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Conveyor Technology: Designing for the future by innovating the present

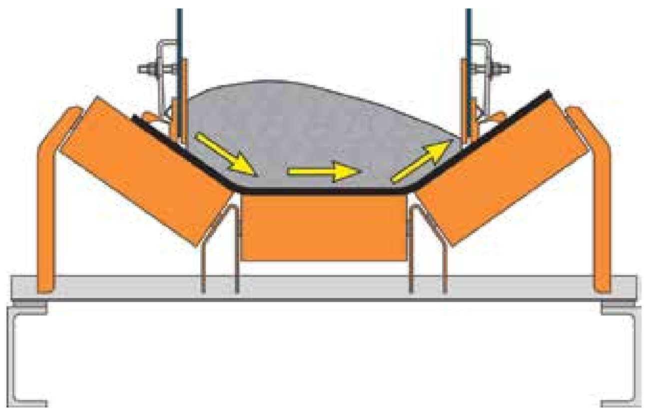
Higher production demands across all bulk handling segments require increased efficiency at the lowest cost of operation, in the safest and most effective manner possible. As conveyor systems become wider, faster and longer, more energy output and more controlled throughput will be needed. Add an increasingly stringent regulatory environment, and cost-conscious plant managers must closely review which new equipment and design options align with their long-term goals for the best return on investment (ROI).

SAFETY AT HIGHER BELT SPEEDS

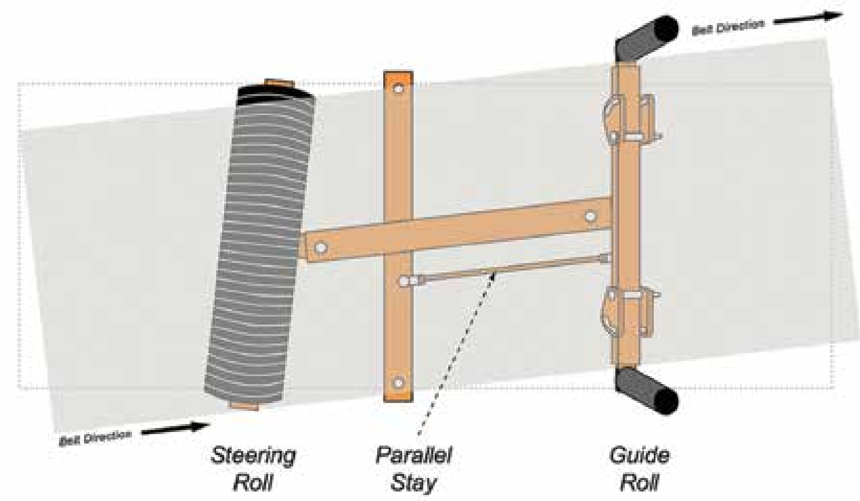
Safety is likely to become a new source of cost reduction. The percentage of mines and processing facilities with a robust safety culture are likely to increase over the next 30 years to the point where it is the norm, not the exception. In most cases, with only a marginal adjustment to the belt speed, operators quickly discover unanticipated problems in existing equipment and workplace safety. These problems are commonly indicated by a larger volume of spillage, increased dust emissions, belt misalignment and more frequent equipment wear/failures.

Higher volumes of cargo on the belt can produce more spillage and fugitive material around the system, which can pose a tripping hazard. According to the US Occupational Safety and Health Administration (OSHA), slips, trips and falls account for 15% of all workplace deaths and 25% of all workplace injury claims[1]. Moreover, higher belt speeds make pinch and sheer points in the conveyor more dangerous, as reaction times are drastically reduced when a worker gets clothing, a tool or a limb caught from incidental contact[2].

The faster the belt, the quicker it can wander off its path and the harder it is for a belt tracker to compensate, leading to spillage along the entire belt path. Caused by uncentered cargo, seized idlers or other reasons, the belt can rapidly come in contact with the mainframe, shredding the edge and potentially causing a friction fire. Beyond the workplace safety consequences, the belt can convey a fire throughout the facility at extremely high speed.



When a conveyor isn't center-loaded, the cargo weight pushes the belt toward the more lightly-loaded side.



Another workplace hazard – one that is becoming progressively more regulated – is dust emissions. An increase in the volume of cargo means greater weight at higher belt speeds, causing more vibration on the system and leading to reduced air quality from dust. In addition, cleaning blade efficiency tends to decline as volumes rise, causing more fugitive emissions during the belt's return. Abrasive particulates can foul rolling components and cause them to seize, raising the possibility of a friction fire and increasing maintenance costs and downtime. Further, lower air quality can result in fines and forced stoppages by inspectors.

CORRECTING MISALIGNMENT BEFORE IT HAPPENS

As belts get longer and faster, modern tracking technology becomes mandatory, with the ability to detect slight variations in the belt's trajectory and quickly compensate before the weight, speed and force of the drift can overcome the tracker. Typically mounted on the return and carry sides every 70 to 150 feet (21 to 50 m) – prior to the discharge pulley on the carry side and the tail pulley on the return – new upper and lower trackers utilise innovative multiple-pivot, torque-multiplying technology with a sensing arm assembly that detects slight variations in the belt path and immediately adjusts a single flat rubber idler to bring the belt back into alignment.

MODERN CHUTE DESIGN

To drive down the cost per ton of conveyed material, many industries are moving toward wider and faster conveyors. The traditional troughed design will likely remain a standard. But with the push toward wider and higher-speed belts, bulk handlers will need substantial development in more reliable components, such as idlers, impact beds and chutes.

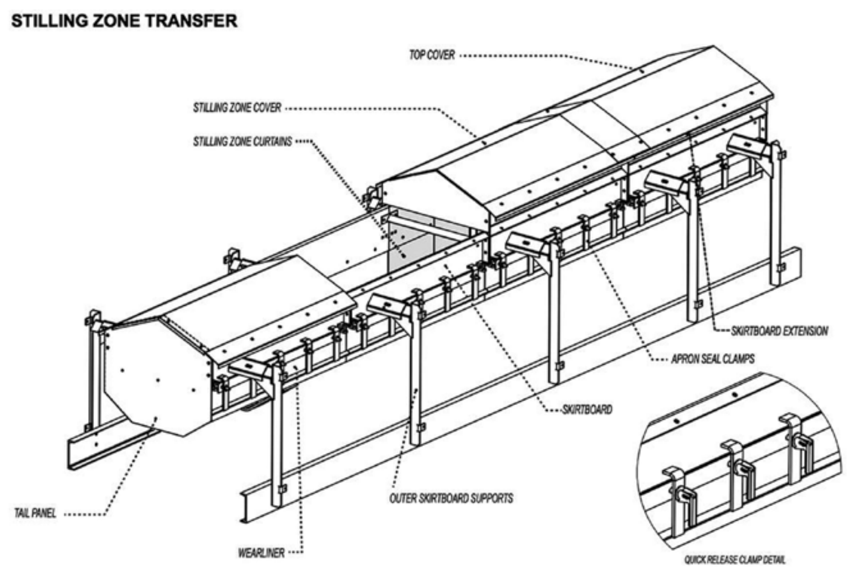
A major issue with most standard chute designs is that they are not engineered to manage escalating production demands. Bulk material unloading from a transfer chute onto a fast-moving belt can shift the flow of material in the chute, resulting in off-center loading, increasing fugitive material spillage and emitting dust well after leaving the settling zone.

Newer transfer chute designs aid in centering material onto the belt in a well-sealed environment that maximises throughput, limits spillage, reduces fugitive dust and minimises common workplace injury hazards. Rather than material falling with high impact directly onto the belt, the cargo's descent is controlled to promote belt health and extend the life of the impact bed and idlers by limiting the force of the cargo at the loading zone. Reduced turbulence is easier on the wear liner and skirting and lowers the chance of fugitive material being caught between the skirt and belt, which can cause friction damage and belt fraying.

Longer and taller than previous designs, modular stilling zones allow cargo time to settle, providing more space and time for air to slow down, so dust settles more completely. Modular designs easily accommodate future capacity modifications. An external wear liner can be changed from outside of the chute, rather than requiring dangerous chute entry as in previous designs. Chute covers with internal dust curtains control airflow down the length of the chute, allowing dust to agglomerate on the curtains and eventually fall back onto the belt in larger clumps. And dual skirt sealing systems have a primary and secondary seal in a two-sided elastomer strip that helps prevent spillage and dust from escaping from the sides of the chute.

RETHINKING BELT CLEANING

Faster belt speeds can also cause higher operating temperatures and increased degradation of cleaner blades. Larger volumes of cargo approaching at a high velocity hit



Modern stilling zones feature components designed to reduce maintenance and improve safety.

primary blades with greater force, causing some designs to wear quickly and leading to more carryback and increased spillage and dust. In an attempt to compensate for lower equipment life, manufacturers may reduce the cost of belt cleaners, but this is an unsustainable solution that doesn't eliminate the additional downtime associated with cleaner servicing and regular blade changes.

As some blade manufacturers struggle to keep up with changing production demands, industry leaders in conveyor solutions have reinvented the cleaner industry by offering heavy-duty engineered polyurethane blades made to order and cut onsite to ensure the freshest and longest lasting product. Using a twist, spring or pneumatic tensioner, the primary cleaners are forgiving to the belt and splice but are still highly effective for dislodging carryback. For the heaviest applications, one primary cleaner design features a matrix of tungsten carbide scrapers installed diagonally to form a 3-dimensional curve around the head pulley. Field service has determined that it typically delivers up to 4x the service life of urethane primary cleaners, without ever needing re-tensioning.

Taking belt cleaner technology into the future, an automated system increases blade life and belt health by removing blade contact with the belt any time the conveyor is running empty. Connected to a compressed air system, pneumatic tensioners are equipped with sensors that detect when the belt no longer has cargo and automatically backs the blade away, minimizing unnecessary wear to both the belt and cleaner. Additionally, it reduces labor for the constant monitoring and tensioning of blades to ensure peak performance. The result is consistently correct blade tension, reliable cleaning performance and longer blade life, all managed without operator intervention.

POWER GENERATION

Systems designed to operate at high speeds over considerable distances are generally powered only at vital locations such as the head pulley, disregarding adequate power for autonomous 'smart systems,' sensors, lights, accessories or other devices along the length of the conveyor. Running auxiliary power can be complicated and costly, requiring transformers, conduits, junction boxes and oversized cables to accommodate the inevitable voltage drop over long runs. Solar and wind can be unreliable in some environments, particularly in mines, so operators require alternative means of reliable power generation.

