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Towards continuous bulk production from below 2.5 km

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Abstract

Current underground mining practice consists of a series of discrete tasks and subtasks, rather than a continuous process. These discrete tasks involve a great deal of human intervention including equipment relocation and equipment maintenance and repair. As mining becomes deeper, the intervention of human intelligence will remain essential to the process, and environmental conditions will make physical intervention prohibitively expensive and undesirable.

Despite progress in automation and tele-operation, the prospect of a fully man-less operation underground seems as remote as ever. The Centre for Excellence in Mining Innovation (CEMI) believes that the problem lies not with automation, but with the design of the activities that have been automated. Industry has chosen to use automation simply to eliminate people from the activities and has left the equipment, the tasks they perform, and the process in which they are engaged all but unchanged. The CEMI approach is to redesign the individual activities in the production process so they can be managed as a series of simple, linked activities in a semi-continuous production system, made possible with the advent of underground wireless communication systems capable of conveying large amounts of data at low cost. We address the kinds of changes that must be made if we are to approach a much more cost-effective, semi-continuous ore production process with 100% utilisation of the face and maximum productive utilisation of the stope.

1 Introduction

Over the last 30 years, since the transition to bulk mining methods in the mines of the Canadian Shield and the Pacific Cordillera, the Canadian mining industry along with national and provincial governments, has invested hundreds of millions of dollars in research and development. This investment has been focused on improving our understanding of the stability of mine excavations, the development of a variety of types of equipment and in the development of backfill – all with the view of firstly improving mine safety and secondly to improve the economics of mining at depth. The implementation of these developments into routine mine operations has been much more successful in the case of safety-related techniques than it has in the case of economic- or efficiency-related solutions.

The reasons for the failure to introduce innovations that have caused a significant improvement in mine productivity are many and varied, ranging from technical to social and demographic. But, in the deep mines of the Canadian Shield, the prospect of mining below 2.5 km presents a challenge to every aspect of the operation – technical, environmental, demographic, social and medical; so for the continuation of mining at this depth and below to be economically viable will require changes to mining practice that are as significant as the mechanisation transition 30 years ago. There are several technologies that can be introduced, but the fundamental change that has to occur is the introduction of lean processing techniques.

2 Historical developments

2.1 Development of backfill mining methods

Mining metal sulphide ore in the Sudbury Area began with open pit mining and has progressed underground, following subvertical nickel sulphide deposits. Underground mining began with very large, blasthole stopes that left completely open voids separated by large pillars and separated from surface by stable crown pillars.

As underground operations became deeper, ensuring the geotechnical stability of the mine workings required greater understanding of rock mechanics, and the cost of managing the safety and stability of the workplace increased. Similarly, the logistic and ventilation costs increased, and mines had to become more productive to remain profitable. During this period of development, the call for much safer working conditions became social standards.

As mining progressed more than a few hundred metres, the stability of the mined-out voids had to be controlled by filling with sand or tailings to prevent the collapse of the surrounding pillars into these voids. In response to several problems with drainage of this 'backfill' material, the technique of classifying the tailings to create a draining material (by removing the silt-sized portion or fines) became common. Finally, to avoid problems with liquefaction of this drained material, the practice of consolidating the tailings with cement became standard across the industry.

For many years, cemented hydraulic tailings was the preferred means of backfilling in underground metal mining operations that used the manpower-intensive methods of cut-and-fill and undercut-and-fill. After the transition, in the early 1980s, from selective mining methods to bulk mining methods such as open stoping, the cement content had to be increased significantly to ensure the stability of free-standing stope walls (at least 60 m high) and the cost of preparation for filling – the materials and labour required to build fill barricades and install drainage towers – also increased. Barricades had to be built to retain relatively high heads of pressure and the pour time was limited to just over 12 hours per day to ensure sufficient time for the transportation water to drain. These changes constrained the backfill rate, and increased the stope cycle time.

