finer ore to surface freeing capacity in the hoisting system and so increase the total mineral value raised to surface.

For block caving mines to generate more value they must shift to continuous, autonomous ore haulage, produce higher-value ore with less waste rock and minimise the cost of fixed infrastructure such as air and water lines and rely on autonomous units to deliver operational consumables and other supplies. The technology to make mine activities autonomous is already operating in other industrial sectors such as most automobile manufacturers and Amazon warehouses. Adopting these technologies is the only way for mines to produce more ore at lower cost and failing to achieve this will make it impossible to supply metals at a price that displaces carbon from the economy and achieve the transition to a low-carbon future.

2 Innovation to increase ore haulage rate

The current focus of innovation for ore haulage is the conversion of trucks and LHDs motivated by diesel engines to the same kind of vehicles powered by electric motors and relying on battery power. Some trucking systems also consider battery-powered trucks augmented by trolley assist systems. While this conversion has the advantage of reducing the GHG emissions from the transportation system it does not address the fundamental problem of a batch transportation – the rate of ore haulage.

The core issue of batch ore-transfer systems is that the loading time for individual trucks and LHDs is very short compared to the transportation time. For haul truck operations the time to fill the bucket by the various types of loading system takes between 2 and 4 minutes and it may take up to an hour for the truck to complete the ore haulage cycle and be ready to be loaded a second time. In the interim the loaded truck moves at some 12–15 km/hour along an 8–12 km route to the discharge point and makes a return trip. The tonnage moved over the entire cycle time is the ore-transfer rate for that vehicle – and for the largest haul trucks this can be 240 tonnes at the cost of moving 160 tonnes of vehicle. The ore haulage rate for the system is determined by the number of trucks involved, allowing for variations when individual trucks are on a maintenance or repair cycle.

In underground mines, the electrification of ore haulage units has focused on converting diesel LHDs to battery power, but this does not address the fundamental effectiveness of the equipment (Morrison 2019). For example, the limitation of the LHD in a drawpoint is that it may take 30 seconds to load the bucket, travel for 1–2 minutes to the discharge point, and discharge for 30 seconds before returning empty. This process moves 10 tonnes in a 4-minute cycle. Because the LHD has been sized to fit in the access tunnel there is little opportunity for multiple units to operate in the same space so that the ore haulage rate of 150 tonnes per hour (10 t/4 min) for one LHD is the same for the system. The production rate for the mine is achieved by multiple active stope drawpoints operating in the same way during a typical 15-hour work cycle – some 2,300 tonnes per day. The cost of these multiple stopes is effectively the operational 'inventory' required to achieve the mine production rate. The stope cycle time for open stoping includes access development, production drilling, production blasting, ore haulage and backfilling, and the scheduling of these activities depends on the backfilling rate (Morrison et al. 2015). This can be doubled by replacing hydraulic slurry backfill with tailings paste fill, and by augmenting production drilling which is the next largest bottleneck.

In block caving mines, there is no primary drilling and blasting activity and no backfill cycle, so production is even more dependent on the ore haulage rate. There can be two LHDs drawing ore from multiple drawpoints in a single extraction drive and the travel time to an orepass it can have an effective ore-transfer rate of 300–350 tonnes/hr in each drive. A 15-hour work cycle can generate 5,000 tonnes/day. The biggest bottleneck is the delay caused by oversize material in drawpoints and the need to manage a uniform rate of draw across the production front. These delays can be overcome by increasing the number of extraction drives, but this increases the cost per tonne of the operation and also has limits in terms of equipment congestion and ventilation (Shelswell et al. 2018).

Regardless of the underground setting or the energy source of the units, the batch process has two critical limitations. First, the LHD activity leaves the ore in the drawpoint untouched over 80% of the time while the haulage units move back and forth to discharge at the orepass. Second, the mass of the LHD is roughly three times the mass of the ore payload, so that over 80% of fuel or energy consumed in ore transport is used to move the equipment – less than 20% of the fuel or energy is used to move the payload. Given the cost involved in creating the payload, no other industry would tolerate such poor operational performance; once the product is complete, it is shipped to the customer or to the next stage in the process as quickly and efficiently as possible. The ratio of total tonnes moved to payload tonnes moved is a measure of the energy effectiveness of the batch process – roughly 6.25:1. The total equipment horsepower underground is used to regulate the ventilation requirements – often the second largest cost after labour.