By attaching a patented mini-generator to idlers and using the kinetic energy created by the moving belt, the accessibility obstacles found in powering ancillary systems can now be overcome. Designed to be self-contained power stations that are retrofitted onto existing idler support structures, these generators can be employed on virtually any steel roller.

The design employs a magnetic coupling that attaches a "drive dog" to the end of an existing roller, matching the outside diameter. Rotated by the movement of the belt, the drive dog engages the generator through the outer housing's machined drive tabs. The magnetic attachment ensures that electrical or mechanical overload does not force the roll to stop; instead, the magnets disengage from

A single Roll Generator has enough power output to run a variety of accessories.

the roll face. By placing the generator outside the material path, the innovative new design avoids the damaging effects of heavy loads and fugitive material.

BULK HANDLING, SAFETY AND AUTOMATION IN THE FUTURE

Automation is the way of the future, but as experienced maintenance personnel retire, younger workers entering the market will face unique challenges, with safety and maintenance skills becoming more sophisticated and essential. While still requiring basic mechanical knowledge, new maintenance personnel will also need more advanced technical understanding. This division of work requirements will make it difficult to find people with multiple skill sets, driving operators to outsource some specialised service and making maintenance contracts more common.

Conveyor monitoring tied to safety and predictive maintenance will become increasingly reliable and widespread, allowing conveyors to autonomously operate and predict maintenance needs. Eventually, specialised autonomous agents (robots, drones, etc.) will take over some of the dangerous tasks, particularly in underground mining as the ROI for safety provides additional justification.

Ultimately, moving large quantities of bulk materials inexpensively and safely will result in the development of many new and higher capacity semi-automated bulk transfer sites. Previously fed by truck, train or barge, long overland conveyors transporting materials from the mine or quarry site to storage or processing facilities may even impact the transportation sector. Stretching vast distances, these long bulk handling networks have already been built in some places with low accessibility but may soon be commonplace in many areas around the world.

REFERENCES

1. "Slips, Trips & Falls Identification and Prevention;" Occupational Safety and Health Administration; Sacramento, CA 2007. https://www.osha.gov/dte/grant_materials/fy07/sh-16625-07/slipstripsfalls.ppt
2. Swinderman, Todd; Marti, Andrew D.; Marshall, Daniel: "Foundations for Conveyor Safety;" Martin Engineering, Section 1, pg. 14. Worzalla Publishing Company, Stevens Point, WI 2016. https://www.martin-eng.com/content/product/690/safety-book

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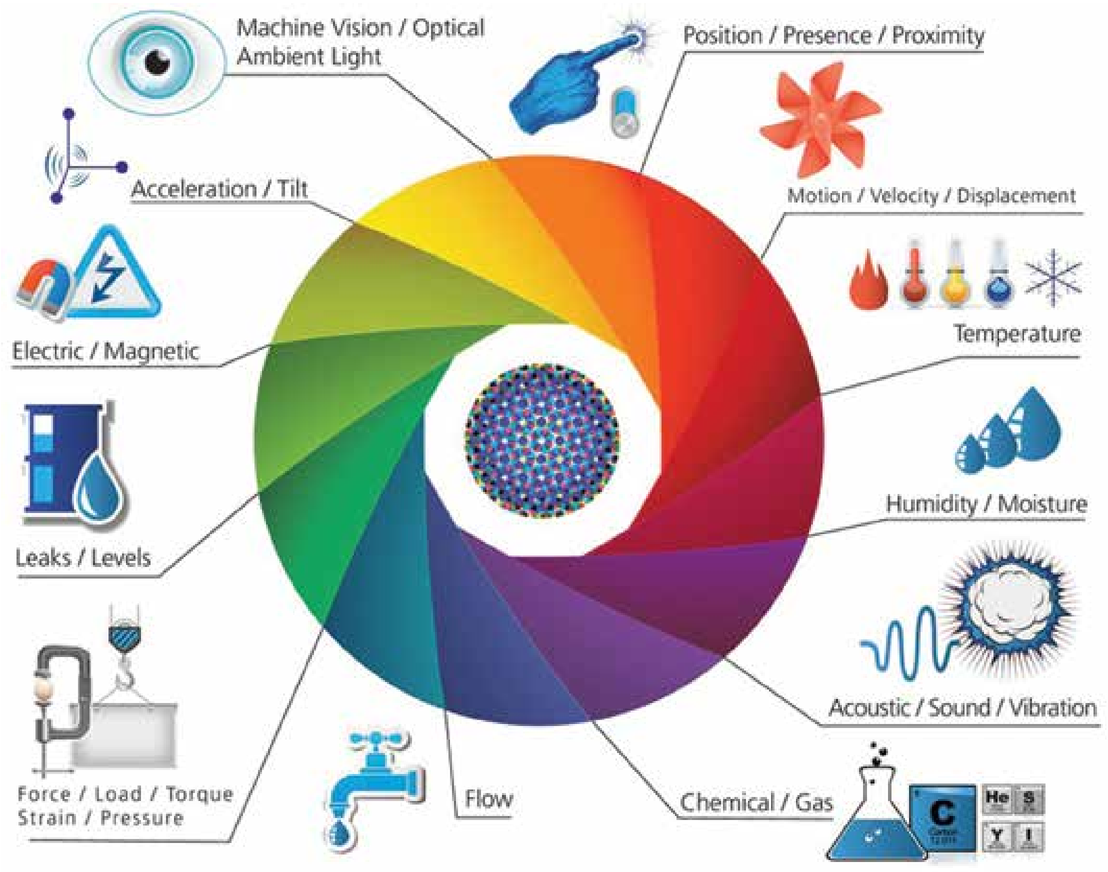
SIGNALS COMMUNICATION AND MONITORING

Communication of sensor data in underground mining environments: an evaluation of wireless signal quality over distance



The technologies of the fourth industrial revolution have the potential to make zero harm possible for the first time in the history of mining. In the journey toward zero harm, rock stress monitoring systems are important for the risk management process. Although communication systems for underground mining have improved significantly over the past two decades, it remains difficult to achieve reliable-all-the-time wireless communication in ultra-deep level underground mines. The aim of this study is to explore and test a smart phone network for communicating sensor data from the underground production environment to the surface. In this paper, the evaluation and performance over distance of a wireless communication system is performed in underground mining environments. The wireless system transmits the data collected from a sensor installed in a narrow reef stope, horizontal tunnel, and vertical shaft area of a mock underground mine. The evaluation was performed using the received signal strength of a mobile receiver over distance. The path loss coefficients of the underground mining environment were then derived for the measurement areas. The results show that a communication speed of 80 Mbps was achieved in a 60 m range, thus, indicating the potential for the support of applications requiring higher data rates.

The advances in mobile computing and hardware designs have enabled the deployment of more efficient functionalities on mobile devices while these devices have become smaller and compact. In underground mining environments, the low rate of mobile device usage is mainly caused by strict safety regulations. Currently, several wired[1,2] and wireless communication technologies are available that satisfy the minimum required criteria for the data broadcast speed and range to support remote mining operations and advanced monitoring systems.

The main advantage of wireless communications is mobility within a closed space. In underground mines, wireless technologies can be used to support the mobility of humans and machines in dangerous working areas. In those areas, conventional cable communication can be easily damaged by heavy machinery and may not advance quickly enough with the required expansion of working areas.

As a result, wireless sensor networks (WSNs) have become useful for measuring and monitoring important data, such as in situ stress and strain, air quality, and data from machines in underground mines. Long term in situ stress and strain monitoring systems are necessary to observe the rock conditions in mining excavations. While numerical modelling methods can provide a faster approach, actual measurements from sensors installed around the areas of interest can provide more accurate stress and strain measurements of the surrounding rock.

These measurements can be more valuable if an efficient communication system is present at the working areas and can deliver the data over long distances to important decision making locations, such as the central processing office, which is usually located at the surface. Before communication technologies can be deployed in situ in underground mining environments, extensive measurement campaigns in safe test-bed environments are necessary to estimate the performance of such technology under harsh conditions.

The measured data have shown to be useful in applications such as optimised network design, file download efficiency, user and machine localisation, and positioning. In order to successfully develop these algorithms, the path loss properties of the wireless signals, such as the received signal strength indicator (RSSI), are collected from test environments and used to train the algorithms offline. The trained models can then be used for actual navigation and the determination of the users' positions in realistic scenarios using existing algorithms, such as the k-nearest neighbour (KNN) or triangulation.

Such methods can also be adopted in underground mining environments and will require extensive RSSI measurements in order to understand the effects of different geometries on direct WiFi signals. In scenarios where the data are required to be transferred over long distances, such as to a surface office for further processing, the effect of deep fading is mitigated by simply re-transmitting the signal over a distance where the signal can be received, decoded, and re-transmitted reliably. Hence, adequate knowledge of the propagation properties, such as the received signal strength (RSS) can inform the placement and deployment of transmitter-receiver pairs in the mine in order to achieve reliable data hops to the destination.

In this paper, the practical integration of a multi-sensor, cell monitoring system with a low-complexity WiFi communication system is evaluated in a narrow tunnel, narrow-reef stope, and vertical shaft of an underground mining environment. The data from the sensor is transmitted directly to a mobile phone receiver that is in the transmitter's line-of-sight (LOS) and non line-of-sight (NLOS). The RSSI as well as throughput performances are evaluated with respect to the distance and geometry of the environments. Using the RSSI data, the path loss propagation properties of the different measurement areas of the mine are also derived. By conducting physical experiments to measure the performance of WSNs, we evaluate the performance in underground mining environments. The results have the potential to inform the transfer speed and signal quality that can be achieved in real severe environments.

This paper is organised as follows: in the introduction, the concept of a wireless monitoring system and path loss model is discussed, Section 3 introduces the proposed *in situ* stress monitoring system. In Sections 4 and 5, the principle of the experiment, the RSSI Model for WiFi Direct, and the setup of the experiment are described. Sections 6 and 7 conclude the paper, discussing the results and proposing further steps for expanding the experiment.

RELATED WORK

Wireless Sensor Networks

The efficient monitoring of natural events that pose a safety risk to humans in underground mining environments can assist with improving the health and safety conditions in the environment. Such risks can emanate from rock movement due to stress, imbalances in temperature and ventilation, and smoke and air quality issues[3]. Generally, in situ stresses increase with depth as, in shallow coal mines, the rate of increase in horizontal stresses as the depth increases is greater than the rate of increase of vertical stress.

