Chapter 3
Emerging Trends in Mining

V. I. Lakshmanan, A. Ojaghi, and B. Gorain

Despite significant advances over decades, gold and silver mining still involves the old paradigm with a significant amount of waste management during haulage, processing, and disposal:

- The first step in a mining operation typically involves removal of overburden to access the ore body for an open-pit mine. This overburden is then either stockpiled as a waste rock or to be re-used at closure.
- After drilling and blasting, haulage of blasted ore which is basically mineralized rock above a certain cut-off grade inclusive of waste dilution material cannot be segregated further during the blasting and mucking activities. The ore is then carried out to the primary crusher or process plant. An ore after mining typically contains mostly gangue minerals. The amount of non-valuable gangue minerals could be more than 99.0% for gold and silver ores.
- The next step is to crush and grind the ore in the process plant mainly to liberate the valuable from non-valuables. Comminution in the mining industry is intrinsically very energy intensive using 2–3% of world's energy. Energy consumption could range from 10 to 25 kWh/ton treated. When treating 100,000 tons/day, this equates to one to two GW/day treated by a comminution circuit drawing 50–100 MW power (Powell 2013).
- Intensive mineral processing steps are then carried out on the ore such as pre-concentration, beneficiation, or concentration to separate valuables from gangue.

V. I. Lakshmanan (✉) · A. Ojaghi
Process Research Ortech Inc., Mississauga, ON, Canada
e-mail: llakshmanan@processortech.com

B. Gorain (✉)
Hindustan Zinc Limited, Udaipur, Rajasthan, India
e-mail: Barun.Gorain@vedanta.co.in

V. I. Lakshmanan, B. Gorain (eds.), *Innovations and Breakthroughs in the Gold and Silver Industries*, https://doi.org/10.1007/978-3-030-32549-7_3

- Once the valuables are recovered in the process plant, tailings management is a major step involving storage of tailings, water reclaim, and detoxification of the mill and/or final site effluent prior to any environmental discharge, when applicable.

It is estimated that the overburden waste produced globally is about 10,000 million tons (Mt) per year, assuming a mining strip ratio of 2.5. This is a significant amount of waste generated by the mining industry. Generally, the lower the head grade, the larger the volumes of ore and waste that are produced. In the Kennecott mine in Utah alone, almost 100 Mt of ore and additional 200 Mt of waste are handled every year (Ericsson 2012). To meet the needs, bigger trucks and shovels are utilized, and the payload trucks have increased from around 200 tons in 1990 to almost 350 tons in 2012. At the same time, the installed power has increased by a similar factor. In just the past 5 years, the bucket volume of wheel excavators has increased from 25 to 40 m^3. The processing plants have followed suit with large 42 ft diameter mills, 500–700 m^3 flotation cells along with larger dewatering and tailings pond facilities.

The trend of increasing throughput and larger equipment is continuing despite all associated challenges along with an ongoing trend of extremely high waste generation. The mining industry is still using the old paradigm. A radical shift is needed, starting with seeking alternatives to handling and processing large amount of waste.

3.1 The New Mining Paradigm

The basic extraction paradigm in the mining industry is “drill, blast, load, haul, dump, crush, grind, separate, leach, dewater, and tailings disposal.” There are many variations, but fundamentally, the paradigm has not changed since ancient times. Almost all the innovations so far have made operations in this paradigm safer, more efficient, automated, and even autonomous (Dunbar 2014). What’s needed is a major shift in this paradigm for a major breakthrough.

Since both mining and processing operations handle a significant amount of waste, the first consideration for any innovation should be to cut down on waste as early as possible in the mining value chain. Some of the major opportunities are:

1. **Minimal removal of overburden to access ore body**: Use of small-diameter drill holes to access the ore body along with use of novel biotechnologies to recover metals are currently in use (Dunbar 2014). In situ recovery of metals such as uranium and copper oxides using solution mining is presently being pursued by the industry, which is a step in the right direction though new technologies and novel ideas are necessary to make this practical for most other ore types. It appears that companies like Rio Tinto are looking at opportunities with in situ recovery as key to the “mine of the future” (Batterham 2003).
2. **Highly selective liberation of ores early in the mining process**: It is important to ask ourselves “Why create waste in the first place?” Comminution begins with mining, and a new generation of drilling and blasting for selective mining of ores

is critical to avoid or reduce waste removal early on in the mining process. This concept is referred to as "grade engineering" and is becoming a major focus of research and development (CRC-ORE 2014).

3. **Minimal haulage of waste**: This focuses on innovations that will allow processing to be closer to the mine site. There is an increasing interest in pre-concentration technologies such as sensor-based mass sorting (ROM shovels/trucks), classification using screens, stream-based ore sorting, gravity, and dense media separation, which is definitely a positive trend.
4. **Efficient comminution and processing**: These focus on highly selective separation of valuables utilizing efficient technologies resulting in minimal capital and lower operating costs along with significantly smaller footprint.
5. **Minimal generation of tailings and high reuse potential**: The important focus here is on the recovery of by-products and non-conventional value-added products such as building materials with a generation of benign tailings for backfilling underground and open-pit mines.

Reflecting on these five opportunities suggests that the ideal scenario will be a "zero waste mining." Is this really possible? History tells us that the capability and ingenuity of mining and processing professionals have been phenomenal (Lynch et al. 2010). If there is a dire need with a strong vision and adequate resources, there is no reason why "zero waste mining" cannot happen. Various innovative technologies that have been developed by the mining industry definitely provide us the confidence. The area of "zero waste mining" is not the focus of this chapter, but all trends in innovations must be seen in light of this ultimate goal.

3.2 A Drive Toward Selective, Continuous, and Automated Mining

Hard rock mining is essentially a batch process involving drill and blast, followed by load, haul, and dump. The challenge with drill and blast is that, despite the best efforts, there is a limit to how much one can control overbreak and external dilution resulting in issues with selectivity and grade control for both underground and open-pit operations. Also drill and blast introduces cycle into mining, and the mining process must fit into the defined time between blasts. Recent emergence of continuous rock cutters in hard rock mining such as surface miners for open-pit and continuous rock cutters for underground has the potential to transform gold and silver mining.

Continuous rock cutters are typically faster than drill and blast methods, allowing faster access to the ore body with significant addition to NPV of a mine (Vogt 2016). Rock cutting generates significantly lower vibrations and noise levels than the use of explosives, and thus has significant advantages where local communities live closer to the mine. The cutting process affects the rock surrounding the excavation less than the explosives; thus, the rock is stronger and safer or easier to support.

Cutting can produce excavations very close to the desired shape and size of tunnels, so that the cost of extra lining due to overbreak is reduced. Also the number of people exposed to dangerous underground conditions is lowered due to elimination of the need to store and handle explosives. For narrow reefs, cutting offers the opportunity to greatly reduce waste dilution in a process that has similar advantages to ore sorting. If the mine can be created with smaller excavations with cutting, the seismicity and ventilation requirements will both be reduced significantly.