An alternative technique for moving broken ore is a continuous loader that draws material on to a steel conveying system within it and discharges the material into a waiting transport system. Figure 2 shows the transition of ore loading equipment from before 1982 to the present. Before 1980 the rock removal systems were very small and under-powered with compressed air and were replaced by diesel powered front-end loaders now known as LHD units. These have continued to be the workhorse of the underground mining industry despite the development of continuous loaders that can move material faster and more cheaply. The continuous loaders that are commercially available today are not well suited to moving dense, abrasive mine ore, but these limitations can be addressed by adding replaceable wear plates and by augmenting the strength of the moving components in the system. In caving operations these units will require relatively rapid relocation from one drawpoint to another, requiring wheeled vehicles rather than tracked units currently available. There can be more than two loaders in any one extraction drive since the loaders are stationary while they are delivering ore from the drawpoint.

These continuous loaders must also have a means of controlling the size of the material, with a hydraulic chisel to break up oversize and, in the worst case, loading has to be suspended while overly large material is broken down. The advantage of a new robust continuous loading unit is that it can move ore at around 450 tonnes per hour producing over 7,000 tonnes/day in a standard 15-hour work cycle. There are relatively few moving parts, so the energy–effectiveness ratio of the continuous loader system is about 1.25:1 total tonnes moved to payload tonnes moved. This is five times less energy than the batch production process and the lower horsepower would mean a reduction in the ventilation cost by well over 50% of the current cost. This is a conservative estimate; ventilation cost is often a mine's second highest line item after labour, and the transition to battery electric vehicles has yet to take the advantage offered by re-designing completely new, autonomous units motivated by electric power. The loader in Figure 2 is an ITC312SL operating in 2009 and contributing to the record drill-blast performance of the Kjøsnefjorden Hydroproject in Norway. An autonomous version of this unit with no operator cab would allow the width of the conveyor to increase and increase the rate of ore-transfer. The other photographs are historical examples over 30 years old.

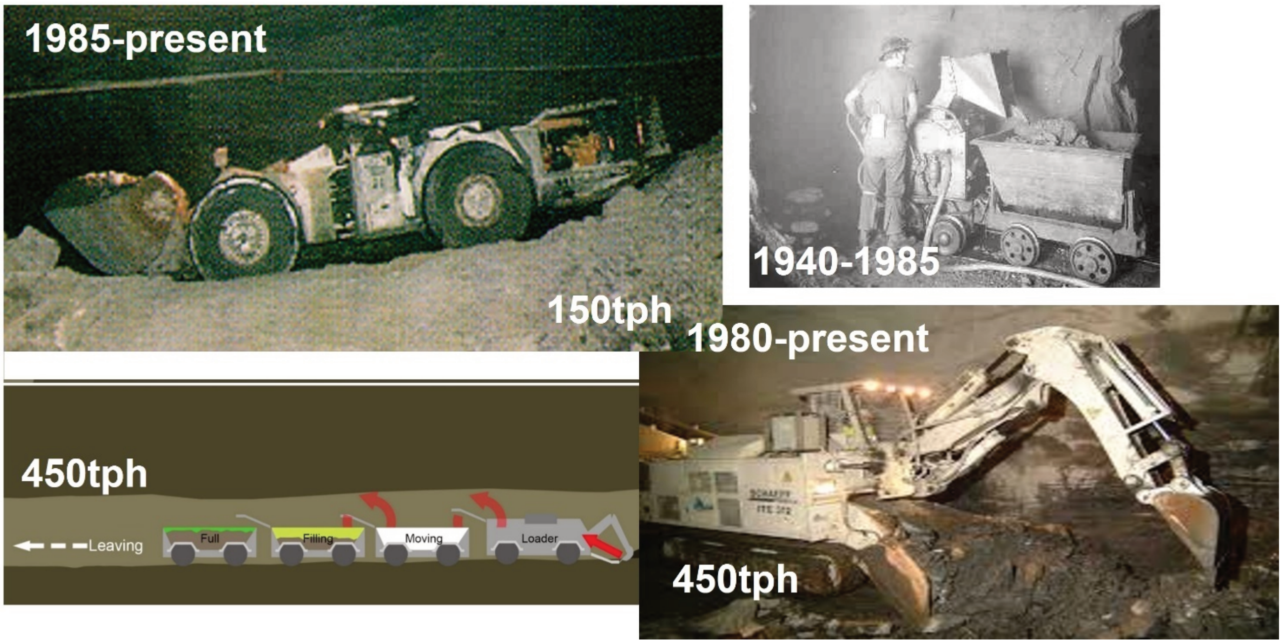

Figure 2 Evolution of ore/rock transfer systems 1982–2022

The biggest limitation of any continuous loading system is the ability to ensure the entire ore-transfer process keeps pace with the continuous loader. The most common trial of a continuous loader system involves discharging into an LHD or truck so that the ore haulage rate of the system is determined by the slowest component. A trial of a continuous loader discharging material at 450 tonnes/hr into a batch system capable of less than half this rate clearly demonstrates the superiority of the technique. When the batch equipment has been filled each unit has to travel to the discharge location and the 'continuous' loader activity has to be suspended until an empty batch unit is ready to receive payload.