On the other hand, with increasing depth, the rate of increase in horizontal stresses decreases. Therefore, a considerable scatter in the in situ stress test data may be due to distinct differences in both the strength and deformation moduli of strata located in different geological environments and coal districts[4].

In monitoring rock masses in deep underground environments, an extra-deep, multiplepoint borehole extensometer was investigated in an iron-ore mine in eastern Jinshandian. The extensometer was demonstrated to be applicable for up to 300 m depth. The in situ monitoring results collected over eight years were analysed[5].

WSNs in underground environments can assist with measuring events that include, but are not limited to, temperature, dust, smoke, air pressure, air quality, humidity, rock stress, and movements. In[6], a review of WSN applications was performed in which the impact of wireless technology, such as ZigBee, was discussed and evaluated for mine collapse monitoring, the tracking of miners in underground environments, and the support of robots for the collection and delivery of data from areas that are inaccessible to humans.

A direct application to gas monitoring was performed in[7] and fire detection was conducted in[8], where the authors evaluated the fire detection speed in a Bord-and-Pillar coal mine using WSN. Using simulations, the authors proposed a prevention system capable of detecting the location of fire breakouts in seconds as well as the direction of the fire as it spreads.

While the data from sensors in an underground environment can be collected and analysed locally, the work in[9] further discussed the potential of integrating an Internet of Things (IoT) system with the data collected from sensors in underground environments.

Trust models of WSNs security have flourished due to the day-to-day attack challenges, which are most popular for the IoT[10]. Designing a robust IoT network imposes some challenges, such as data trustworthiness (DT) and power management. In[11], a repeated game model was used to enhance clustered WSN-based IoT security and DT against a selective forwarding (SF) attack. However, WSN trust models are not considered in this paper, and more details can be found in[10,12].

Using the IP protocol, the data collected from the sensing layer can be available in real-time and remotely through cloud storage. Security challenges, however, exist in the sensing layer, suggesting the need for robust security protocols to safeguard the end-to-end delivery of the data. The transmission of the collected data to the remote cloud can suffer from high latency when using current communication technology. By bringing the server relatively closer to the miner, mobile edge computing (MEC) is a promising distributed computation architecture to seize the opportunity of enabling low-cost, and low-latency data collection. These issues are covered in detail in[13,14].

In the event of a mine disaster, traditional communication networks can potentially be damaged and disrupted, affecting the ability of mine to understand the underground environment's conditions. This influences the quality and speed of decisions due to the disruption of real-time information required for mitigating the effect of any problems that may occur underground. Therefore, ZigBee and geographic information systems (GIS) technologies have been suggested to provide more effective communication systems[15,16].

Moridi et al. investigated various sensor node arrangements of ZigBee networks for underground space monitoring and communication systems[17]. The proposed system integration considering WSNs enables GIS to better monitor and control underground mining applications from the surface office.

Based on the capabilities of WSNs in the study, the ZigBee network was considered applicable for near real-time monitoring, ventilation system control, and emergency communication in an underground mine. The outcomes of such application provide promising, suitable network performance in such environments. Moreover, experimental measurements of ZigBee radio waves attenuation were validated by simulation results[18] for underground mines.

The outcome of this work shows that WSN can be reliable in deploying low data rate applications in underground mine environments, such as ventilation fan remote control, text messaging, and temperature and humidity readings and settings. The system functions of the model were tested and verified in an underground mine in Western Australia[19].

An overview of wired and wireless communication technologies, such as ZigBee, radio frequency (RF), and very low and very high frequency communication in underground mining and tunnel environments, was reviewed in[20]. In particular, the different modelling techniques of RF in underground mines show the different path loss propagation properties of the wireless signals, such as roughness, refraction, and sidewall tilt loss.

From the derived models, it is evident that signal propagation in underground mines is heavily influenced by the topology of the environment, such as the corners in tunnels, the unevenness, and tilting of the walls. Such channel knowledge was shown to be important in the deployment and implementation of underground mine applications for tracking and transceiver designs. An integration of a WSN with optic fibres in[21] was used to deliver the data collected from sensors installed in an underground coal mine to a monitoring centre at the mine surface.

Here, Zhang *et al*. attempted to address the need for safety by proposing a generic, integrated ambient-assisted living system architecture. A mesh network architecture was demonstrated in the WSN such that a cluster head, in the form of a routing node administers connected sensors, played the role of cluster members in the network[21].

Such architecture ensures that a broken sensor or broken link to the cluster head does not break down the entire system, while the cluster head manages dual communication with the surface control center. WSN was also integrated with WiFi in[22]. Here, Tao and Xiaoyang's system showed that WSN-WiFi applications can be used to extend the reach of the WSN system in low to high data rate applications, such as gas monitoring and video surveillance.

Applications of the Path Loss Model

The path loss model[23] for wireless signals can assist with evaluating the RSS of WiFi signals over distance. Other properties describing the fading nature of the signal in the environment, such as shadowing or path loss coefficients, can be determined by direct measurements. These properties not only provide understanding of the effect of the environment on wireless signals but also assist with offline analysis and simulations.

Mobile devices are equipped with RSS functionality. Hence, applications, such as user indoor positioning and navigation[24-31] and battery resource management[32], have emerged. In[24], the localisation accuracy based on RSS was improved by using a priori information obtained from measurements. Introducing the local environment parameters to wireless signal networks enabled better calibration of the WSN.

Aside from the RSSI-based method for fingerprinting and position location, the fine timing measurement (FTM), introduced in IEEE 802.11-2016, uses the properties of the received signal between mobile phone sensors, such as the arrival time and delay, for positioning. Hence, in[25], a comparison of the FTM technology with RSSI-based indoor positioning over a 2.4 GHz wireless system under realistic scenarios was performed.

The IEEE 802.11-2016 introduced FTM, which uses received signal properties, such as the arrival time and delay, for positioning with mobile phone sensors. Using the least squares (LS) method in a given radius, the position of the user in an indoor environment, transmitting over a 2.4 GHz channel is estimated, with the results showing that FTM improves the positioning when compared with the RSSI method. The statistical processing of RSSI measurements can also be used to process RSSI fingerprint data in order to improve the accuracy and reduce the complexity by reducing the amount of data required during offline processing.

In[27], a comparison of the accuracy of machine learning algorithms, such as KNN, singular value decomposition (SVM), and decision tree models, was used to classify finger-printing data used for indoor positioning. The classification enabled offline localisation using predictive measures during offline processing.

In[28], a hybrid of a KNN algorithm and particle filtering algorithm[29] was adopted to improve the positioning accuracy of a robot in an indoor environment. The effect of Bluetooth interference with the wireless signals on the positioning accuracy was also investigated in[30]. This was performed by comparing the statistical approaches, such as the Weibull distribution and the probability of occurrence of an observed RSSI measurement.

Studies investigating the propagation of wireless signals in the underground tunnel coal mines go as far back as the work in[33] done in 1975. In this work, the effect of the geometry of the walls and corners were evaluated over high frequency radio waves in the MHz range. Since then, several works have studied the propagation models of wireless signals over higher frequencies.

The propagation properties of 900 MHz radio signals were measured in[34] for longwall underground coal mines. In, the delay, impulse response, and power profiles of signals received over 2.4 and 5.8 GHz frequencies were reported for an underground mining environment.

The measurements for LOS and NLOS scenarios show the fading characteristics as Rice and Rayleigh distributions, respectively. In underground environments, an adaptive fingerprinting technique, using RSSI data obtained from measurements, was used to improve the localisation of users in[26].

IN SITU STRESS MONITORING SYSTEM

In this study, in situ stress is used as input data. The input data will be sent to the surface and data centre via the proposed communication system, which will be further available in the cloud. The proposed data transfer system design is shown in **Figure 1**.

A data logger installed inside an underground mine senses in situ stress, enabling it to be transferred to a mobile device owned by a nearby miner[36]. Such data can then be sent to another miner's mobile phone using WiFi Direct. In order to develop a differential in situ stress or strain monitoring system,

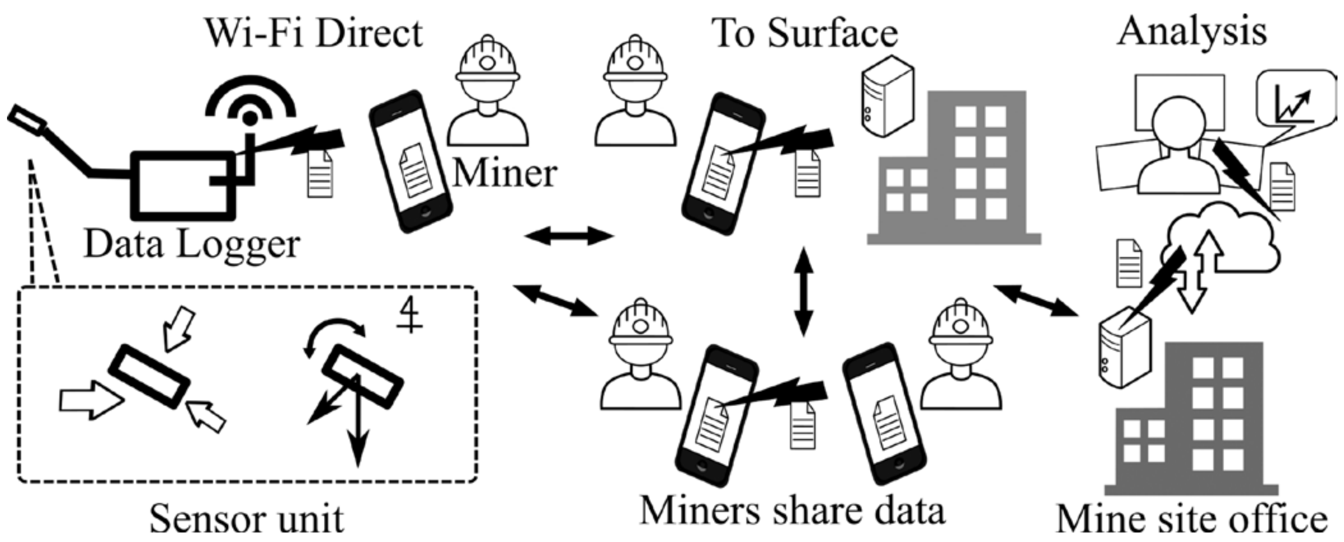


Figure 1: The data transmission monitoring system design.