Barrick Gold already has now extensive experience using Sandvik roadheaders, with the first MH620 unit successfully tested at Cortez gold mine in Nevada, USA. This roadheader weighs 125 tons and is driven by a 300 kW cutting motor. This rock cutter at Cortez was used at the Range Front mine decline, which is one of the world's largest roadheaders. According to Barrick, this technology has allowed to improve safety, increase throughput, and reduce mining cost per tonne. This has led Barrick Gold to acquire a second rock cutting machine Sandvik MR361 roadheader in 2017 (Fig. 3.1) for their Turquoise Ridge operation in Nevada to help with their mechanization, automation, and innovation drive (International Mining Journal 2019).

Continuous mining has been practiced over a century now for coal and soft rock mining; it is only now that slowly technology is evolving after decades of research and development. Caterpillar commercially launched the Cat Rock Straight System during the MINExpo 2016, a fully mechanized long wall system for continuous hard rock mining that features the cutting-edge HRM220 hard rock miner. Atlas Copco is planning a commercial launch of its continuous cutter after various efforts

Fig. 3.1 Sandvik cutting machine, Roadheader MR341 roadheader for mining (Sandvik Mining and Construction 2007)

involving collaboration of Rio Tinto during 2009 and also with Anglo American on a project named Rapid Mine Development System (RMDS), since 2012. Joy Global, now Komatsu Mining, has been testing prototype for its DynaMiner, which features DynaCut hard rock cutting technology, since September 2016 with promising results appearing to be demonstrated at Newcrest's Cadia operation. Sandvik is also developing a continuous hard rock miner called the MX650 (CIM Magazine 2017). It seems that by 2020, there should be several launches of hard rock cutting systems by various OEMs.

3.3 A Vision for Continuous Mining Integrated with Processing

A vision for continuous mining integrated with processing was presented at the International Mineral Processing Congress at Quebec City (Gorain 2016). A schematic is shown in Fig. 3.2.

This vision entails continuous rock cutting for mine development for access to ore body in underground operations. Also rock cutting for selective mining of ore to produce fragmentation is carried out that does not require any primary crushing. The mined ore will undergo a secondary crushing step followed by ore sorting to remove any undesired waste rock or dilution material. The rejects from ore sorting will be utilized for backfilling underground. The concentrate from ore sorting will

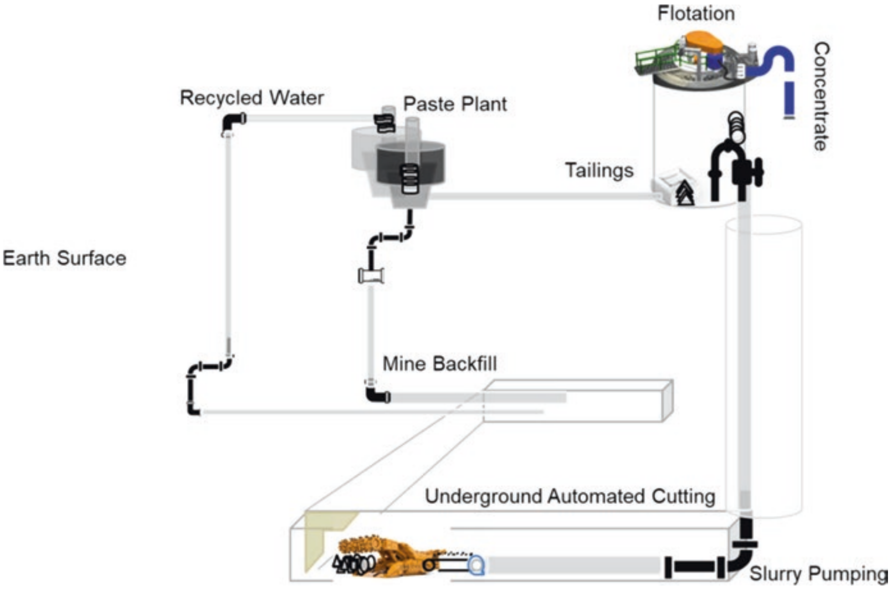

Fig. 3.2 A vision for a continuous integrated mining and processing (Gorain 2016)

be ground to a maximum particle size of 6 mm or below using a small milling circuit underground. The ground ore is then pumped to the surface using a hydraulic system or a suitable positive displacement pumps. The time required for pumping could be utilized for reagent conditioning of the ore for any concentration or hydrometallurgical step on the surface.

On the surface, a coarse flotation step is involved to reject any gangue minerals to reduce comminution energy costs and to further upgrade the ore. A finer grinding stage is then carried out on the concentrate from coarse flotation followed by fine particle flotation in a normal milling circuit. The concentrates produced from fine flotation are then sent for further processing. All flotation tailings on the surface are then collected for making paste fill, which is then sent underground for paste or backfilling underground.

A major advantage of this integrated mining and processing is that the footprint required is significantly lower than a conventional mining operation, with minimal or no need for tailings storage on the surface. This is a continuous process, and hence the whole chain could be automated with minimal need for manual intervention underground. In addition, this system has the potential to be a 100% electric mine with minimal ventilation requirements. This will be a safer, low-cost, and highly productive mine with much lower environmental challenges.

3.4 Early Integration with Processing

The vision presented above will need some time as the technology is slowly becoming matured. In the meantime, it is important to realize that the various steps in the process are being implemented by various mining operations. Just like Barrick Gold has been operating continuous cutting machine successfully now, there are other operations utilizing hydraulic pumping for transporting ore from underground. Also, there are operations where ore sorting is being carried out underground or on the surface to reject mine dilution material before milling.

The key to advancement is to bring processing early in the mining value chain to avoid transportation of waste. The next section will discuss some key technologies that are being tested and operated by various companies across the globe.

3.4.1 Drill and Blast Optimization (Mine to Mill)

Blasting is the first stage of comminution in most mining and should not be seen solely as a means of reducing rock size enough to load it on a truck. The run-of-mine (ROM) size distribution has a large impact on the performance of downstream crushing and grinding processes.

Drilling and blasting is an established technology that evolved over the last century. This is a batch process and often closely embedded in the macho culture of a traditional tough and rough miner (Ericsson 2012). Hard rock cutting, a viable alternative to enable continuous mining, is gaining wider acceptance in metal mining since its success with softer and non-abrasive bedrock and minerals such as potash and coal. This innovation seems to be attractive for narrow veins and reef mining allowing a more selective mining with less waste rock and dilution with positive impact in processing along with the economic benefits associated with continuous mining.

Mine to mill optimization in various operations over the years has shown significant benefits such as high mill throughput rates from reduced top size from mining through increased powder factor or blast energies (Dunbar 2014). There are however some safety and environmental areas where special care and attention are needed to prevent any high wall damage, fly-rocks, noise, and vibrations from using higher blast energies which can become challenges. The introduction of electronic detonators and other techniques however allows mitigating some of these risks. New blasting technologies are emerging that have the potential to significantly increase powder factor through innovative blasting practices such as dual blast layers within a single blast event (Brent et al. 2013).