The obvious solution is to design a coarse ore transport system that can keep pace with the discharge rate of custom-designed continuous loaders. Existing continuous ore haulage systems such as Railveyor and Muckahi are very efficient, but both rely on a rail permanently installed on the floor or roof, and they still involve intermittent ore transport. These may be a valuable interim step, but in the long-term, mines have to minimise the cost of permanent infrastructure in all excavations.

A more flexible continuous ore-transfer system, currently in development, is the Mascot Mining System designed as a series of wheeled vehicles carrying sections of a steel conveying system that overlaps to create a continuous flow of material from the loader to the discharge point (Figure 3). This system is based on techniques adapted from now obsolete pneumatic equipment used in various forms in the past and has yet to move from the design stage to protype development. The core objective is to keep the payload moving at the same rate as the discharge rate from the continuous loader using a series of steel conveyor segments on a wheeled carrier. The Mascot units are narrow enough to allow other vehicles to pass by in a 5 m wide drift and the transfer point design ensures that access intersections are always passable. The individual units can be configured for multiple access geometries and since they are stationary when moving payload, they can operate on direct power. Once the source of payload is exhausted, the loader and the Mascot units can relocate under battery power to a new drawpoint or heading and the Mascot units will then re-align themselves behind the continuous loader as before. This approach relies on a much larger fleet of vehicles and a greater capital cost, but this is more than off-set by the higher production rate and lower operating cost (Morrison & Labrecque 2020).

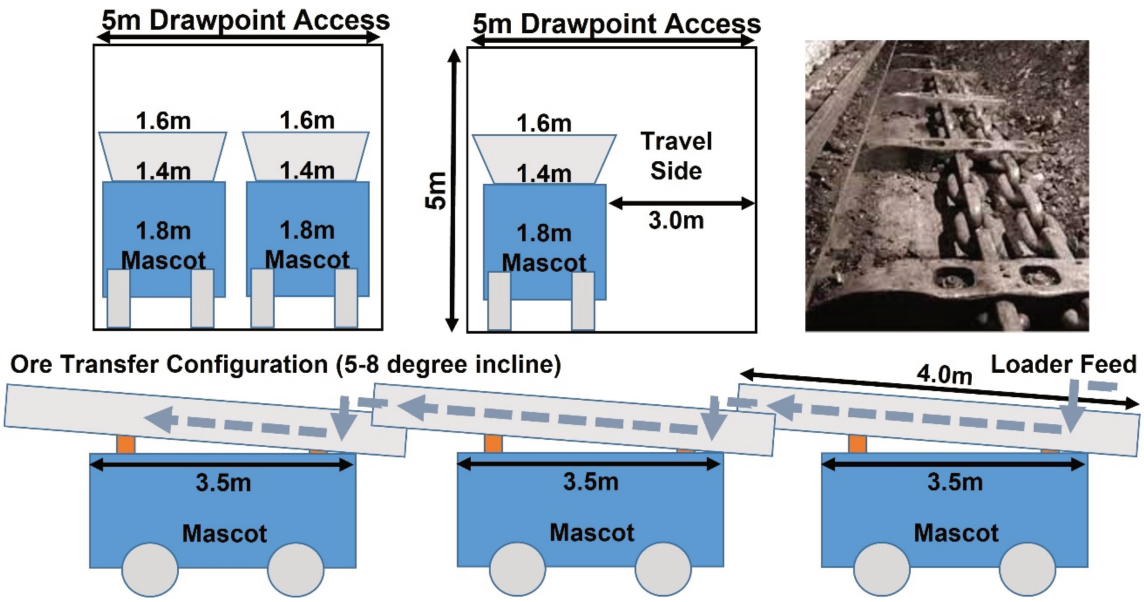

Figure 3 A schematic of the Mascot steel conveying system

A variation of the Mascot units are units with a storage capacity for a fixed volume of broken rock and a similar self-discharging system. These Mascars make it possible to clear a newly blasted heading in less than an hour. They will park against one wall while all the equipment needed to drill, load and install ground support at the face can pass by and be configured to operate at the face concurrently. The face equipment will include the newly developed Tesman System for autonomously cleaning drill-holes, charging explosives and installing initiators. This allows all the essential face activities to be completed in less than 10.5 hours, allowing a 4.25 m face advance to be completed every 12-hour shift. Once the face equipment is in place and the drill-blast activities have begun, the filled Mascar rock-storage units have around 8 hours to move to the waste rock discharge point and return to park along one wall outside the active blast zone, ready to move back into the heading after the next blast. Once the face activities are complete, the face equipment can exit the heading by travelling past the waiting Loader and Mascars, so as to be maintained and re-supplied with consumables.