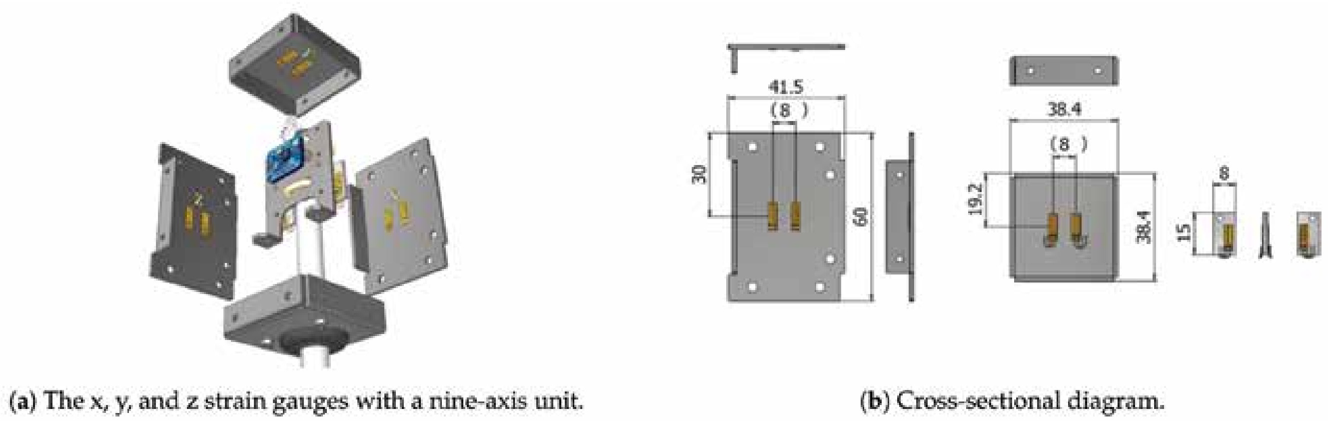


Figure 2: Sensor unit.

it is necessary to find a suitable device in the market or to develop a measurement unit (sensing), fulfilling the needs of the experiment, in addition to the communication unit.

The sensor unit, developed by[37] can be installed by drilling a hole into the support system of an underground mine with a 60 φ drill-bit. The computer-aided diagram of the sensor unit is shown in **Figure 2**. In **Figure 2a**, **b** the blue-coloured unit, installed close to the centre of the device, is the sensing unit. In addition to a pair of strain gauges attached on the X, Y and Z surface, a nine-axis sensor (LSM9DS1) is installed to detect the orientation of the sensor unit during installation.

Within the sensor unit, each sensor has its advantages and disadvantages. Each sensor's disadvantages are mutually complemented by its advantages to improve the accuracy of three-dimensional (3D) orientation estimation. Since the stresses measured by the strain gauges are relative to the rock surface, the magnitude and direction of the stresses inside the rock mass are clarified by combining the results of the attitude detection.

The strain gauges are placed according to the 3D coordinate system (X, Y, Z). The relationship between the strain and stress is determined from the load and displacement of the sensor unit (in situ stress). This can be determined by material testing and the values of the strain gauges. In addition, the in situ differential stress is obtained from the strain applied to the sensor unit in the underground mine.

A load response test was conducted, using Marui's manual uniaxial compression testing machine (the rated capacity of the load cell is 20 tf) to apply a load to the sensor unit. The load was varied in increments of 50 kgf, and the load-displacement curve (between elastic deformation), the strain, acceleration, angular velocity, and geomagnetism of the sensor unit were collected as the measurement data. The displacements from different load values and strain in the experiments are shown in **Figure 3**.

The sampling frequency was set to 1 Hz, and the data were transmitted to the receiver via ad hoc communication (WiFi Direct). In the material test, the load was applied up to 5 MPa in terms of stress. By following the steps above, the possibility of the in situ stress measurement in underground mine via WSN is shown. In situ stress and displacement in the underground mine requires attitude and stress detection of the sensor unit. This enables us to identify the direction and the degree of stress in the underground mine. In **Figure 4**, a complete system with integrated the wireless transmitter with the data logger is shown.

RECEIVED SIGNAL STRENGTH INDICATOR MODEL FOR WIFI DIRECT

Tunnels in underground mines typically have rough and irregular wall surfaces. The irregularities of the walls influence the scattering, fading, and delay properties of a 2.4 GHz WiFi signal's propagation. Consider a setup in which a mobile phone is placed at w meters (m) from a

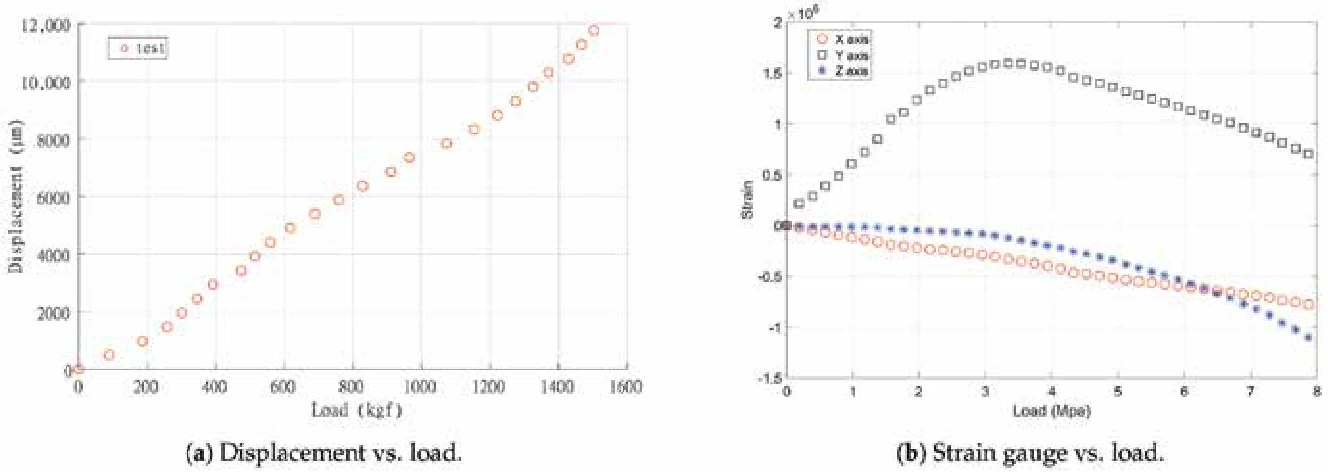


Figure 3:. Sensor unit load experiments.

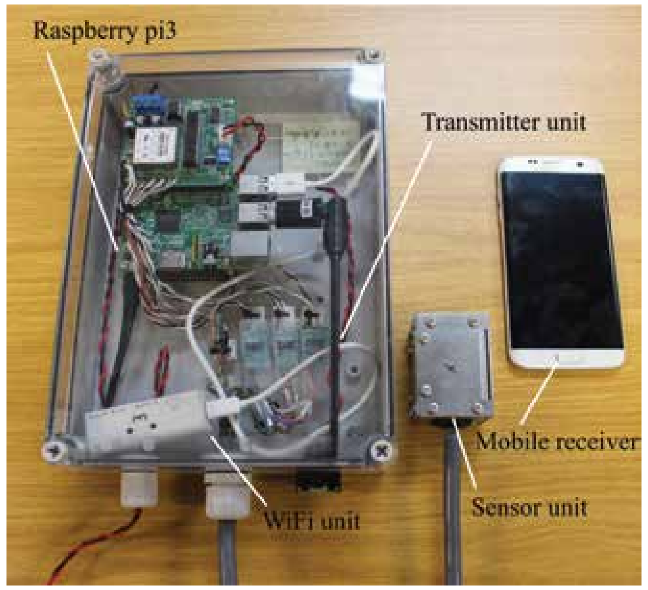


Figure 4: Sensor unit with a WiFi transmitter unit and mobile phone receiver.

datalogger, placed at a reference position w0. The path loss, which follows the normal distribution, is expressed as

Equation 1

$$PL_{dB}(w) = \bar{PL}_{dB}(w_0) + 10\eta \log_{10}\left(\frac{w}{w_0}\right) + N,$$

in decibels (dB) is used, assuming the antennas used at the transmitter and receiver have unity gain. The average path loss PLdB(w0) is measured at the reference position w0, η is a constant that describes the path loss exponent, and N is modelled as Gaussian noise samples having a zero mean and a standard deviation σN. From the measured values of PLdB(w), the values of η and N can be approximately obtained using the LS regression method for curve-fitting.

EXPERIMENTAL SETUP

The data collected by the sensor unit is transmitted over a WRH-300WH3-S WiFi module through a Raspberry Pi 3 module. The WRH-300WH3-S unit implements the IEEE 802.11n standard, with a power consumption of 2.4 W. The WiFi receiver is an android operating system mobile device. Measurements are then carried out in a model underground mock mine.

The mine contains a part representing a vertical shaft, tunnel, and narrow-reef stope with the corresponding cross-sections shown in **Figure 5**. The dimensions of the measurement areas are defined as (w, b, h), where w is the width, b is the length, and h is the height in meters (m). The position of an object in the measurement areas is described as (x, y, z) in meters, where x is the horizontal position of the object along the width w, y is the horizontal