3.4.2 Ore Tracking

All stages of a mining operation are influenced by ore characteristics. The SmartTag™ system tracks ore from the mine through the process, allowing ore characteristics to be correlated with important operating parameters in the mine and processing plant. These parameters can then be adjusted and optimized for different ore types to increase profitability.

SmartTag™ can be used to track ore from the mine into the plant using the system shown in Figs. 3.3, 3.4, and 3.5. When used this way, we can correlate ore characteristics with important operating parameters in the mine and processing plant, such as ore dilution, ore losses, fragmentation, throughput, and energy consumption. This provides an understanding of how different ores affect mine and plant operation and the final product. Operating parameters and control strategies in the mine and processing plant can be adjusted and optimized for different ore types, thereby reducing costs and increasing profitability.

Metso patented SmartTag™ system is used to track parcels of ore from the mine into the plant and beyond. SmartTag™ is an innovative system which uses hardened Radio-Frequency Identification (RFID) tags, detectors, and custom software to track ore through the mining process. SmartTag is a radio-frequency identify cation (RFID)-based technology designed to allow tracking of ore from its source through blasting, run-of-mine (ROM) pads, crushers, and intermediate stockpiles and finally into the concentrator (Wortley et al. 2011).

The SmartTag™ system is also used to automate geometallurgical modelling enabling throughput forecasting and life-of-mine optimization.

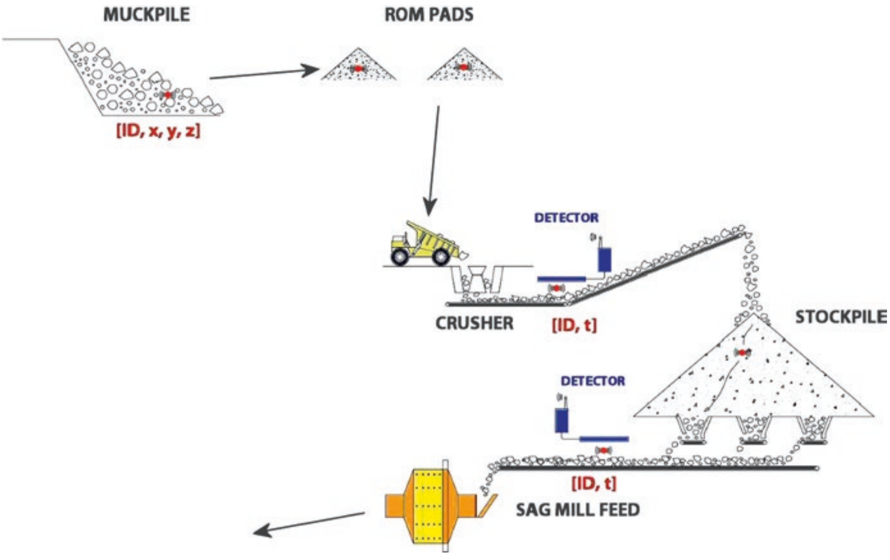

Fig. 3.3 Schematic of RFID tag-based material tracking system (Isokangas 2012)

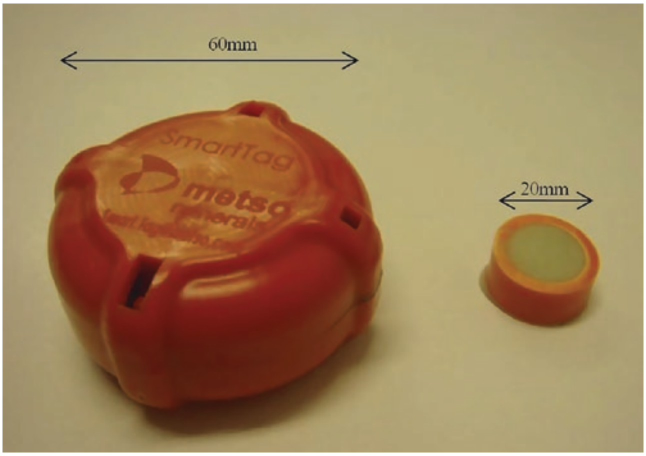

Fig. 3.4 Normal and mini SmartTag (Wortley et al. 2011)

SmartTag™ work principles

- SmartTag™ are placed with source ore in the mine (blast holes, muck piles, etc.), and the starting location of each unique tag is recorded using a ruggedized handheld computer.
- Tags survive the blast and travel with the ore.
- They are detected when they pass antennas at critical points before milling.

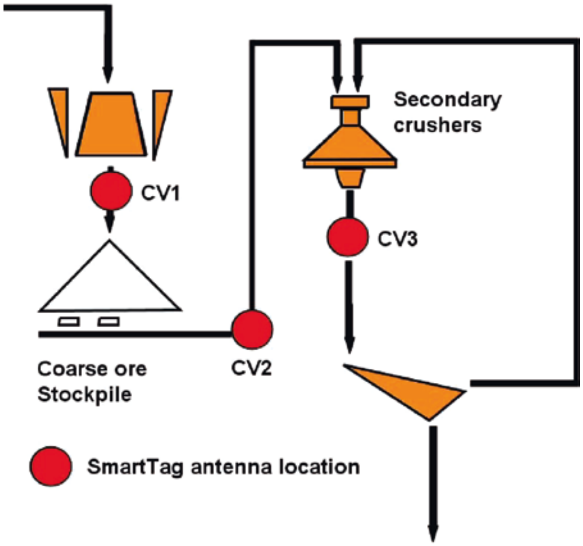

Fig. 3.5 Secondary crushing circuit (Wortley et al. 2011)

- With no internal power source, they can remain in stockpiles for extended periods.
- The physical ore properties in the mine can then be linked with time-based performance data from the plant.

SmartTag™ benefits

- Inexpensive and versatile material tracking from mine to the plant and beyond.
- Valuable information on material movements.
- Link the physical properties of the ore in the mine to the time-based performance data of the plant to optimize the process as a whole.
- Track material through the delivery chain to monitor and optimize product supply management, transport logistics, and margin management.

3.4.3 In-Pit Crushing and Conveying System (IPCC)

Transporting ore and waste rock is one of the most crucial elements of an open-pit mining operation. A successful haulage system can make the difference between a mine that is consistently profitable and one that is struggling to meet its marginal costs.

Haul trucks are generally favored based on their flexibility of operation compared to conveyors or trains, which were the preferred method until the 1960s. Since then, technical developments have gradually led to much larger-capacity vehicles capable of hauling more ore in fewer cycles. More recently, diesel emissions regulations have resulted in haul trucks that emit less pollutant while retaining performance and productivity. Telematics and GPS technology now allow haul trucks to be tracked and scheduled for maintenance with improved efficiency. Mining operational costs have increased significantly due to increased prices for diesel, large truck tires, equipment maintenance, and manpower.