In a block caving layout, there are multiple drawpoints on both sides of the extraction drives and the continuous loaders have to access both sets of drawpoints to meet the operational constraints of production rate and maintaining the draw rate of the cave above. Figure 4 shows a schematic of a short section of three extraction drives, each with Mascots positioned along one wall of the extraction drive. These will be fed by continuous loaders discharging from both the near-side and the far-side drawpoints, and will be designed to mobilise on wheels rather than tracks for speed and mobility. From the near-side drawpoints the loader discharges directly into the Mascots. From the far-side drawpoints the loader discharges into a chute hung at the brow of the far-side drawpoint, directing the payload into the Mascots at an angle that matches the direction of ore-flow, either to one end of the extraction drive or the other. From the end of the extraction drive, the ore is transferred by a similar chute mechanism to another set of steel conveyors in the perimeter drive that deliver it to the orepass.

When a loader is required to move into a drawpoint on the closed side of the extraction drive, the Mascots on either side of the entrance adjust to allow the loader to enter. The Mascot discharge tray can elevate and retract, allowing the unit to create an opening for the loader unit to pass underneath. In allowing the loader to pass into the near-side drawpoints the two adjacent Mascot units have to suspend operation by creating a gap in the flow of ore. The accessing loader communicates with the other loaders to suspend delivery of payload, creating a gap in the ore-flow at this location. When this gap arrives at the drawpoint the empty Mascots can move aside to allow the loader access. As soon as the loader has entered the drawpoint the Mascots can return to operational mode and allow the other loaders to resume ore production and fill the gap in the ore-flow. The objective is to keep the interruption to the flow of ore to a minimum. A similar process is initiated when personnel equipment has to access the near-side drawpoints for inspection or to allow other equipment, such a secondary blasting unit, to access a near-side drawpoint. In either case, the equipment will request access and will be informed when the ore-flow gap arrives, the Mascots move aside and allow the unit to pass. Egress from the near-side drawpoints is achieved in exactly the same way. The machine-to-machine communication system and pre-established priority protocols is the kind of technology operating in autonomous warehouse facilities such as Amazon, using autonomous guided vehicles (AGV) or autonomous navigation technology (ANT).

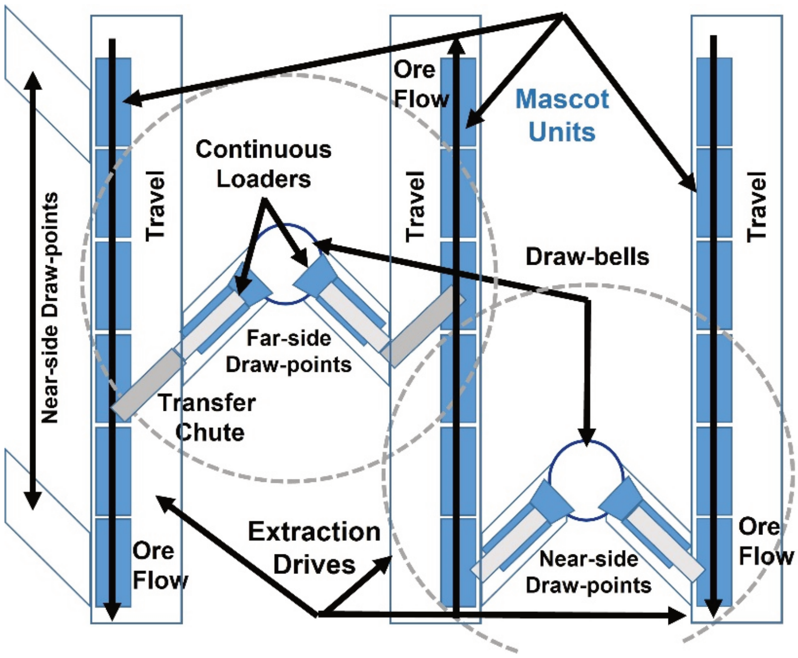

Figure 4 A plan layout of continuous loaders transferring ore to Mascot units

It may not be possible for caving operations to eliminate LHDs completely because newly opened drawpoints often have to deal with very large oversize and hang-up blockages and only LHDs can cope with these conditions. However, as drawpoints mature and the effect of the cave reduces the size of the ore in drawpoints the continuous, autonomous loaders and conveyors are more effective at moving large tonnages of ore at lower cost and can easily produce over 100,000 tonnes per day (Shelswell et al. 2018). As block caving operations develop there will be a transition from LHD haulage in immature drawpoints to continuous, autonomous haulage in mature drawpoints.