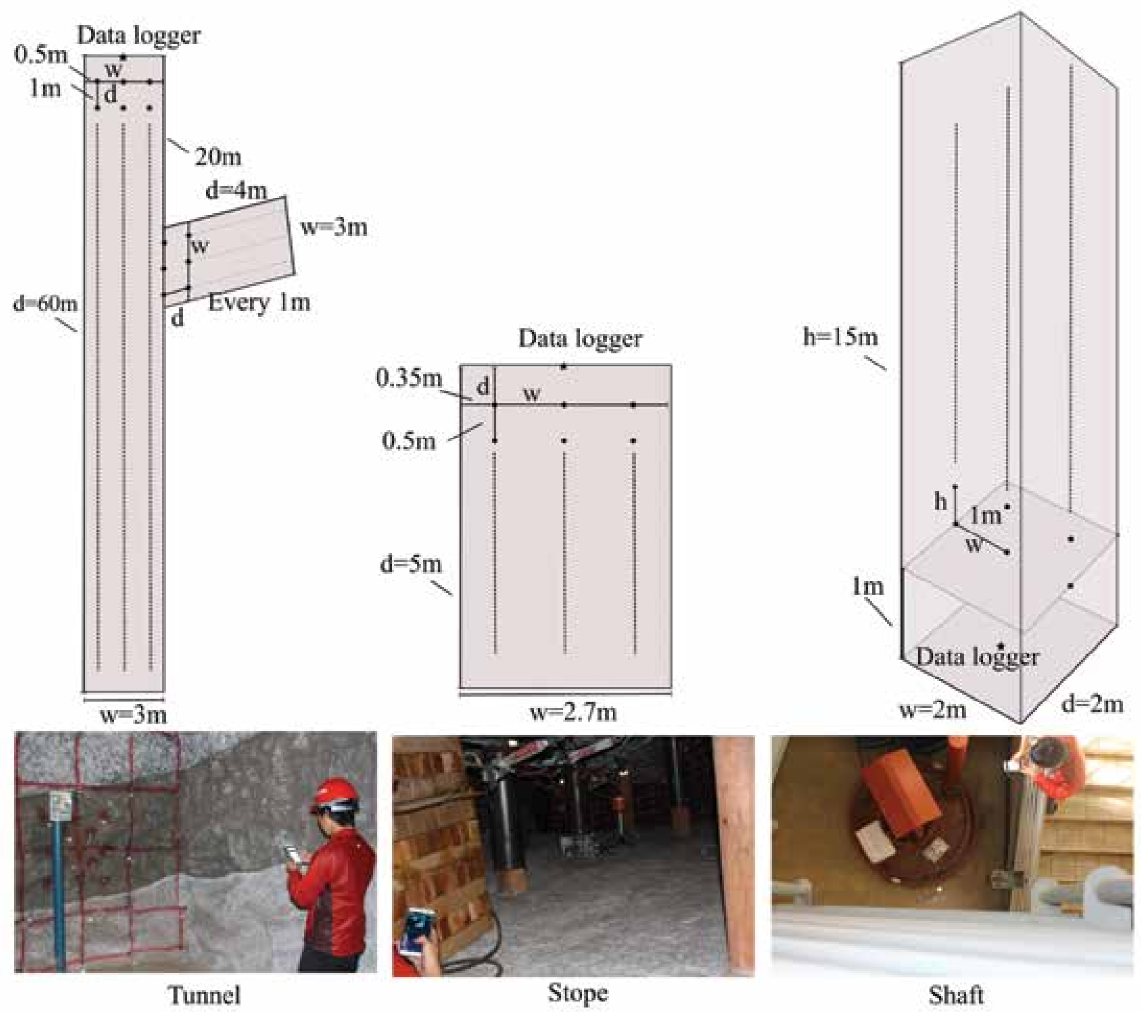


Figure 5: Cross-sectional diagram of the tunnel, stope, and shaft.

position along the length b, and z is the vertical position of the object along the height h. The dimensions of the tunnel, stope, and shaft are given in **Table 1**.

In the tunnel that has a height of 3 m, the sensor along with the transmitter are mounted on a pole and positioned at three different positions, namely (0.5, 0, 1), (1.5, 0, 1), and (2.5, 0, 1). The RSSI is then measured by centering the mobile receiver at position (1.5, y, 1), where y = 1, 2, 3, ... , 60 m along the tunnel. In the stope, which is 1 m high, the transmitter is positioned at positions (0.35, 0, 0.5), (1.35, 0, 0.5), and (2.35, 0, 0.5), while the transmitter is placed at the floor of the shaft in positions (0, 1, 0), (1, 1, 0), and (2, 1, 0). The receiver is placed at positions (1.35, y, 0.5), y = 0.5, 1.0, 1.5, ... , 5 m and (1, 1, z), z = 1, 2, 3, ... , 15 m, respectively.

Table 1: Dimensions of the experimental environments.

	Tunnel (m)	Stope (m)	Shaft (m)
w	3	2.7	2
b	60	5	2
h	3	1	15

RESULTS AND DISCUSSIONS

Measurements are retrieved in the tunnel, stope and shaft of the mock-up mine testbed in order to evaluate the RSSI and throughput performance in terms of speed of the WiFi signals over distance. The throughput is the ratio between a size (in megabytes) of a transmitted file and the amount of time (in seconds) that it takes the receiver to download the file. Using the measurements and (1), **Table 2** shows the path loss coefficients as well as the corresponding variance σN of N. The path loss coefficients of the tunnel and shaft are lower than the free space path loss of η = 2. However, the path loss coefficient of the stope is higher. The stope is narrower and also attenuates signals faster when compared to the tunnel and shaft, according to the **Figures 6a**, **7a** and **8a**.

The RSSI over distance is also visualised using heat maps. The colours range from dark blue to dark red, which depicts weak signal strength to strong signal strength, respectively.

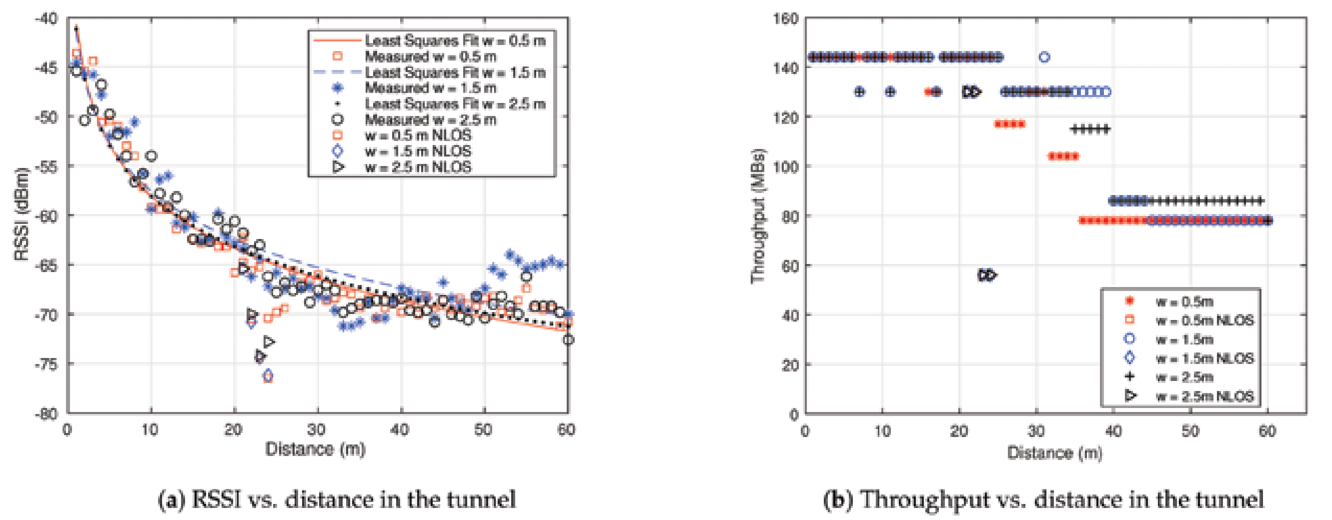
It is presumed that there is no other radio-emitting equipment in the measurement areas while measurements were taken.

The graph in **Figure 7a** shows the sharp decrease in the RSSI values in the stope as compared to the RSSI values in the tunnel and shaft. The stope, however, has stronger RSSI values closer to the transmitter, which can be attributed to constructive reflections due to the more confined area. The tunnel and stope showed different RSSI values at the same distance, and the difference can be attributed to the horizontal measurement of signal propagation in the tunnel and vertical measurements in the shaft.

As observed in **Figure 9a**, **b**, the RSSI values of the transmitter positioned at the edges of the measurement areas show stronger received signal power as the receiver moves away from the transmitter. This is in comparison with the transmitter positioned at the centre of the measurement areas. Furthermore, some regions, such as 54-59 m in the tunnel, show stronger RSSI values compared with the 30-

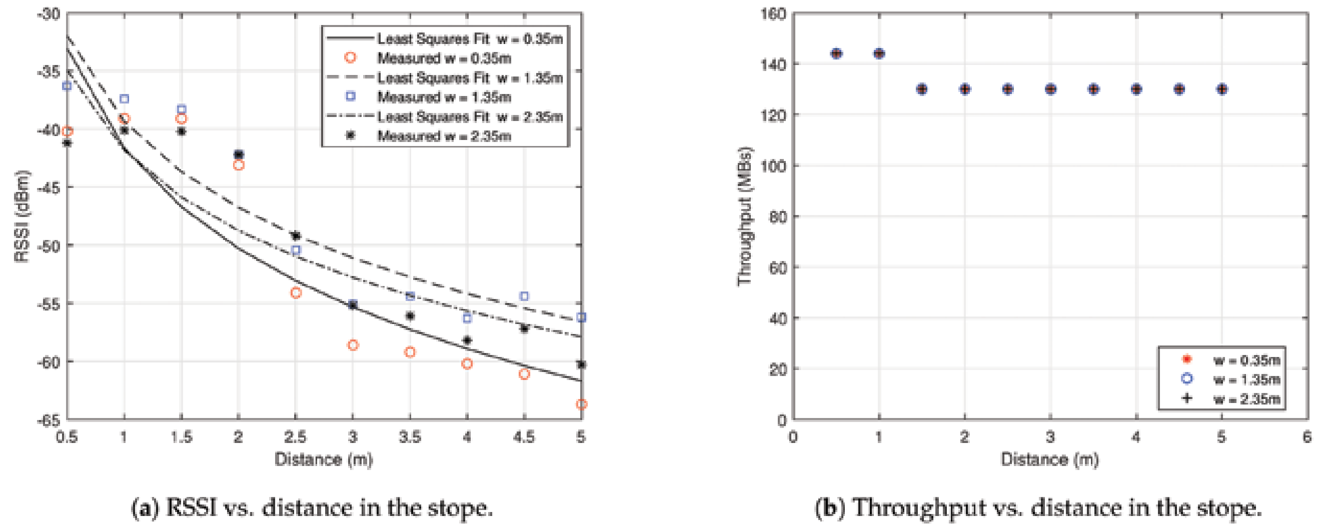
Table 2: Dimensions of experimental environments.