In light of these challenges, in-pit crushing and conveying (IPCC) is a technology that has grown in popularity since it was first implemented in the 1950s. The purpose of an IPCC system is to allow the ore to be crushed in the pit and transported out using a conveyor system. In-pit crushers can be mobile which means they can be moved within days or even hours, depending on their size and complexity and the relocation distance, or semi-mobile, referring to units that are more permanent and need to be moved less frequently, typically everyone to 10 years. The specific configuration depends on the mine plan.

Since 1980, several studies performed on existing in-pit crushing installations and models have showed cost savings (Darling 2011). As a result, there is a tendency in the direction of high-speed, large-capacity conveyors due to better productivity. Classic belt conveyors can transport materials at angles up to 37°. This type of conveyor has been used in numerous hard rock operations in Canada with a maximum capacity of 57,500 tons per day (Vergne 2017). High-angle belt conveyors, such as the sandwich and the pocket wall conveyors, can transport material at high angles up to 90° while keeping the positive features of conventional conveyors (Duncan and Levitt 1990). The Conveyor Equipment Manufacturers Association (CEMA) recommends designing belt conveyors with a maximum width of 3.2 m and belt speeds of 8 m/s for rough crushed material.

Capital investment for IPCC system is greater than a truck-shovel (TS) system. When the mine goes deeper, the IPCC operational costs are considerably cheaper compared with TS, and the total NPV increases throughout the project life. An analysis showed that both systems were sensitive to production rate (Andres 2017) (Fig. 3.6).

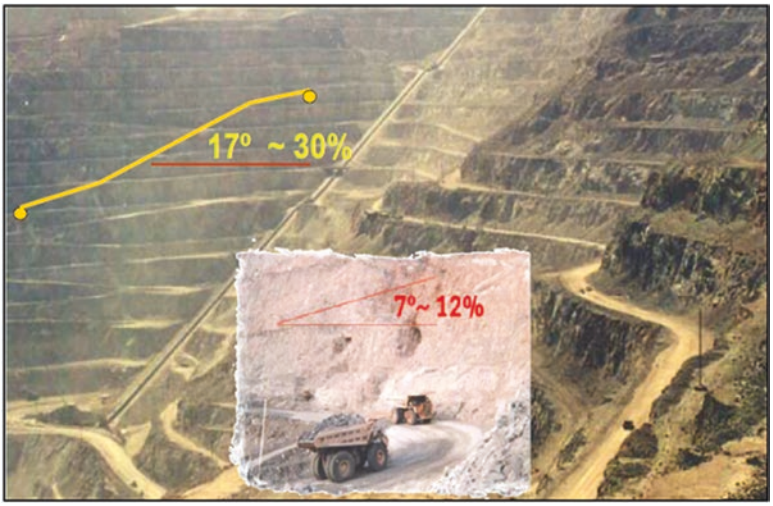

Fig. 3.6 Comparison slope of ramps in conventional and IPCC system (Szalanski Scot 2009)

3.4.3.1 IPCC Advantages

There are several advantages of an IPCC over a haul truck system. The first and most obvious is a marked reduction in costs due to less need for road and truck maintenance, along with significantly less fuel use and labor costs (a small number of haul trucks are retained in an IPCC operation). IPCC systems are usually reliable, requiring less maintenance and service employees than trucks, and are not impaired by bad weather.

IPCC systems cut truck haulage to a minimum and build operational resilience; they substantially reduce the operational expenditures and hold other environmental and safety benefits too.

The capital and operational cost directly depend on the material transport system. Conventional truck haulage as today's predominant means of material transport in surface mines are well established and provide excellent flexibility; however, they contribute up to 60% of the overall mining cost. IPCC represents a viable, safer, and less fossil fuel-dependent alternative. They comprise of fully mobile, semi-mobile, or fixed in-pit crusher stations connected to conveyors and spreaders (for waste) or stackers (for ore) to transport material out of the mine.

Besides the potential operational expenditure reduction, IPCC systems offer a number of other benefits to mining operations (Radlowski 1988; Darling 2011; Johnson Marc 2014; Andres 2017):

- Reduced manning requirements of between 40 and 60% due to higher automation
- Reduced spear part requirements
- Possible electrical power generation at downhill conveyors
- Reduced greenhouse gas emissions of up to 25%
- Noise level reduction of up to 35%
- Dust emission reduction of up to 40%
- Reduced bad weather downtimes
- Improved safety due to fewer mobile vehicle usage

IPCC system is looking at savings of 20–40% over a truck haulage system, depending on productivity rates and whether the trucks are hauling aggregates or mineral ore.

IPCCs work well where there is horizontal movement of the mine faces, but not so great in deep mines with a lot of benches.

3.4.3.2 IPCC Types

There are a number of different system configurations, largely depending upon whether truck haulage forms any part of the of the material movement chain or not. The three major configurations are:

1. **Fixed or semi-fixed systems**: These are where trucks dump directly into a fixed crusher location. The fixed crusher is not able to be relocated within a reasonable period of time (not be for less than 10 years) (Figs. 3.7 and 3.8).

Fig. 3.7 Fixed IPCC system (Szalanski Scot 2009)

Fig. 3.8 Semi-mobile IPCC system (Cooper Allen 2010)

2. **Semi-mobile systems**: This unit works close to the mine face but is moved less frequently than a mobile crusher. Semi-mobile systems are suited to harder rocks and higher capacities. In this method, trucks are used to transport material from the mine face to the in-pit crusher, often moving between levels (Fig. 3.9).
3. **Fully mobile systems**: These types of crushers work at the mine face; are loaded directly by a shovel, front end loader, or excavator; and move in unison with the excavator on their own transport mechanism as mining progresses (or sizer) (Figs. 3.10, 3.11, and 3.12).

Fig. 3.9 Semi-mobile IPCC system (Courtesy of Sandvik) (Johnson Marc 2014)

Fig. 3.10 Fully mobile IPCC (Koehler 2010)

Fig. 3.11 Fully mobile sizer (Crusher) (Courtesy of MMD) (Johnson Marc 2014)

Fig. 3.12 Fully mobile IPCC system

3.4.4 *Underground Preprocessing*

Underground mineral processing would reduce the costs of bringing ore to the plant and returning backfill waste to the mine workings. As mines become deeper, cost savings from underground processing become more significant. Underground pre-concentration also allows for increased underground mining rates for a fixed shaft haulage capacity. This translates into increased tons of metal transported to the surface and higher grades feeding the surface processing facility. The objective of pre-concentration is to reject barren waste at as coarse a particle size as possible. Therefore, the ability to apply pre-concentration is determined by the liberation characteristics of the ore. Liberation was achievable at sizes that could be produced by crushing. The main technology used for pre-concentration is dense media separation which has been applied to the separation of metal-bearing sulfides from siliceous gangue. Over the last 40 years, a number of coarse particle processing technologies have been developed that may now be ready to apply industrially for applications such as pre-concentration (Klein et al. 2002).