While the redesigned continuous loaders can move frequently from drawpoint to drawpoint, to meet the needs of the production system, the Mascot carriers remain stationary while they are transferring ore from one unit to another. It is only the conveyor mechanism on top of the unit that is moving and it determines the speed of ore-transfer as the ore is fed by the continuous loaders. The energy consumption is related to the total mass moved by the unit, roughly 125% of the ore tonnage, as compared to roughly 600% of the tonnage moved in an LHD batch cycle. In the ore-transfer configuration the units will be motivated by a direct powerline and will rely on battery power only when relocating from one extraction drive to another, or when a failing unit has to move out of the active train of Mascots to be replaced by another unit. When the Mascots temporarily suspend ore-transfer to allow a continuous loader to access a near-side drawpoint they will remain connected to direct powerline.

3 Impact on productivity

The overall effect of implementing autonomous ore haulage systems is to reduce the cost of production and increase the rate of production. The simulation results comparing the autonomous ore transport in block caving operations (Morrison & Labrecque 2020) are represented in Figure 5.

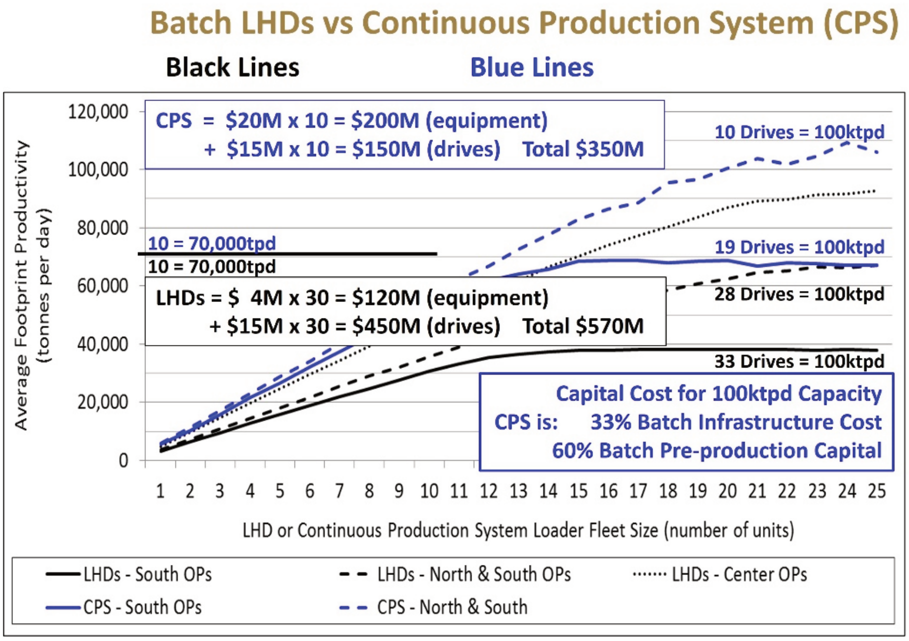

Figure 5 Simulation results of a Batch LHD process and a CPS process

Figure 5 shows the results of a batch LHD process (black lines) and a continuous production process (blue lines) each with only 10 extraction drives. The simulation model also calculates the number of drives each scenario would need to achieve 100,000 tpd. With an average of 30 extraction drives the batch process is limited to 70,000 tpd, although this particular model is conservative since there are many mines that operate with a much larger number of active extraction drives to approach this production rate. The effect of opening many more extraction drives has the effect of reducing the undercut angle (Fitzgerald et al. 2020) and increasing the length of the production front, making it more difficult to maintain a uniform draw from a larger number of drawpoints. The continuous process can produce 100,000 tpd with either 20 extraction drives delivering to only the South Perimeter ore passes, or 10 extraction drives delivering to both North and South Perimeter drives. The continuous production process requires much higher capital equipment cost ($20 M per extraction drive) compared to the batch LHD process, but with fewer extraction drives, the overall capital cost of the continuous process is less than the batch process. In addition, this approach reduces the number of extraction drives and increases the undercut angle, making it easier to maintain a uniform rate of draw along a shorter production front. Fewer drawpoints and a higher production capacity makes it possible to increase the rate of draw at each drawpoint.

The importance of this result is the potential of these two approaches to produce more than 100,000 tpd, based on the ability to process to scale. The capacity of the batch process to increase production levels is limited by the high cost and low productivity of the batch LHD performance, even in mines that operate 40–50 drives. The continuous ore-transfer process has higher productivity and lower operating costs and so has greater capacity to scale up to 150,000 tpd simply by increasing the number of active extraction drives to at least 15. More work is being done to try to identify the limits of this type of system.