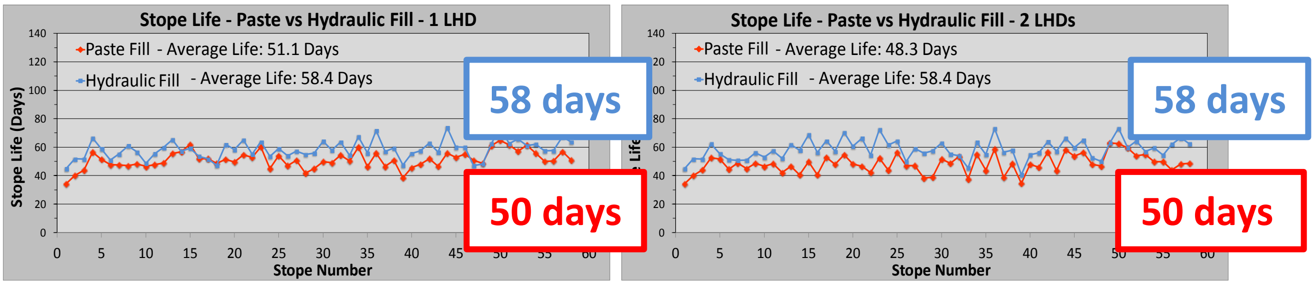
By the early 1990s the use of tailings paste had been developed – using a higher percentage of fines to retain the water and prevent the separation of solids and water. While the correct mix design is often defined by size distribution, a successful design is actually determined by the rheological behaviour of the fine material. The advantage of tailings paste is that it is a tightly controlled mix design (using PLC controls) which allows for a designed performance of the fill, and the lower porosity of the material means less cement for a given in situ design strength. Operationally, the major advantage is the dramatic reduction in the cost and time required to prepare a stope for filling. A simple rock berm replaces the designed barricade, and since all the transportation water is consumed in hydrating the cement, there is no drainage requirement, and tailings paste can be placed 24 hours per day. Overall, the benefit of tailings paste fill is a higher-reliability of backfill product placed, with designed performance characteristics and a reduction in the stope cycle time.

In the 1990s many mines around the world that were moving to underground mining using a backfill method installed a paste fill system despite the higher capital cost compared to a hydraulic backfill plant. In many cases, mines that already used hydraulic tailings backfill did not make the transition because it meant replacing an existing, completely depreciated plant.

The introduction of paste fill does require a plant that is higher cost than a conventional hydraulic plant. But the pay-back on this investment is not achieved only by the lower cement cost and higher strength, but by the ability to decrease the stope cycle time and increase production – or produce the same production at lower operating cost.

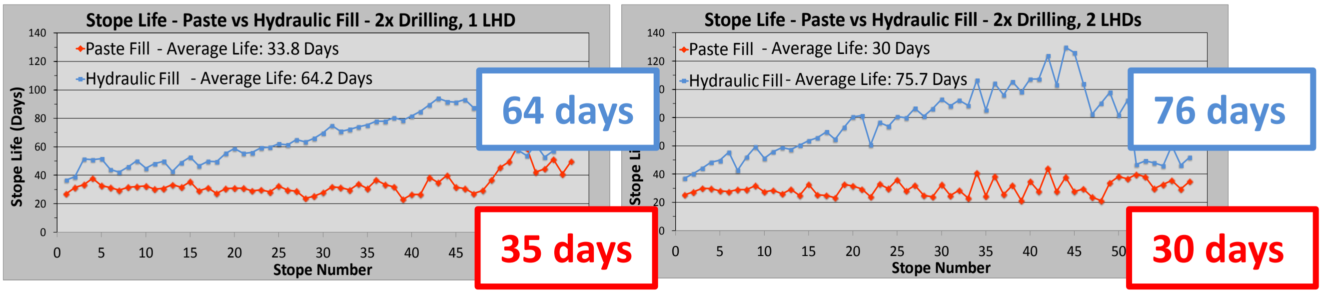
The Centre for Excellence in Mining Innovation (CEMI) employed Labrecque Technologies Inc. to perform simulations of a standard, base-metal open-stoping-with-fill production system to and compare the stope cycle time for hydraulic fill and for paste fill. The report (Labrecque 2014) described four scenarios comparing the base-case (Scenario 1) stope cycle time for both hydraulic and past fill, to the cycle times for (a) double the number of load-haul-dump (LHD) units, (b) double the amount of production drilling; and (c) doubling both LHDs and drilling.