The dense media separation process is characterized by a high processing capacity and the ability to make sharp separations at coarse particle sizes. There are two basic classes of dense media separators referred to as static separators and dynamic separators. Static separators, such as drums, vessels, and baths, are suited for particle sizes ranging from approximately 2 to 500 mm and have a unit capacity of up to 300 tons/h. Dynamic separators, such as the DSM Cyclone, Dyna-Whirlpool, and Tri-Flo, utilize centrifugal acceleration to achieve separation. Large-diameter separators (up to 1 m) can process particles up to 100 mm at a rate of up to 400 tons/h; the bottom size limit is typically close to 0.5 mm. An underground dense media processing facility would include crushing, screening, dense media separation, and a dense media recovery circuit. The products are essentially dry (Klein et al. 2002).

A Chamber of Mines of South Africa research project developed and piloted underground processing of gold ores from the Witwatersrand. The process design was based on consideration of underground space limitations for a processing facility, mineralogical/liberation properties of the ore, and the capacity to return waste backfill to excavations. The raw ore is ground in a centrifugal mill and screened at 3 mm. The minus 3 mm fraction is floated in specially designed flotation cells for use with very coarse particles to recover gold and gold-bearing sulfide minerals. The flotation tailings are classified using hydrocyclones, which return coarse gangue, moderately coarse valuable minerals, and locked valuable minerals to the mill. The cyclone overflow is a waste product which is thickened for backfill. The estimated gold recovery is 98% while rejecting 60% of the raw feed. In this case, pumping would be required to transport a bulk concentrate to the surface and to return the tailings to the underground excavations. Bulk sulfide flotation followed by selective flotation is a common practice for surface processing plants (Klein et al. 2002).

Ore sorting process is another popular technique which has been used for underground preprocessing. Several coarse particle sorting technologies can be considered for pre-concentration. Sorting machines must be capable of effectively eliminating waste rock at coarse particle sizes and at high throughput rates. The suitability of technologies will depend on the principle of separation, the capacity and applicable particle size range, and factors relating to infrastructure requirements, space, and portability. Processes that do not require water and are relatively small and mobile, which allows them to be mobile for operation close to the mining face, are favored over processes that do not meet these requirements (Klein et al. 2002).

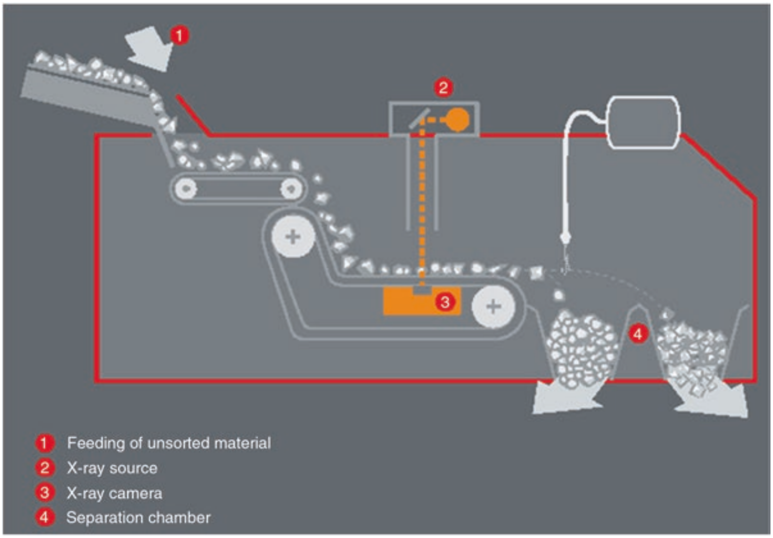

Fig. 3.13 Diagrammatic representation of mechanized ore sorting at underground preprocessing (Lynch and White 2013)

Optical sorters consist of an image scanner and processor to distinguish between particles of different colors, brightness, sizes, and shapes. Optical sorting has been applied to ore processing and recycling for particles up to 350 mm and rates up to 300 mtph (Klein et al. 2002).

Ore sorting testing has been undertaken by Citigold at both laboratory scale and also preliminary bulk sample trials using mechanized ore sorting technology (Fig. 3.13) to reduce the level of waste in the ore to be hoisted. Initial trials by Citigold in 2003 and 2005 have demonstrated the potential for success with ore sorting using photometric (PM) (He-Ne laser light), electromagnetic (EM), and radiometric (RM) detection systems. Responses were only achieved with PM. Samples of +20 to −45 mm material were successfully processed within excess of 85% recovery of ore from waste. Processing of the screened −20 mm material was not successful, with significant misplacing of high-grade dark sulfide ore material into the waste stream. However, advances in technology since that date have indicated greater promise for gold ore using color, X-ray transmission (XRT), and near-infrared (NIR) sensors. Repeat trials will be carried out shortly using a range of techniques. Larger-size particles (50–100 mm) will be used, and the philosophy will be to sort waste from the ore to avoid grade loss. The particles will be washed and screened, with finer material (undersize) reporting directly to the "concentrate" stream. As with the geophysics, the target will be the sulfide proxies for the gold as they represent a more substantial target and this should be a potentially more reliable approach. Selection of waste, rather than ore, means that if there is any doubt about a particular particle, it will report to ore, thus obviating loss of values due to miss-sorting. It is currently anticipated that 50% of the waste component of the run-of-mine ore should be removed, to provide a head grade to the mill of approaching mineral resource grade. The retrieved waste will be used as fill material for disposal in the mined out stope voids, thus further reducing hoisting and disposal costs (Lynch and White 2013).

3.4.5 Bulk Ore Sorting

Conducting bulk ore sorting at the mining face, either in-pit or underground, allows ore and waste to be directed to the appropriate destination (waste dump or process) immediately. In open-pit mines, bulk ore sorting could potentially fit well with in-pit crushing and conveying systems.

Because the natural heterogeneity of the ore makes sorting more effective, a bulk ore sorter should be placed as early as possible in the process. This also avoids extra costs and the lost capacity associated with treating non-economic material. In fact, the benefits of discarding barren material early on are carried through all the downstream process steps.

In almost all cases, bulk ore sorting would need to be implemented after primary crushing to present material at a size that can be handled by the sorter. Each additional crushing or material transfer stage incorporated prior to sorting increases mixing, costs, and unnecessary energy consumption, so these should be avoided if possible.

Conducting bulk ore sorting at the mining face, either in-pit or underground, allows ore and waste to be directed to the appropriate destination (waste dump or process) immediately. The feasibility of this approach will depend on having suitable space available for the sorter as well as on the mining method employed and potential impact on mining productivity.

Underground pre-concentration, prior to haulage or hoisting, produces solid waste underground, which can be combined with tailings and cement from the surface as required and disposed of as fill. In open-pit mines, bulk ore sorting could potentially fit well with in-pit crushing and conveying systems. The sensor(s) would be located on a conveyor leaving the pit and would use a flop gate to separate waste and ore onto their respective conveyors. Furthermore, a system equipped with multiple flop gates could be used to separate different ore types onto separate stockpiles, which could be either blended according to the downstream process requirements or sent to different process routes (Metso 2018).