The simulation of the batch and continuous processes was also able to compare the operating cost of the two approaches. The results showed that continuous autonomous ore-transfer in block caving mines can reduce the cost per tonne by more than 40% of the batch process cost because ore haulage is the primary productive activity in this mining method. In the case of open stoping mines the impact of autonomous ore haulage on operating cost will be much less since this is only one of several activities that contributes to the cost. This example, however, demonstrates the impact that autonomous systems can have and while autonomous activities will be different in every case, the overall effect is to reduce the operating cost and increase the rate of production by eliminating the time lost between successive activities. A reduction in operating cost of the order of 50% changes the ore cut-off grade and effectively creates more 'ore' to be produced. This appears to be one of the best ways to address the projected demand–supply gap that must be resolved in the next 15 years if we are to achieve the first stage of the transition to a low-carbon economy by 2035.

4 Payload upgrading

In recent years, excellent progress has been made in commercialising techniques for ore sorting in batch production operations. Following successful commercialisation of Minesense's ShovelSense technology at Teck's Highland Valley Copper operations in 2019, in Canada the technology is now being implemented at Teck's Carmen de Andecollo Mine in 2022, in Chile (Gleeson 2022). Both surface mining operations have achieved an improvement in ore to mill key performance indicators. On surface, the reject material is easily disposed in a waste pile, but this is not feasible in underground operations because of the cost of disposing of the reject material and lack of storage. This is the principal constraint in implementing ore sorting in underground mines, although it is the large-volume low-grade underground mines that could most benefit from the technique. Introducing less expensive continuous, autonomous ore transportation underground also makes it less expensive to set up a waste reject disposal circuit, making upgrading of the payload material more attractive.

Although surface ore sorting techniques use relatively sophisticated technologies, for low-grade ores, the simplest upgrading technique is to remove waste rock from the ore stream. By definition, low-grade ore has a great deal of barren waste rock in between the particles of valuable mineral and, in most cases, the density of the valuable minerals is greater than waste rock and they are easily identified by X-ray fluorescence techniques. In a continuous conveying system, it is relatively easy to set up a sorting system for fine material and a simple 'scalping system' can divert larger material for inline crushing. The newly crushed material can then go through the sorting process to remove more value-less rock product from the ore stream.

The key to success in disposing of the value-less reject material lies with finding a destination for the reject material and a low-cost technique for delivering the reject to the destination. In open stoping operations, once the waste material can be elevated to the highest production level, the reject material can be stored in an open stope, ready for adding to an active backfill system. From there it can be consumed in stope that is being backfilled, either as crushed waste in cemented tailings slurry, as cemented rockfill, or as the course fraction addition to a tailings paste fill system. The elevation of the reject can be accomplished with a small bucket conveyor inside a raisebore to move the conditioned waste rock reject from the haulage level to the production level.

In block caving operations there is no backfill circuit in which the reject material can be consumed and since a conventional ore upgrading process must have a destination for the reject material, it appears an ore upgrading system is achieved. But applying upgrading techniques in block caving – mines that produce the lowest grade ore of any mining operation in the world – is essential for their future economic viability as the current trend is for grades to decline with depth. Given the significant impact of waste diversion through ore sorting in surface mines, it has a similar impact underground. The easiest disposal site for the reject material are the extraction drives and drawpoints no longer required for production, and these will allow for the economic evaluation of the technique. Beyond the volume redundant extraction drives, the only remaining disposal site that could be used for waste diversion and internal disposal (WDID), are the gaps between the blocks of waste rock above the closed drawpoints and behind the production front.

The technique for elevating the reject material above the cave to the excavations used for cave monitoring and preconditioning activities would be the same as in open stoping mines. The expertise of placing crushed reject into the interstices of the waste rock behind the production front will have to be developed. The simplest approach would be to deliver it as a slurry, but this creates a huge excess water problem and can easily result in ponding and blockages. A better approach is to deliver the dry reject material into the voids inside the cave pneumatically, to avoid ponding problems and pumping costs. The air decompression also introduces a cooling factor in place of a humidity factor, and temperature sensors in drawpoints could identify areas that are filled to capacity with reject material. Cool air cannot report to these drawpoints, so adding more reject material in these areas will not allow penetratration of the gaps in the cave waste and further reject disposal should be discontinued.

The technique of disposing waste reject material depends on the practical considerations relevant to different operations; it is not possible to describe the details of the technique that will be successful in every case. The development of the technique will require significant experimentation and is an objective that several block caving operations could collaborate on. It is not a technique that will be easily accepted by mine operators since it will add another level of complexity to the operation. In this sense, implementing waste rock reject disposal in block caving mines is a *strategic innovation,* as distinct from a tactical innovation to current operating practice that has incremental impact on operating performance. It is not a capability that would be requested by mine operators to make their work easier or safer; it is a technique that will affect the overall economic viability of the operation; a strategic corporate decision, not a tactical operational one.