	Path Loss Coefficient (η)			Variance (σN)		
	ω1	ω2	ω3	ω1	ω2	ω3
Tunnel	1.745	1.618	1.692	2.5597	3.9103	2.6163
Stope	2.865	2.461	2.295	7.7357	5.5932	6.7104
Shaft	1.669	1.776	1.463	3.9315	3.4931	4.4972



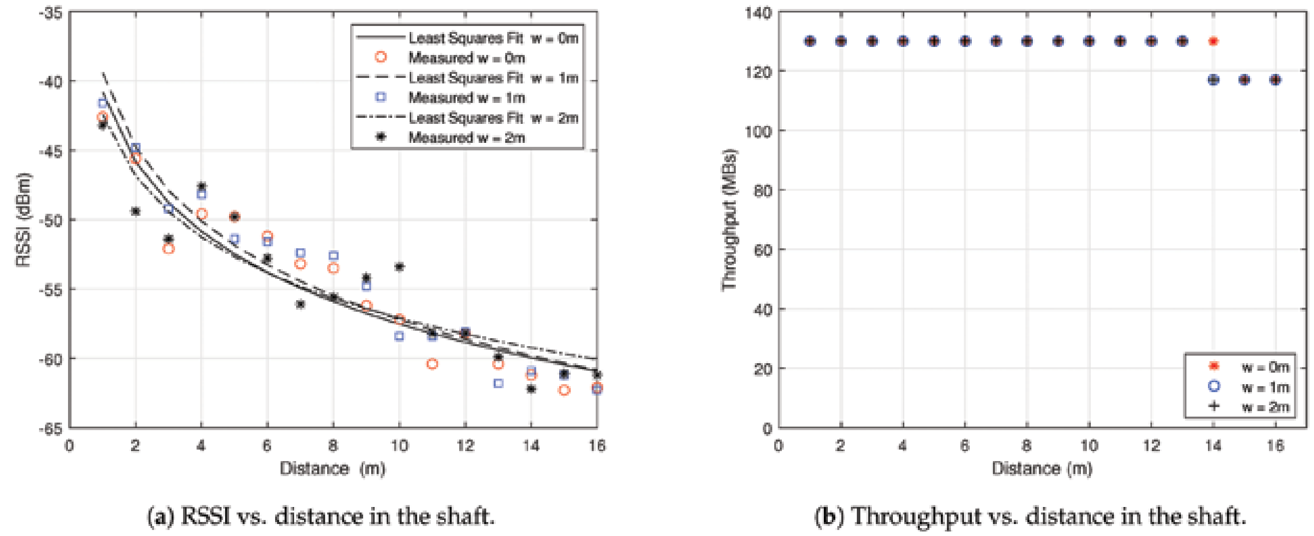
(a) RSSI vs. distance in the tunnel (b) Throughput vs. distance in the tunnel

Figure 6: RSSI and throughput obtained at distance points in the tunnel.



(a) RSSI vs. distance in the stope. (b) Throughput vs. distance in the stope.

Figure 7: RSSI and throughput obtained at distance points in the stope.



(a) RSSI vs. distance in the shaft. (b) Throughput vs. distance in the shaft.

Figure 8: RSSI and throughput obtained at distance points in the shaft.

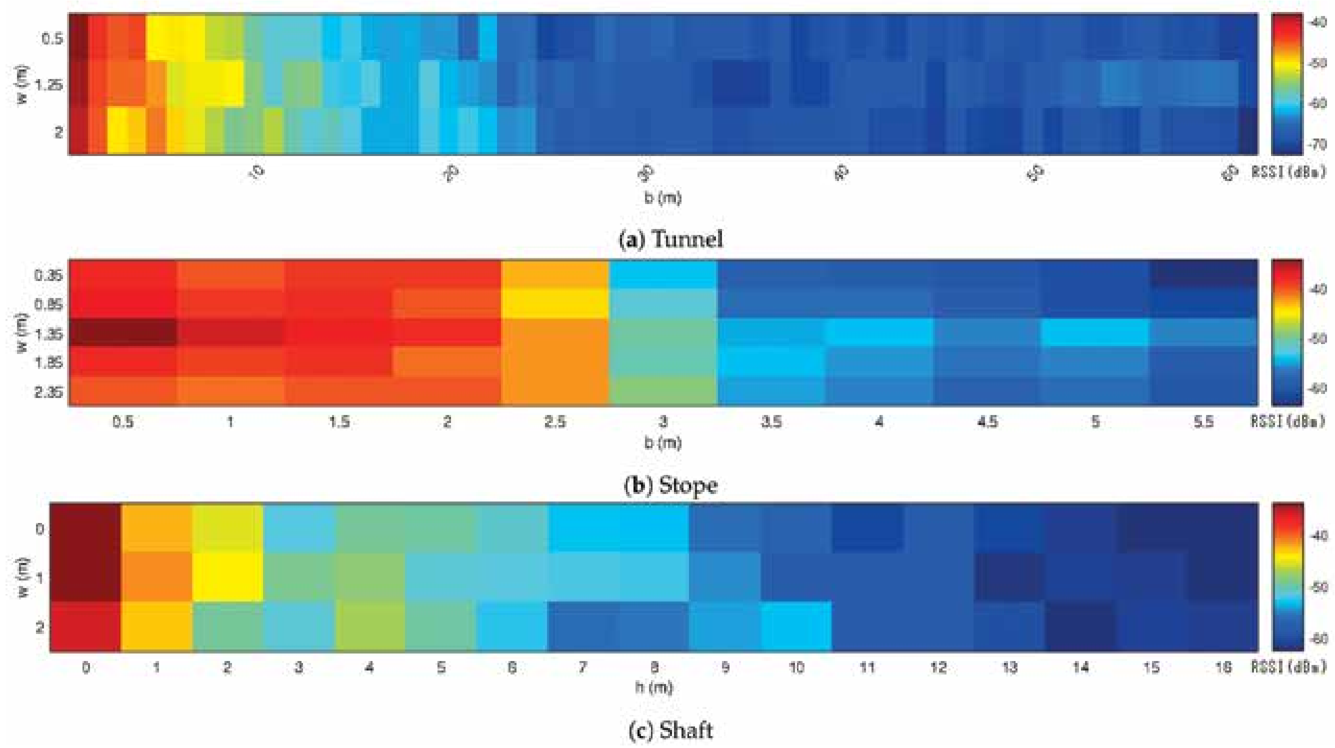


Figure 9: Heat maps visualisation of the RSSI values.

SIGNALS COMMUNICATION AND MONITORING

40 m shorter distance. Since the 54-59 m region is closer to the end of the tunnel, which contains steel gates, higher RSSI values in this region may be attributed to multipath reflections in that region.

The heat maps in Figure 9a-c show more detailed RSSI distributions across the width of the measurement areas. The transmitter was placed in the centre of the width w of the measurement area, and the RSSI values are obtained along the w axis every 0.5 m in the tunnel, 1 m in the shaft and 0.35 m in the stope. The throughput was measured in terms of bits transmitted per second or bits per second (bps).

In **Figures 6b**, **7b** and **8b**, the throughput drops gradually with distance in most regions, although a sharp drop was observed in some regions in the tunnel. The same throughput of 130 Mbps was observed in all the measurement points in the stope.

Figure 7b showed that high throughput was achievable at lower RSSI values in the stope due to the small area, while the throughput dropped to about half from 63 dBm in the tunnel. Therefore, reliable speed was guaranteed in stope environments to transmit data out of the stope to the next available communication link. Overall, an Mbps communication speed over 60 m was sufficient to communicate important sensor data in real-time. The RSSI values remained above the recommended limit of 80 dBm in all the measurement areas considered.

CONCLUSIONS

In the near future, underground mines will become deeper and more complex in structure. This necessitates the continuous improvement of worker safety and productivity. One area in which improvements can be made is in communication systems, which are crucial for the safe operation of underground mines, preventing potential accidents and losses from occurring.

Reliable communication is also an important pre-requirement for mechanisation and enabler for automation. There is a significant recent body of research on WSN because of its added-value to safety, worker health, improving infrastructure and general efficiency in mining.

In this study, the practical communication of critical sensor data in three underground mining environments was demonstrated and analysed using the RSS. According to the experimental results, a communication speed of Mbps at a distance of 60 m was sufficient for real-time communication of important sensor data. In addition, the recommended RSSI value to maintain was 80 dBm in all measurement areas. The statistical properties of the path loss associated with the measurement environments were derived. In addition, this communication system does not require a central access point.

Communication is, therefore, possible, not only from the base unit to the mobile terminal but also from the mobile terminal to other mobile terminals. Hence, the signal strength information can influence the placements of the signal repeaters for longer distance transmissions. Furthermore, the communication speed observed from the measurements indicates that high data rate applications can be supported. More than 70 Mbps is possible in LOS environments, while the speed drops to over 50 Mbps in NLOS environments.