3.5 Automation and Digitization

Mineral processing operations present many challenges due to variations in unmeasured ore properties, material transport delays, and non-linear response characteristics. Advanced process control technologies such as expert systems and multi-variable model predictive controllers are often used to improve the control of these processes to increase productivity and recovery efficiency. Typically these systems are applied after the mine has been in operation for a period of time (Carr et al. 2017).

3.5.1 Model Predictive Control

David Carr et al. evaluated the application of BrainWave Model Predictive Controller (MPC) and Advanced Control Expert (ACE) Advanced Supervisory Control System on the SAG mill, ball mill, and rougher flotation cells for a new gold processing line at the OceanaGold (Carr et al. 2017).

The advanced control was tested against the IDEAS™ dynamic simulator and commissioned during the startup of the processing plant to help achieve target production as quickly as possible. Operators were able to run the equipment in a consistent and optimized manner from an early stage of the plant operation, increasing efficiency and profitability. MPC is able to reduce process variability beyond the best performance that can be obtained with conventional proportional-integral-derivative (PID) control methods. MPC is able to optimize the control of processes that exhibit an integrating type response in combination with transport delays or variable interaction, which are characteristic of many gold processes including SAG mill weight control and flotation cell froth level control (Carr et al. 2017).

Model predictive control provides an additional tool to improve the control of critical processes where PID- or rule-based expert control is not well suited to the application. In particular, MPC is able to optimize the control of processes that exhibit an integrating type response in combination with transport delays or variable interaction. This type of response is particularly difficult to control, and it is common in mineral processing for many different processes including level control of flotation cells and crushers and SAG mill weight control.

MPC has been successfully applied to many of the critical processes at a mineral processing plant including SAG mill control, ball mill control, and rougher flotation control. MPC has consistently demonstrated the ability to reduce process variability and increase stability compared to PID- or expert system-based control (Carr et al. 2017).

3.5.1.1 SAG Mill

An MPC was installed to control the SAG mill weight, the feed rate in the ore feed system, and the SAG mill sound emissions as part of the ACE solution. A diagram of the control strategy is shown in Fig. 3.14. The ACE control system manages the SAG weight using both the ore feed rate and the SAG mill rotation speed (RPM). This approach ensures that the maximum possible production rate is achieved at all times while automatically reducing the RPM when required to reduce energy consumption and retain an adequate minimum mill fill weight to reduce liner wear or when excessive sound emissions are detected.

3.5.1.2 Ball Mill

The ANDRITZ Ball Mill ACE control strategy adjusts the pump speed to maintain stable cyclone pressure. The ball mill sump level is allowed to vary over a specified range so that minor changes in production rate are managed in the sump. This

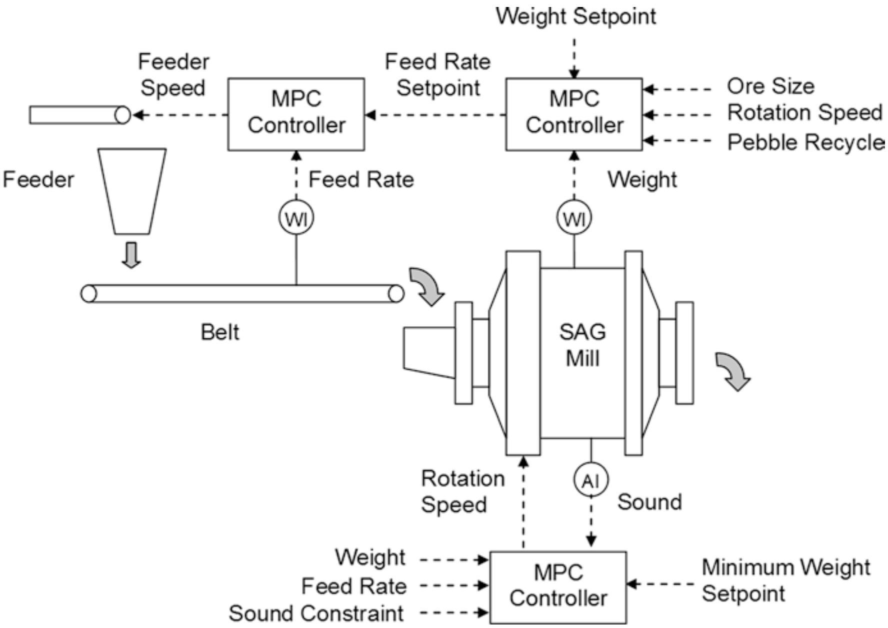

Fig. 3.14 SAG mill MPC control strategy (Carr et al. 2017)

approach avoids unnecessary disturbances to the cyclone pressure and the number of cyclones in service, resulting in increased stability of the cyclone pressure and the P80 to the flotation cells. Dilution water to the sump is adjusted to maintain infeed density to the cyclones, which is also an important factor in stabilizing cyclone performance. The control strategy is shown in Fig. 3.15.

The MPC is used to control the cyclone feed pressure and cyclone feed density by adjusting sump pump speed and dilution water flow. The ACE system is used together with the MPC to control the sump level by adjusting the number of cyclones in service. The ACE system also adjusts the cyclone pressure setpoint over a small specified range to assist with the sump level control for the purpose of minimizing the number of cyclone openings or closings.

Optimal performance of the flotation process requires stable control of the froth depth in each flotation cell. If the froth level can be maintained, a stable froth layer is formed without excessive bubble breakage, and there is a steady overflow of froth over the lip of the flotation cells. A well-chosen froth depth allows time for some “drainage” of entrained water and gangue particles before the froth overflows the cell; however, greater froth depths can result in lower recovery and increased use of expensive frother chemicals. The target froth level for the cell is often determined by the operator, but can be automated using a camera-based supervisory system.