The potential for this approach to improve the economics of producing low-grade disseminated ore mines is significant. Ore that is more than 99% waste rock is the easiest to benefit from waste diversion and disposal; simply removing 20% of the negative-value (waste) material and replacing it with the same volume of revenue-generating payload will see a significant increase in profitability. The substitution ratio of 20% was chosen since this is easy to achieve with a bulking factor of at least 45% in the block caving waste, however disposing a volume of crushed waste higher than 20% becomes progressively more difficult to achieve. Any process flow sheet can identify the potential value to that operation, depending on the operating cost and ore value of the operation. This calculation will also identify how much each operation can afford to invest in order to make this option a reality, and to apply a sensitivity analysis to identify the target substitution ratio for any mine. Mines that produce over 99% waste material cannot afford ***not*** to invest in developing an approach to waste diversion and internal disposal (WDID), since the alternative is progressively lower returns and earlier closure.

5 Other cost reduction options

There are significant gains to be made by increasing the rate of access development and reducing its cost. The recent success of remote-controlled equipment to clean face holes and charge them with explosives and initiators (Tesman, Sudbury, Ontario, private communication) completely changes the prospect of autonomous activities in drill-blast development headings. Computerised face holes and remote rock removal have been possible for many years, but their effectiveness has been limited by the number of tasks that still had to be executed manually. As the Tesman equipment is implemented in the next few years, it could make it possible to have all face activities completely autonomous.

Combining autonomous face activities with the Mascot rock removal system will eliminate safety issues at the face and increase the advance rate performance. The development of a continuous, in-cycle ground support installation system that is now being designed to operate in concert with the Mascot continuous rock removal system will further improve performance. Simulations of these technologies reveal that the development rate of 10–12 m/day are feasible – in a 5 × 5 m heading. It is possible to achieve this kind of performance using larger drives that can accommodate ever larger vehicles, but this approach carries the cost of removing large amounts of value-less waste and is limited by the negative stability implications of larger drives in low quality rock at depth. Further refinements of time-sensitive autonomous systems will allow for a completely lean process that will achieve drill-blast advance rates of 12–15 m/day. Time study data (Morrison 2017) still represents the large amount of unproductive time lost between sequential face activities. The largest amount of inactive time (over 90 minutes) is for crews to set up equipment to execute the initial activities. As autonomous systems mature, and concurrent supply and resupply become common, autonomous systems will become highly reliable, just-in-time processes, as they are in the manufacturing sector. This next stage in implementing autonomous systems will compress the cycle time to achieve three advances in each 24 hours, with drives with a face of less than 20 square metres.

Access development headings are the most constrained systems in a mine, and making these core activities completely autonomous will provide the impetus to design autonomous equipment to execute all the other production activities. The need for these systems is greatest in high labour-cost economies that already have the demographic and recruitment challenges that have limited underground mine productivity for decades (Morrison 2017). Labour statistics in Canada (MiHR 2021) project chronic labour shortages in most categories, especially in engineering and geology, and in the 18–30 age group, mining has the lowest recruitment potential (11%) and the highest recruitment resistance (42%) of any sector of the economy. In contrast, the high-tech sector with greatest capacity to autonomise mine operations has the highest recruitment potential (35%), and lowest resistance (33%) to youth recruitment.

At this stage in the conceptual design of completely autonomous mining operations, the Autonomine™ of the future should require no more than 12 individual units, augmented by data drones, to make it possible to execute all production activities autonomously. The trade-off is that while manual and automated operations have a few equipment units with multiple applications, autonomous units are activity-specific, resulting in a larger number of equipment types. To compensate for the greater number, future designs must be modular, involving few variations in components. The entire equipment fleet will use the same carrier as is required for the ore haulage vehicles with interchangeable modular components that reduces warehousing requirements.

6 Wholescale cultural change

The overall impact of autonomous systems will be a dramatic reduction in labour cost, but there will still be a few personnel required to ensure the units are adequately resourced with consumables and to replace failing components. These underground personnel will operate in climate-controlled conditions some distance from the active extraction processes. On the few occasions when personnel have to inspect an area or investigate some unusual occurrence close to the operational activity, these personnel will be protected from the extreme mine atmosphere. Their all-electric utility vehicles will be cooled by cryogenic air and if they have to leave their vehicles, they will be protected against all possible physical hazards with suits that have full voice-data-video capability and supplied by small personal cryogenic air tanks. This is protection in very much the same way as nurses have been protected in dedicated infectious hospital wards during the pandemic, but it is dramatically different mine coveralls.

As underground mines become deeper and significantly hotter, the cost of maintaining tolerable working conditions with this technological approach will cease to be viable. Flow-through ventilation was essential when all activities were manually executed, but as autonomous systems mature, it will have no place in the Autonomine™ of the future.