The results in Figure 1 clearly show the reduction in stope cycle time from 58 days for the hydraulic system to about 50 days for the paste system and shows that doubling the number of LHDs makes very little difference. Doubling the amount of drilling reduces the cycle time for the paste fill system to 34 days, and doubling both drilling and LHDs reduces the paste fill system cycle time to 30 days. So by introducing paste fill it is possible to increase the production rate by 40-50%. In contrast, for a hydraulic fill system the same changes increase the stope cycle time to well over 80 days because of increase in the number and duration of delays activities related to in preparing stopes for backfilling.



Scenario 1 - Base Case

Scenario 2

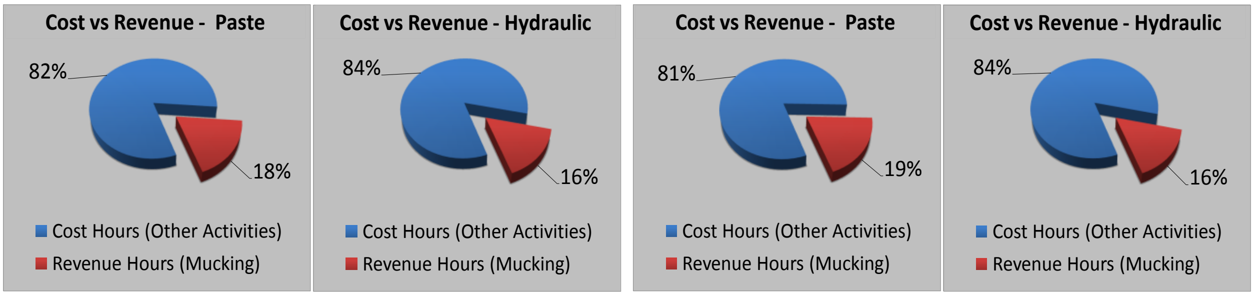


Scenario 3

Scenario 4

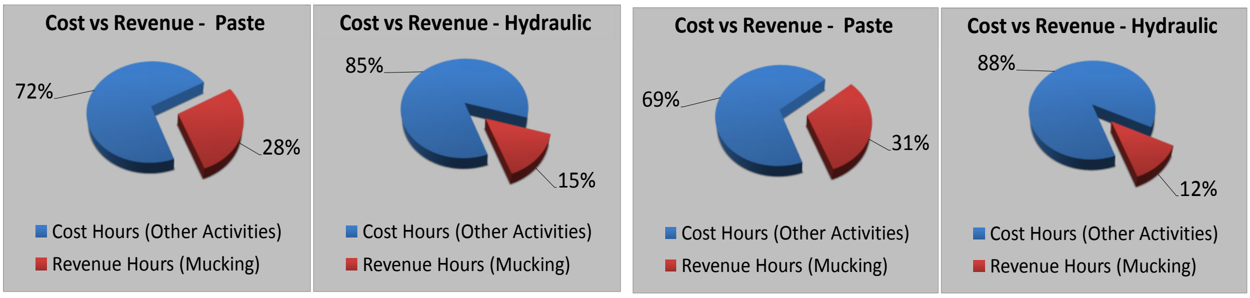
Figure 1 Stope cycle times using hydraulic and paste tailings backfill, showing increased production potential from tailings paste backfill

Figure 2 shows the same variations from the base case, but comparing the amount of time spent mucking as a percentage of all activities – essentially the amount of time generating revenue versus the time absorbing costs. The results from Scenarios 1, 2 and 3 show mucking at 16% for the hydraulic system regardless of the number of LHDs or the amount of drilling, dropping to 12% for Scenario 4. For the paste fill system, Scenarios 1 and 2 show mucking at 18 and 19% of the time. Increasing the amount of drilling increases the amount of mucking time to about 30% – almost twice the amount of mucking time made available by the paste fill system.



Scenario 1 - Base Case

Scenario 2 – 2 LHDs



Scenario 3 – 2× Drilling

Scenario 4 – 2× Drilling, 2 LHDs

Figure 2 **Percentage of time spent mucking versus all other activities, showing the limitations imposed by hydraulic fill**

These results show how the introduction of a superior backfill system can significantly increase the amount of production, or reduce the cost of the given production rate. In particular, Figure 2 clearly shows that production is limited by the hydraulic backfill because no matter what additional equipment is brought to bear, production cannot be increased. The potential benefit of tailings paste backfill is very clear.