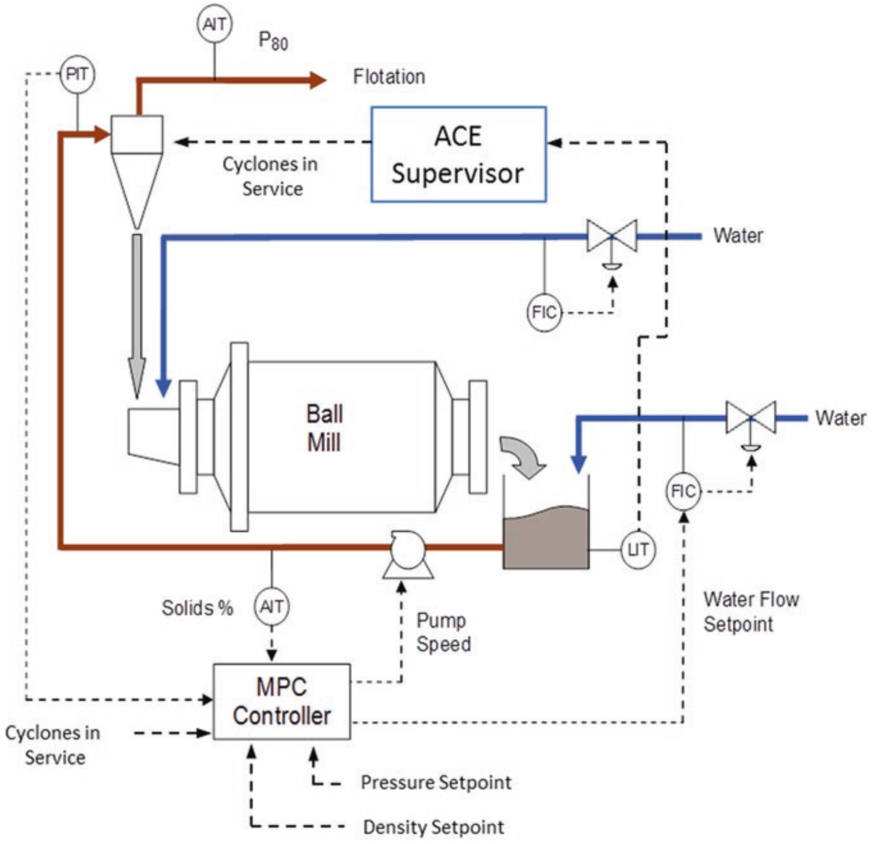

Fig. 3.15 Ball mill control strategy diagram (Carr et al. 2017)

3.5.1.3 Advanced Control of Flotation Cell Level

Optimal performance of the flotation process requires stable control of the froth depth in each flotation cell. If the froth level can be maintained, a stable froth layer is formed without excessive bubble breakage, and there is a steady overflow of froth over the lip of the flotation cells. A well-chosen froth depth allows time for some “drainage” of entrained water and gangue particles before the froth overflows the cell; however, greater froth depths can result in lower recovery and increased use of expensive frother chemicals. The target froth level for the cell is often determined by the operator, but can be automated using a camera based supervisory system.

The MPC was installed on the flash cell and two rougher flotation cells. The control strategy uses the cell levels and cell valve positions to estimate the flow between the cells. These low estimates are used as feed-forward inputs to the MPC to improve the rejection of level disturbances caused by the actions of the upstream controllers.

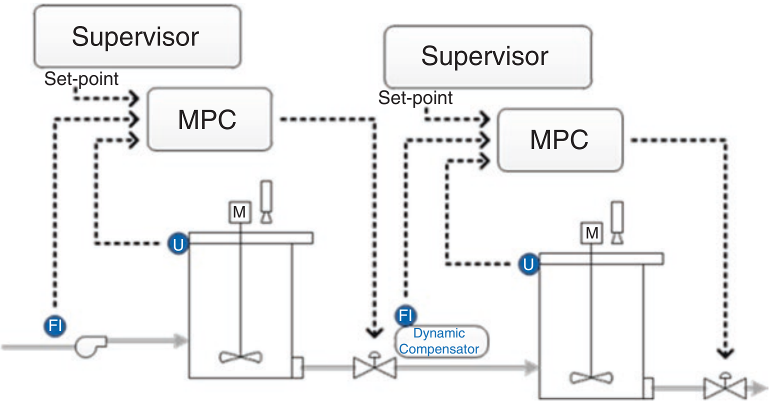

Fig. 3.16 Flotation cell level control strategy (Carr et al. 2017)

Separate MPC are used for each flotation cell instead of a single multi-variable MPC as the interaction of the actuators is coupled only in the direction from the upstream cell to the downstream cell. In addition, as the flow change from a given actuator change is a function of the relative cell levels, a dynamic compensator is used to convert the valve movements into estimated flows as this is a better feed forward to the downstream MPC than the actual valve position at the outlet of the upstream cell. A diagram of the control strategy is shown in Fig. 3.16.

3.5.2 *Robust Non-linear Model Predictive Controller (RNMPC)*

Reagent consumption in gold processing plants significantly contributes to the total operational costs. In a typical carbon-in-pulp (CIP) circuit, the reagent consumption associated with leaching, adsorption, elution, and regeneration contributes to approximately 15% of the total operational costs (Stange 1999). At Loulo Gold Mine, the reagent consumption associated with leaching, adsorption, elution, and regeneration contributes to 6% of the total operational costs. As such, a reduction in reagent consumption will present a significant opportunity for savings on operating expenditure. Variability in feed ore characteristics results in continuous changes in steady-state operating regions, which presents process control challenges as a result of the long residence times in some of the process units associated with gold processing plants. Overdosing often occurs in the presence of process variability to ensure safe operation and to maintain recovery targets. As a means of reducing reagent consumption and accounting for significant changes in the feed to gold plants, some of the plants have resorted to improving their process control strategies around their circuits.

A robust non-linear model predictive controller (RNMPC) was commissioned as the model-based predictive controller. This controller is suitable for handling processes with long time delays, such as the thickener underflow density control using flocculants. The time delay in density control using flocculants is a function of the rate of reaction of the flocculants with the slurry which in turn affects the settling rate of the solids, and thus the underflow slurry density. There is also a delay in the thickener underflow density when the underflow flow rate is changed, for example, if the flow rate is increased, the already-compacted solids will be discharged faster without causing the underflow density to change. Only when the previously compacted solids have been discharged will the reduced settling time have an effect on the amount of compaction of new solids entering the thickener, which in turn will result in a reduced underflow density.

Furthermore, the RNMPC is also suitable for controlling non-linear processes such as pH control which is highly non-linear due to the non-linear characteristics resulting from the feed and the ion concentration in the controlled system (Lazar et al. 2007).

The main objectives of the controller were to stabilize the feed to the CIL process by controlling the thickener underflow density to setpoint and also to control the pH of a CIL tank to setpoint, taking into account the long residence times (Makhado and Sagara 2017).

Figure 3.17 illustrates the RNMPC configuration of the thickener underflow density and pH (CIL Tank 1) control commissioned at a gold mine in Mali. The aim of the RNMPC is to control the thickener underflow density feeding CIL Tank 1 to setpoint, without violating the thickener torque and slurry bed level constraints, and control the pH in CIL Tank 1 to setpoint.

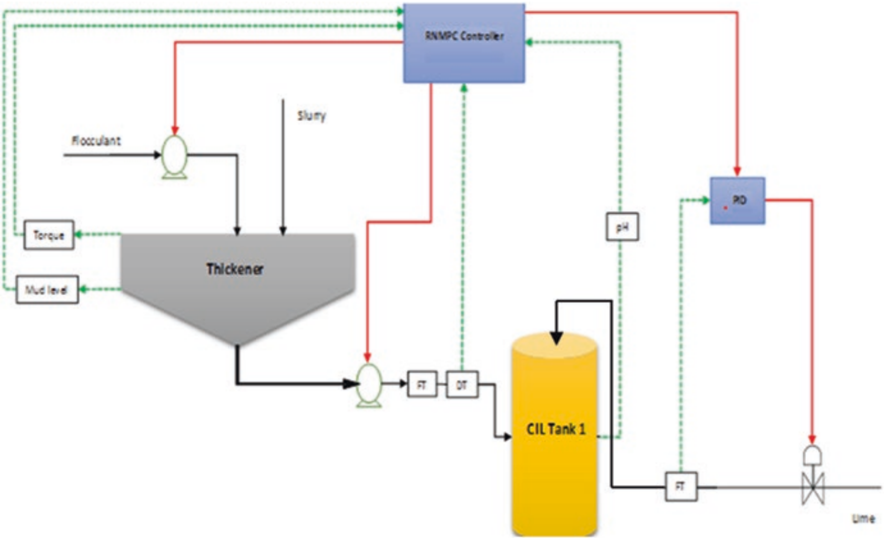

Fig. 3.17 Process configuration and commissioned control loops (Makhado and Sagara 2017)

3.5.3 Era of Automation and Digital Mine

Until few years ago, the mining industry has been fairly conservative with implementing new technologies in comparison to other industries. Australian mining is entering a new era of automated operations. The two imperatives of reducing operating costs and improving safety are the key drivers. It is interesting that many mineral processing plants are state of the art and fully automated, yet surface and underground mining operations have evolved at a much slower pace.