Innovations such as these also have application in surface mining operations. The physical conditions in mines on the Altiplano of Peru and Chile are arduous and the heat and diesel particulates in the mine atmosphere of deep open pits in Western Australia present workplace conditions that are unique to the mining industry and which few other workers in society must endure. The innovations that are essential for the continued viability of ultra-deep underground mines also offer significant economic and social benefits to surface mining operations around the world. In the opinion of the author, leadership of the global mining industry needs only adopt the innovations that have already been implemented in many other industrial sectors. Mr Mark Cutifani, formerly the CEO of Anglo American, has predicted that even the largest mining companies risk being taken over by technology companies, such as Tesla, as they pursue opportunities to expand their reach into mining to ensure their supply of the raw resources they need.

The transition to autonomous systems will also transform the skillsets needed for the future mine workforce – expertise that will allow workers to digitally control equipment activities in every way, skills that will require a much younger and more diverse workforce. In the interim, the current workforce skillsets will remain essential to help transition to a completely autonomous operation successfully. As the transition proceeds many of the existing workforce will either retire or will re-train to take on some of these roles until they reach retirement age. The key factor for the industry is not to continue to recruit for the current skillsets, but to accelerate the hiring of a workforce with the future skillsets. This will either be done by visionary leaders in the mining industry or by the leaders in the technology companies that replace them.

Reducing the volume of waste excavated to enable ore production increases the rate of access to ore and reduces the cost as well as free up hoisting capacity – unless there is a waste diversion and disposal circuit. For ultra-deep base-mines (below 3 km from surface) the delivery of consumables and the hoisting of ore will remain the greatest constraint on operations. As many consumables as possible must be delivered by pipeline and the oil and gas industry already has the expertise that could be implemented to reduce consumable delivery to shaft operations. The reduced demand for personnel access makes it possible to reconfigure existing shafts to move a greater volume of modular equipment components.

Implementing autonomously wheeled vehicles can make all this possible. Production units can carry shift-long air and water supplies and be re-supplied by mobile re-charge units if necessary. Any operating unit that runs low on battery power can be supplemented and re-supplied by mobile re-charge units. Any break in telecommunications can be overcome by data drones designed to ensure essential information flows between individual units. Mines need have no fixed infrastructure such as rail systems, air and water lines, ventilation tubing, communication cables or power cables except in a few central areas reserved for personnel. These technologies are available in various industrial settings today – the need to design, build and adopt these technologies for use in operating mines is urgently necessary.

7 Conclusion

The technology that will make continuous autonomous ore haulage feasible has already been designed and awaits investment to build prototypes in the near future. This development is low-risk since the mechanical performance of steel conveyors are well-understood and highly effective, and need only be improved by electrification and autonomous control. The high ore-transfer rates achievable by stationary equipment units is complimented by their low operating cost (labour and energy) and greater reliability. The implementation of these kinds of ore-transfer systems is only the first step in the process that will convert mines to completely autonomous operations, first in high-wage economies, then migrating to all mines.

The implementation pneumatic injection of mine waste reject into the gaps in the waste rock inside the cave will require some development to become effective, no more than was true for the other forms of waste disposal techniques in other mining methods that use in-cycle backfill. These are now common practice, and one day so will be the WDID technique in block caving mines. Failing to adopt some form of waste rock disposal prevents ore upgrading and the effect of increasing operating cost and decreasing grades will be to make them unprofitable except at very high metal prices. When the future of the planet depends on producing more metals at a lower price than fossil fuels, this is an unacceptable outcome.

Implementing waste diversion and internal disposal (WDID) is only one of many techniques and technologies being developed by mining SMEs in Canada and innovators in other sectors of the economy that can be implemented in the ore production systems of the future. These developments are only now attracting the attention of technology companies that recognise the potential to apply their solutions in an industry that is dire need of transformation. These companies recognise that the mining industry has a critical role to play in addressing climate change and that the larger GHG emitting industries such as transportation, infrastructure and manufacturing depend on the mining industry meeting their needs.

The public has been unaware of the decades-long decline in performance of the global mining industry but the performance of the metal mining industry in the next 15–20 years will be the determining factor in the transition toward a low-carbon economy. A wholescale transformation of the means of extracting and processing ore, as well as managing the industry’s waste material, is essential if the global mining industry is to be able to meet the demands of the new, low-carbon global industrial economy. Lack of significant change in the mining industry is a significant risk to the transition to a low-carbon economy; the consequences of this failure have already been predicted by the IPCC and the trends are already evident.

It was mining that propelled humanity from the Stone Age toward the progress that society has achieved to date. Expanding the scale of the mining industry in the 19th and 20th Centuries was often accompanied by brutal social consequences that have since largely been mitigated. But the lack of strategic innovation in the global mining industry at the beginning of the 21st Century may yet prove to be cause of humanity's ultimate retreat in the face of unrestricted climate change.

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