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REFERENCES

1. Kolade, O.; Cheng, L. Markov Model Characterization of a Multicarrier Narrowband Powerline Channel With Memory in an Underground Mining Environment. *IEEE Access* 2021, **9**, 59085-59092]
2. Kolade, O.; Familua, A.D.; Cheng, L. Channel models for an indoor power line communication system. *IET-Commun. Technol. Netw. Smart Cities* 2021, **90**, 67
3. Dohare, Y.S.; Maity, T.; Das, P.S.; Paul, P.S. Wireless communication and environment monitoring in underground coal mines-review. *IETE Tech. Rev*. 2015, **32**, 140-150.]
4. Singh, A.; Singh, U.K.; Kumar, D. IoT in mining for sensing, monitoring and prediction of underground mines roof support. In Proceedings of the 2018 4th International Conference on Recent Advances in Information Technology (RAIT), Dhanbad, India, 15-17 March 2018; pp. 1-5.
5. Bhattacharjee, S.; Roy, P.; Ghosh, S.; Misra, S.; Obaidat, M.S. Wireless sensor network-based fire detection, alarming, monitoring and prevention system for Bord-and-Pillar coal mines. *J. Syst. Softw*. 2012, **85**, 571-581.
6. Misra, P.; Kanhere, S.; Ostry, D.; Jha, S. Safety assurance and rescue communication systems in high-stress environments: A mining case study. *IEEE Commun. Mag*. 2010, **48**, 66-73.
7. Qin, X.; Fu, M.; Shen, B. Coal mine gas wireless monitoring system based on WSNs. In Proceedings of the 2011 Second International Conference on Digital Manufacturing & Automation, Zhangjiajie, China, 5-7 August 2011; pp. 309-312.
8. Kang, H.; Zhang, X.; Si, L.; Wu, Y.; Gao, F. In-Situ stress measurements and stress distribution characteristics in underground coal mines in China. *Eng. Geol*. 2010, **116**, 333-345.
9. Xia, K.; Chen, C.; Deng, Y.; Xiao, G.; Zheng, Y.; Liu, X.; Fu, H.; Song, X.; Chen, L. In Situ monitoring and analysis of the mining-induced deep ground movement in a metal mine. *Int. J. Rock Mech. Min. Sci*. 2018, **109**, 32-51.
10. Abdalzaher, M.S.; Samy, L.; Muta, O. Non-zero-sum game-based trust model to enhance wireless sensor networks security for IoT applications. *Inst. Eng. Technol. Wirel. Sens. Syst*. 2019, **9**, 218-226.
11. Abdalzaher, M.S.; Muta, O. A Game-Theoretic Approach for Enhancing Security and Data Trustworthiness in IoT Applications. *IEEE Internet Things J*. 2020, **7**, 11250-11261.]
12. Abdalzaher, M.S.; Seddik, K.; Muta, O. An effective Stackelberg game for high-assurance of data trustworthiness in WSNs. In Proceedings of the 2017 IEEE Symposium on Computers and Communications (ISCC), Heraklion, Greece, 3-6 July 2017; pp. 1257-1262.
13. Fang, L.; Ge, C.; Zu, G.; Wang, X.; Ding, W.; Xiao, C.; Zhao, L. A Mobile Edge Computing Architecture for Safety in Mining Industry. In Proceedings of the 2019 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI), Leicester, UK, 19-23 August 2019; pp. 1494-1498.
14. Zhang, Y.; Zhao, L.; Yang, K.; Xu, L. Mobile Edge Computing for Intelligent Mining Safety: A Case Study of Ventilator. In Proceedings of the 2020 IEEE International Conference on Parallel & Distributed Processing with Applications, Big Data & Cloud Computing, Sustainable Computing & Communications, Social Computing & Networking (ISPA/BDCloud/SocialCom/SustainCom), Exeter, UK, 17-19 December 2020; pp. 1300-1305.
15. Forooshani, A.E.; Bashir, S.; Michelson, D.G.; Noghanian, S. A survey of wireless communications and propagation modeling in underground mines. *IEEE Commun. Surv. Tutor*. 2013, **15**, 1524-1545.
16. Zhang, Y.; Yang, W.; Han, D.; Kim, Y. An integrated environment monitoring system for underground coal mines-Wireless Sensor Network subsystem with multi-parameter monitoring. *Sensors* 2014, **14**, 13149-13170.
17. Kawamura, Y.; Dewan, A.M.; Veenendaal, B.; Hayashi M.; Shibuya, T.; Kitahara I.; Nobuhara, H.; Ishii, K. Using GIS to develop a mobile communications network for disaster-damaged areas. *Int. J. Digit. Earth* 2014, **7**, 279-293.
18. Moridi, M.A.; Kawamura, Y.; Sharifzadeh, M.; Chanda, E.K.; Wagner, M.; Okawa, H. Performance analysis of ZigBee network topologies for underground space monitoring and communication systems. *Tunneling Undergr. Space Technol*. 2018, **71**, 201-209.
19. Moridi, M.A.; Kawamura, Y.; Sharifzadeh, M.; Chanda, E.K.; Wagner, M.; Jang, H.; Okawa, H. Development of underground mine monitoring and communication system integrated ZigBee and GIS. *Int. J. Min. Sci. Technol*. 2015, **25**, 811-818.
20. Moridi, M.A.; Kawamura, Y.; Sharifzadeh, M.; Chanda, E.K.; Jang, H. An investigation of underground monitoring and communication system based on radio waves attenuation using ZigBee. *Tunneling Undergr. Space Technol*. 2014, **43**, 362-369.
21. Moridi, M.A.; Sharifzadeh, M.; Kawamura, Y.; Jang, H.D. Development of wireless sensor networks for underground communication and monitoring systems (the cases of underground mine environments). *Tunneling Undergr. Space Technol*. 2018, **73**, 127-138.
22. Tao, P.; Xiaoyang, L. Hybrid wireless communication system using ZigBee and WiFi technology in the coal mine tunnels. In Proceedings of the 2011 Third International Conference on Measuring Technology and Mechatronics Automation, Shanghai, China, 6-7 January 2011; Volume 2, pp. 340-343.
23. Rappaport, T.S. *Wireless Communications: Principles and Practice*; Prentice Hall PTR: Hoboken, NJ, USA, 1996; Volume 2.
24. Blumrosen, G.; Hod, B.; Anker, T.; Dolev, D.; Rubinsky, B. Enhanced calibration technique for RSSI-based ranging in body area networks. *Ad. Hoc. Netw*. 2013, **11**, 555-569.]
25. Bullmann, M.; Fetzer, T.; Ebner, F.; Ebner, M.; Deinzer, F.; Grzegorzek, M. Comparison of 2.4 GHz WiFi FTM-and RSSI-Based indoor positioning methods in realistic scenarios. *Sensors* 2020, **20**, 4515.
26. Qian, J.; Song, M. Research and application of underground WLAN adaptive radio fingerprint database. *Sensors* 2020, **20**, 1182.
27. Rana, S.P.; Prieto, J.; Dey, M.; Dudley, S.; Corchado, J.M. A self regulating and crowdsourced indoor positioning system through Wi-Fi fingerprinting for multi storey buildings. *Sensors* 2018, **18**, 3766.
28. Shi, Y.; Zhang, W.; Yao, Z.; Li, M.; Liang, Z.; Cao, Z.; Zhang, H.; Huang, Q. Design of a hybrid indoor location system based on multi-sensor fusion for robot navigation. *Sensors* 2018, **18**, 3581.
29. Ebner, F.; Fetzer, T.; Deinzer, F.; Grzegorzek, M. On Wi-Fi model optimizations for smartphone-based indoor localization. *ISPRS Int. J. Geo-Inf*. 2017, **6**, 233.
30. Pei, L.; Liu, J.; Chen, Y.; Chen, R.; Chen, L. Evaluation of fingerprinting-based WiFi indoor localization coexisted with Bluetooth. *J. Glob. Position. Syst*. 2017, **15**, 1-12.
31. Bahl, P.; Padmanabhan, V.N. RADAR: An in-building RF-based user location and tracking system. In Proceedings of the Proceedings IEEE INFOCOM 2000. Conference on Computer Communications. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies (Cat. No.00CH37064), Tel Aviv, Israel, 26-30 March 2000; Volume 2, pp. 775-784.
32. Li, H.; Chen, L. RSSI-Aware energy saving for large file downloading on smartphones. *IEEE Embed. Syst. Lett*. 2015, **7**, 63-66.
33. Emslie, A.; Lagace, R.; Strong, P. Theory of the propagation of UHF radio waves in coal mine tunnels. *IEEE Trans. Antennas Propag*. 1975, **23**, 192-205.
34. Zhang, Y.P.; Zheng, G.X.; Sheng, J.X. Radio propagation at 900 MHz in underground coal mines. Antennas and Propagation. *IEEE Trans. Antennas Propag*. 2001, **49**, 757-762.
35. Boutin, M.; Benzakour, A.; Despins, C.L.; Affes, S. Radio wave characterization and modeling in underground mine tunnels. *IEEE Trans. Antennas Propag*. 2008, **56**, 540-549.
36. Ikeda, H.; Kawamura, Y.; Tungol, Z.; Moridi, M.A.; Jang, H. Implementation and verification of a Wi-Fi Ad Hoc communication system in an underground mine environment. *J. Min. Sci*. 2019, **55**, 505-514.
37. Ikeda, H.; Kawamura, Y.; Jang, H.D.; Mokhtar, N.; Yokokura, J.; Tungol, Z. Development of an underground in situ stress monitoring system for mining safety using multi sensor cell and Wi-Fi Direct technology. In International Symposium on Mine Planning and Equipment Selection; Springer: Cham, Switzerland, 2019; pp. 236-244.

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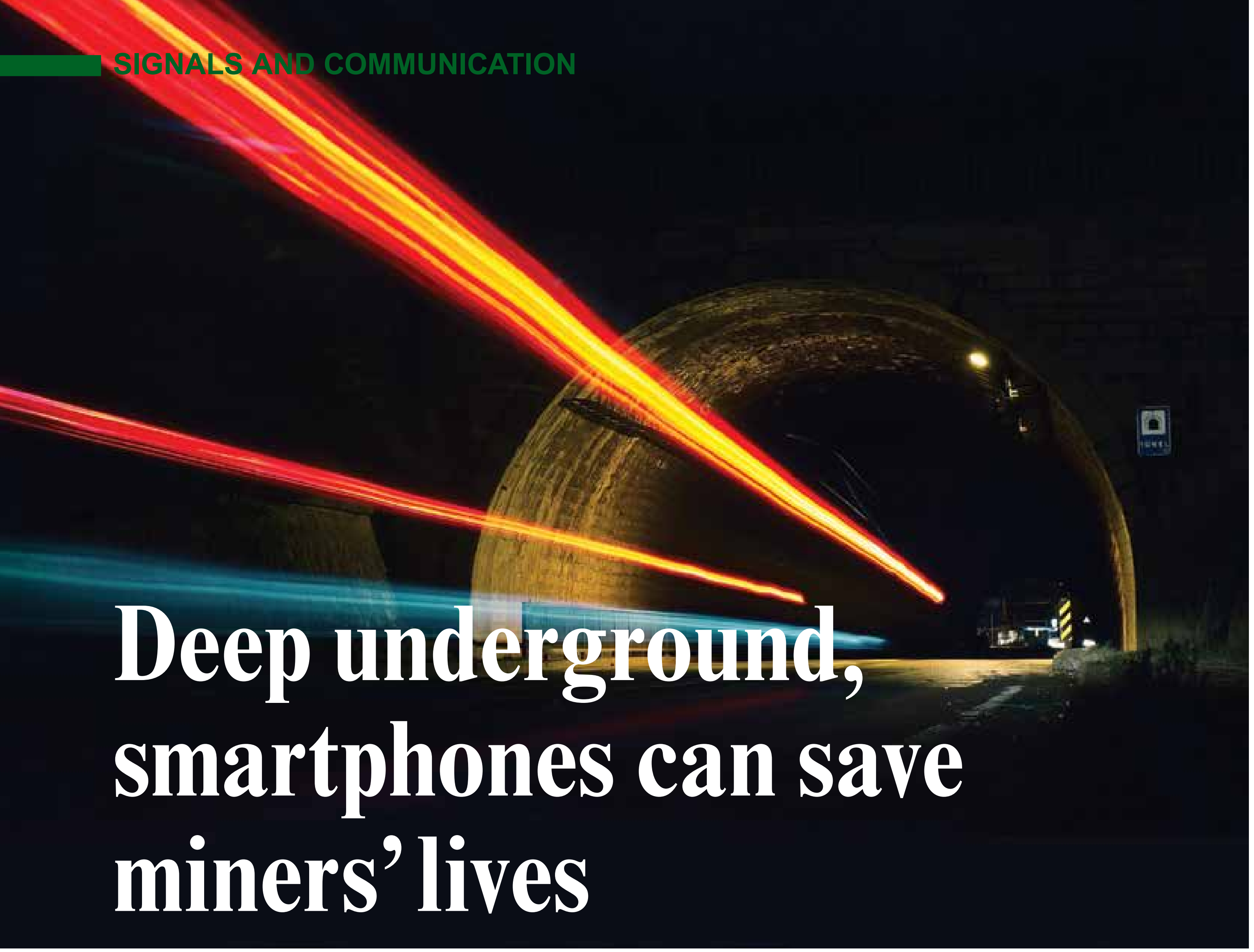


Deep underground, smartphones can save miners' lives

American mining production increased earlier this decade, as industry sought to reduce its reliance on other countries for key minerals such as coal for energy and rare-earth metals for use in consumer electronics. But mining is dangerous – working underground carries risks of explosions, fires, flooding and dangerous concentrations of poisonous gases.