Processing plants, being one integrated unit, were easier to automate. Mining operations, the excavation and moving of rock, have traditionally been a sequence of disconnected steps, but these can now be digitally integrated using technologies that have evolved over the last 5–10 years. With automation comes big gains in productivity and machinery output, which leads to cost reductions. Safety is substantially improved because operators are removed from the more hazardous areas. Also operator error is reduced by eliminating what are often boring repetitive tasks that can now be done by algorithm-guided computers (Lynch and White 2013).

Digitization of mining operations is now strategic to the growth and sustainability of today's mining companies. Recent evolution of sensor and network technologies along with easier access to computing power and subject matter expertise from almost anywhere in the world has created an ecosystem which has the potential to transform mining. Real-time monitoring and predictive analytics along with the ability to control an operation remotely have allowed mining companies to redefine their business models. Autonomous machines are now increasingly being adapted to many operations across the globe. Companies are starting to realize the benefits of digitization through better safety and higher productivity along with lower maintenance costs.

A conventional underground mine is almost like a black box with no visibility of actual progress in underground activities until the end of the shift at best. This lack of visibility and communication leads to poor productivity. To bridge this gap, mining companies are investing to establish high bandwidth network to have a two-way communication, track activities in real time and manage the data centrally. This enables us to provide the right information at the right time and in the right format to the right person to help in data-driven decision-making.

A digital mine essentially consists of the following modules that enhance interoperability across the operations:

- Reliable high bandwidth communication network
- Two-way voice and data communication with workforce and equipment
- Real-time tracking of assets—man, machine, and material
- Real-time status of the mining processes
- Obtaining equipment health and productivity data
- Integrating auxiliary services, viz., dewatering, ventilation, electric substations, seismic monitoring system, CCTV, ambient air quality system, and other data through smart sensors
- Automated traffic control system

- Fleet management system
- Three-dimensional visualization of complete mine for real-time monitoring of operations
- Digital twin with predictive models and prescriptive action items

Details of the different aspects of mine digitization will be presented in Chap. 11.

References

Andres, Jimenez Builes Carlos. 2017. A mixed-integer programming model for an in-pit crusher conveyor location problem. University of Montreal.

Batterham, R.B. 2003. The mine of the future, will it be visible? XXII In *International mineral processing congress*, Cape Town, South Africa.

Brent, G.F., P. Dare-Bryan, S. Hawke, and M. Rothery. 2013. Ultra-high-intensity blasting—a new paradigm in mining. In *Proceedings of world gold conference*, Brisbane, Australia.

Carr, David, Johnson Quenton, and W.A. Gough. 2017. In *Optimization of the Haile Gold mine grinding and flotation line using model predictive control, COM 2017,* Vancouver, Canada.

CIMMagazine.2017.http://magazine.cim.org/en/technology/hard-rock-revolution-on-the-horizon.

Cooper Allen. 2010. In-pit crushing and conveying (IPCC).

CRC-ORE. 2014. Transforming mining productivity with grade engineering. www.crcore.org.au

Darling, P. 2011. SME mining engineering handbook, 3rd ed. https://books.google.ru/books?id=5uq-kdfHLWUC

Dunbar, W.S. 2014. Will the mine of the future be a mine at all? In *Globe and Mail*.

Duncan, L.D., and B.J. Levitt. 1990. Belt conveyor. In *Surface mining*, ed. B.A. Kennedy, 2nd ed., 692–705. Littleton: SME.

Ericsson, M. 2012. Mining technology—trends and development, Polinares consortium journal, working paper # 29.

Gorain B.K. 2016. A vision for continuous mining integrated with processing. In 28th International Mineral Processing Congress 2016 in Québec City.

International Mining Journal. 2019. https://im-mining.com/tag/cortez.

Isokangas, E. 2012. Using smarttag to track ore in process integration and optimization: some case studies in a variety of applications. The Southern African Institute of Mining and Metallurgy Platinum.

Johnson Marc. 2014. Impact of in-pit crushing and conveying on pit shell optimization. D CONVEYING Deswik.

Klein, B., W.S. Dunbar, and M. Scoble. 2002. Integrating mining and mineral processing for advanced mining systems. *CIM Bulletin* 95 (1057): 63–68.

Koehler, F. 2010. In-pit crushing looms the way into Australia. In *Mining magazine congress*.

Lazar, C., R. Pintea, and R. de Keyser. 2007. Nonlinear predictive control of a pH process. In *17th European symposium on computer aided process engineering*, Vol. 24, 829–834.

Lynch, M., and B. White. 2013. Brave new world autonomous mining systems. In *Proceedings world gold 2013*, 157–166. Brisbane: The Australasian Institute of Mining and Metallurgy.

Lynch, A.J., G.J. Harbort, and M.G. Nelson. 2010. *History of flotation*. Melbourne: AusIMM.

Makhado, V.G., and D. Sagara. 2017. Implementation of an advanced thickener underflow density control at LOULO gold mine, MALI.

Metso. 2018. www.metso.com.

Powell, M. 2013. Utilising orebody knowledge to improve comminution circuit design and energy utilization. In 2nd AusIMM International Geometallurgical Conference, Brisbane, 30 September to 2nd October.

Radlowski, J.K. 1988. In-pit crushing and conveying as an alternative to an all truck system in open pit mines. The University of British Columbia.

Sandvik Mining and Construction. 2007. Bulk materials handling in mining [Report].

Stange, W. 1999. The process design of gold leaching and carbon-in-pulp circuits. *Journal of the South* 99: 13–25.

Szalanski Scot. 2009. Optimizing in-pit crusher conveyor performance: P&H Mining Equipment.

Vergne, J.N. de la. 2017. Hard rock Miner’s handbook, ed. S.L. Anderse. Alberta: Stantec Consulting.

Vogt, D. 2016. A review of rock cutting for underground mining: past, present and future. *The Journal of South African Institute for Mining and Metallurgy* 116: 1011–1026.

Wortley, M., E. Nozawa, and K.J. Riihioja. 2011. Metso SmartTag the next generation and beyond. In *35th APCOM symposium,* Wollongong, NSW.