2.2 Automation

As a result of the mechanisation transition that occurred in the early 1980s, the implementation of electric-hydraulic equipment made it easier to realise the potential for equipment automation and the use of tele-robotics. In the last 20 years, surface mines have made huge strides in making this possible with many large mining vehicles now operated remotely from human-friendly environments, but underground mines have lagged far behind because of the cost and difficulty of installing adequate telecommunications systems. Tele-operation of stationary equipment such as rock breakers has been operational for several years and a few large-tonnage mines, both surface and underground, have proven the capability of operating LHDs. Smaller more complex mines will have the opportunity to use this approach as the technology matures.

The kind of automation that has taken place in these surface mining operations – and that has been attempted several times in underground mines could be described as opportunistic or tactical - it involved automating the equipment essentially as it was operated by humans, with minimal change in the activity or the process. Many aspects of underground mining have parallels in surface mines – labour, maintenance and the increasing logistic cost of longer supply lines – but the exception is ventilation and the increasing cost of managing heat.

While many mines operating in the Canada Shield have been able to use a natural heat exchange system to reduce the impact of hot summer air, this ceases to be effective at around 2.5 km below surface. Some of the current ventilation demand is to meet the requirements for particulates and gas emissions from diesel engines and electric engines are seen as an easily-implemented, if costly, alternative. In the case of the mobile fleet, the greatest demand for ventilation is created by the use of large trucks which generate a lot of heat that has to be dissipated and the trucks block the flow or air in the main haulage excavation. The size of the trucks has required the development of very large drifts, 5 m square and larger, and the slow rate of development of these large drifts using conventional drift development methods has a negative impact on the NPV of a project by delaying the time to first production.

Because some of the ventilation required by mine regulators is needed to dissipate particulates, there is a view that the industry need only replace diesel trucks with electric trucks to solve a large part of the problem, but a recent study (Mining Innovation, Research and Rehabilitation Corporation [MIRARCO] 2014) on alternative mine cooling systems has shown that this alone will provide little benefit. The study goes on to show that a variety of the heat-exchange systems using mined-out excavations have a great deal to offer as a mine cooling system.

3 Future developments

3.1 Production effectiveness

The obvious difference between underground mines and surface operations is the cost of creating physical space to allow equipment to manoeuvre – which makes the optimal design of equipment different from surface operations. For a front-end loader, or LHD unit, to move a pile of rock or ore, it has to reverse and turn around after having filled the bucket, so as to then transfer the load into a waiting vehicle or hopper. While this is easy to do on surface, to achieve this underground, the turn-around activity has to be accommodated by creating a short drift perpendicular to the main direction.

In addition to the cost of creating the turn-around space, this process is both time-inefficient and energy-inefficient. Firstly, the pile of rock is being touched by the LHD unit less than 20% of the time, while the loader reverses and transfers the load, and a continuous loader would engage the pile of rock close to 100% of the time. Secondly, since the LHD unit returns empty, the energy required to move the machine is large compared to the percentage used to move the rock. With the weight of the load at 25-35% of the vehicle weight, then about 80-85% of the energy is consumed moving the equipment – so the energy efficiency of the system is 15-20% (the percentage of the energy used to move the rock). Equipment capable of moving the pile of rock from the front of the loading machine to the back of the loading machine, without moving the machine, was developed many years ago but today is not in common use, despite being more effective and efficient. In the case of mine trucks, the load/vehicle ratio is 50% and the energy efficiency is 25%.

One limitation of continuous loading equipment is its inability to handle over-sized material, while mobile loaders and LHD have greater flexibility in coping with over-size. In mines that use explosives for primary blasting the opportunity exists to design the size profile of the broken ore or rock to conform to the limitation of the most effective ore/rock handling system. Unfortunately, most mines choose to minimise the direct cost of drilling and blasting and allow the fragmentation profile to dictate the kind of equipment that must be used to transport ore to surface – but if we are to smooth the transportation of ore using cost- and time-effective, low-maintenance equipment the fragmentation profile of the rock and ore will have to be conditioned, mostly by explosives. This is an example of a lean production approach; increasing some direct expenditures in order to reduce the overall cost of production.

In the context of moving material through drifts and tunnels, the physical constraint on the ore and rock transportation system is that it be long and thin, as opposed to short and wide so as to conform to the physical space we have to work with. Trucks are short and wide; conveyors and trains are long and thin. Another constraint is the desirability about hauling up an incline or ramp, as opposed to being limited to the horizontal like a train. So the ideal is a small, train-like system where the speed or frequency of the carriers determines the ore flow rate.

3.2 Human effectiveness

The conditions underground at around 2.5 km depth are 35-40°C and more than 80% humidity – very arduous conditions, especially with long shifts greater than 10 hours – and mines will have to go deeper still. No other segment of the Canadian workforce is required to work in these conditions as a matter of routine. In most mines the communication systems are very limited – most miners do not have continuous telephone or radio communication with other staff or with surface and a great deal of work is performed alone. Over the last 30 years, personal protective equipment (PPE) has evolved tactically, beginning first with a hardhat and protective boots, to add hand, ear and eye protection and traditional cap-lamps still involve a battery on a waist belt. CEMI believes that it is time for a strategic redesign of the miner's PPE. Helmets should provide all the necessary physical protection – sight, hearing and breathing – and be integrated with LED helmet lamps, and hands-free voice-data-video communications. Coveralls should also provide cooling and all personal equipment should be ergonomically designed. Without these changes, the human presence in deep mines will be very difficult and while tele-operation has a great deal to offer, there will always be break-downs that require human intervention.

Based on the author's experience, the current workforce in underground mines is predominantly male Caucasian, with an age demographic of around 50 years old and while there is no one segment of the modern population that the industry would especially want to attract, the largest potential group is the female population. The current mine population has evolved to cope with the change in physical and social conditions that currently exist, e.g. going from 25°C working in a team of at least two people, to close to 40°C working alone - but the workforce that must replace it over the next ten years will have to deal with these difficult conditions on day-one. Without a strategic redesign of the miner's PPE, the industry will not be able to offer any employee conditions that would widely be considered as 'acceptable' in the 21st Century, and it certainly will not be able to attract a significant portion of the potential female workforce. The desirability of attracting a much larger portion of this segment of society is not political correctness. It is because, in the view of the author, in general women are more proactive and less reactive to problem solving than are men and they are very well suited to the kinds of production systems the mining industry will have to employ in the future.

3.3 Mine design

The current approach to mining subvertical orebodies is to select a target horizon, at a certain depth below surface, and begin mining upwards with a series of sublevels towards the top of the orebody, or towards the previous bottom-up mining horizon. In the past, mines have experienced serious difficulties in mining the sill pillar below the upper horizon, but these are now well understood and well managed.

However, the bottom-up approach to mining requires a much larger upfront capital expenditure – the extension of the main mine infrastructure – shaft (or decline), pumping, ventilation to the bottom horizon – before ore production can deliver any return on the investment.

The development of high-quality tailings paste makes it possible to reliably place backfill of sufficient quality that it can be used as a stable roof component. This would allow normal mining operations, such as up-hole production blasting to be used and therefore to mine from the top of the orebody downwards. This reduces the upfront capital required before ore production begins to provide a return on the investment. Rapid development of smaller drifts further reduces the time to first production.

4 Conclusion

Very little of the research work that was done in Canadian underground mines over the last 30 years has been implemented into routine operations and some, like tailings paste fill, that have been widely implemented in mines around the world have found few applications at home. CEMI has rejuvenated some of the older projects with new ideas and has initiated new projects – in collaboration with university-based researchers, consultants and entrepreneurs in the service and supply sector. The equipment used to transport ore underground can be made very much smaller and more energy-efficient, allowing for smaller drifts, faster advance rates and a shorter time to first production. All equipment underground must become simpler and more robust so as to minimise the maintenance costs. What is required is a quasi-continuous production system that requires very little manual involvement during the steady-state operation but that will require human intervention – intelligent decisions made possible with data-rich communications systems, augmented by automated and tele-operated equipment.

CEMI believes that technological changes alone are not sufficient and that the results from these projects must be combined with the philosophy of lean manufacturing that was adopted by the automotive industry over 30 years ago, to further refine the production systems that are essential in deep underground mines to be successful. We believe the implementation of a lean production process is the only approach that will make it possible to dramatically increase the productivity, and therefore the profitability, of base-metal bulk mining operations below 2.5 km depth.

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