Mine accidents have killed tens of thousands of mine workers worldwide in just the past decade. Most of these accidents occurred in structurally diverse underground mines with extensive labyrinths of interconnected tunnels. As mining progresses, workers move machinery around, which creates a continually changing environment. This makes search and rescue efforts even more complicated than they might otherwise be.

To address these dangers, U.S. federal regulations require mine operators to monitor levels of methane, carbon monoxide, smoke and oxygen – and to warn miners of possible danger due to air poisoning, flood, fire or explosions. In addition, mining companies must have accident-response plans that include systems with two key capabilities: enabling two-way communications between miners trapped underground and rescuers on the surface, and tracking individual miners so responders can know where they need to dig.

So far, efforts to design systems that are both reliable and resilient when disaster strikes have run into significant roadblocks. My research group's work is aimed at enhancing commercially available smartphones and wireless network equipment with software and hardware innovations to create a system that is straightforward and relatively simple to operate.

EXISTING CONNECTIONS

The past decade has seen several efforts to develop monitoring and emergency communication systems, which generally can be classified into three types: through-the-wire, through-the-Earth and through-the-air. Each has different flaws that make them less than ideal options.

Wired systems use coaxial cables or optical fibers to connect monitoring and communications equipment throughout the mine and on the surface. But these are costly and vulnerable to damage from fires and tunnel collapses. Imagine, for example, if a wall collapse cut off a room from its connecting tunnels: Chances are the cable in those tunnels would be damaged too.

Systems that send signals through the Earth use large loop antennas to send low-frequency radio waves through dirt and rock. The signals can't carry much information beyond simple texts or sensor readings, and the equipment is expensive and bulky.

Communications links are often set up only after mine disasters happen. Kyodo News/AP

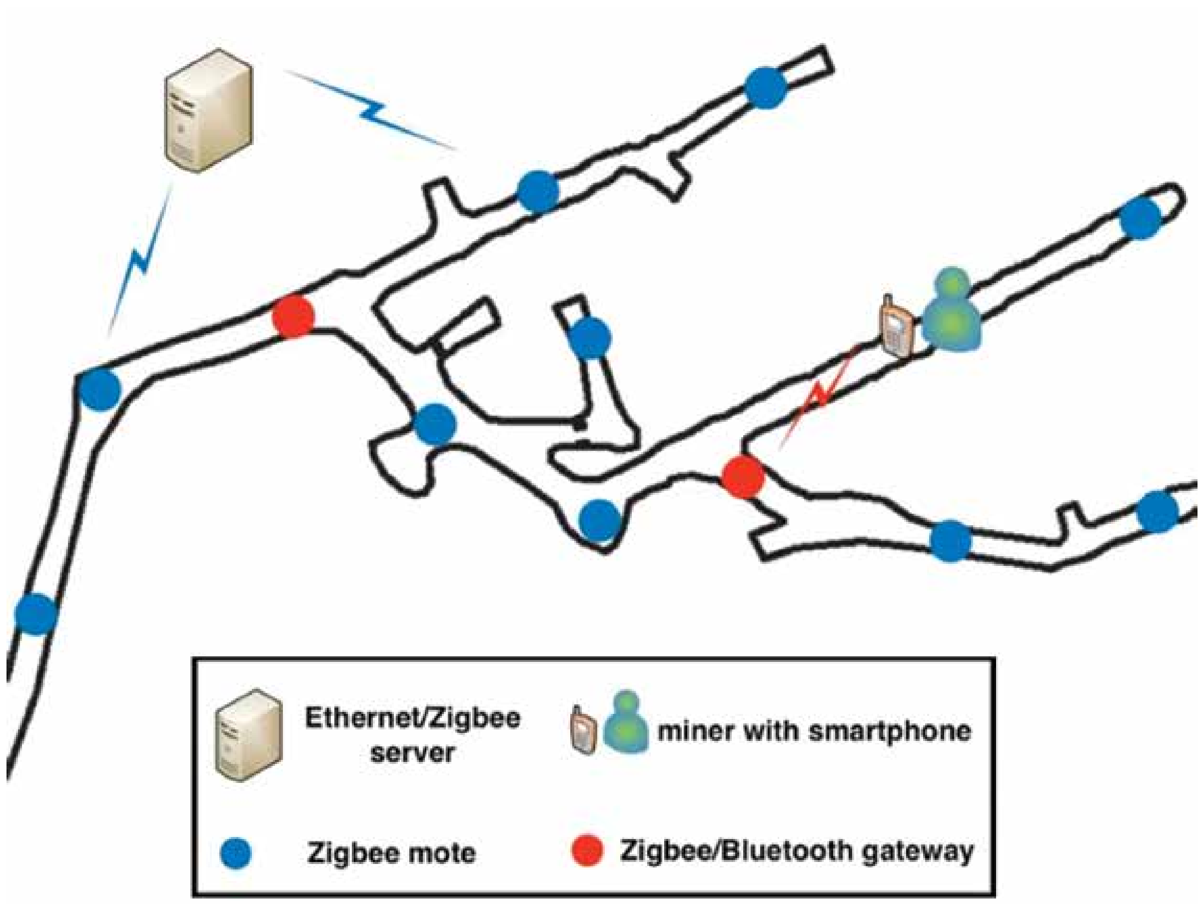
Airwave setups use wireless links, like cordless phones or Wi-Fi signals, to span distances of 1,000 to 2,500 feet. But these have limitations too. They depend on wired base stations distributed throughout mines, which are very like the wired-only systems and have similar cost and connectivity problems.

TRACKING UNDERGROUND

Because they have to track individual miners' movements underground, all of these systems also require every worker to carry expensive custom sensing units. The costs involved have meant that so far, most mines today use equipment that provides the bare minimum amount of safety required. This includes manually tracking miners' locations using two-way pagers or video surveillance.

If newer methods for tracking, sensing and communication could be developed, we could detect precursors to mishaps (such as noxious or combustible gas level concentrations in certain parts of a mine), and better aid rescue efforts in the aftermath of an accident. In my research, we're trying to use regular consumer smartphones and smart wireless devices to solve these problems. This sort of system takes advantage of the facts that most people have phones with them all the time, and that modern smartphones have a wide range of sensors already built in.

It's easy to get lost in here. Sudeep Pasricha/Colorado State University, CC BY-NC



A proposed system layout for underground mine monitoring, tracking and communication. Sudeep Pasricha/Colorado State University, CC BY-ND

Some prior work of mine found a way to use smartphones to navigate indoor spaces. We started by measuring the strength of the Wi-Fi signals the phone was receiving to approximate the distance the phone was from known transmitter locations. We factored in measurements from the phone's inertial sensors to determine speed and direction of movement. And we applied a mathematical technique called Kalman filtering to determine other useful information from additional sensors – such as number of steps taken.

When all these data were processed by machine learning techniques, we could determine a user's location within one to three meters, despite noisy or erroneous readings from Wi-Fi radios and inertial sensors. That was much better than prior methods for indoor location-sensing based on inertial sensor readings and fingerprinting. But these studies were done above ground.

Doing the same thing underground is much more difficult. Not only are Wi-Fi signals unavailable underground, but other wireless signals, such as those from cellphone towers, are also not present. Even what signals are there, from communications equipment in the mine, bounce off uneven surfaces, are absorbed by earthen walls and must pass equipment and other obstacles in tunnels of varying dimensions. These complexities make determining a specific location even harder for an electronic device.

Moreover, sensors and smartphones used in mines must be particularly energy-efficient because recharging stations are scarce. And they must not use much power, to avoid igniting subsurface gases.

A NEW APPROACH

Our research involves designing a wireless network made up of many low-cost stationary Zigbee or Bluetooth sensors deployed strategically around the mine, creating a web or mesh network that can connect with smartphones carried by the miners. We'll design the exact location of the fixed sensors based on an analysis of how radio signals travel in complex, changing and noisy underground mines.

We're also working to design new software algorithms and filtering techniques that can work on smartphones. When connected to the wireless mesh network, they will be able to accurately and efficiently calculate location in mines, despite the highly unpredictable nature of wireless signals.

Our hope is that we'll figure out how to build a combination cyber and physical system for monitoring, communication and tracking in underground mines under normal conditions. Such a setup would also be helpful in emergency response and rescue operations. This could not only improve the safety of hundreds of thousands of American miners, but also offer new opportunities for communications and improving human safety in a variety of extreme environments.

Energy transition: thermal coal will remain important in Asia-Pacific

The reduction of coal demand will be slow and uneven across regions. Currently, coal accounts for about 25% of primary energy globally (and about two-thirds of the power sector's generation), but is set to reduce to 21% by 2030 and trend down thereafter according to S&P Global Commodity Insights (Platts)' reference scenario. China and India together account for 70% of the world's coal demand. The steep rise of power demand expected in those two countries as their economies expand implies that coal generation is not being displaced by renewables, which are not sufficient to meet higher demand, unlike in the U.S. and Europe. Other industrial sectors like cement and steel are also slower to transition but the focus on decarbonization is increasing.

IN EUROPE AND U.S., RISING RENEWABLES LEADS TO FALLING COAL USE

In the U.S., the share of coal in power generation is set to fall to 12% by 2030 under S&P Global Commodity Insights (Platts)' reference scenario, from close to 20% a few years ago. However, the U.S. is also paying increased attention to the reliability of power, which could lead to deferrals of some coal retirements as recently announced by the mid-continent region operator, MISO, to help mitigate the risk of blackouts, with diversity of the power mix playing a key role.

In Europe, climate and emission-reduction policies are the key reasons for an abrupt drop of coal-fired power to less than 5% of the mix in 2030 from 15% in 2020. The risk of

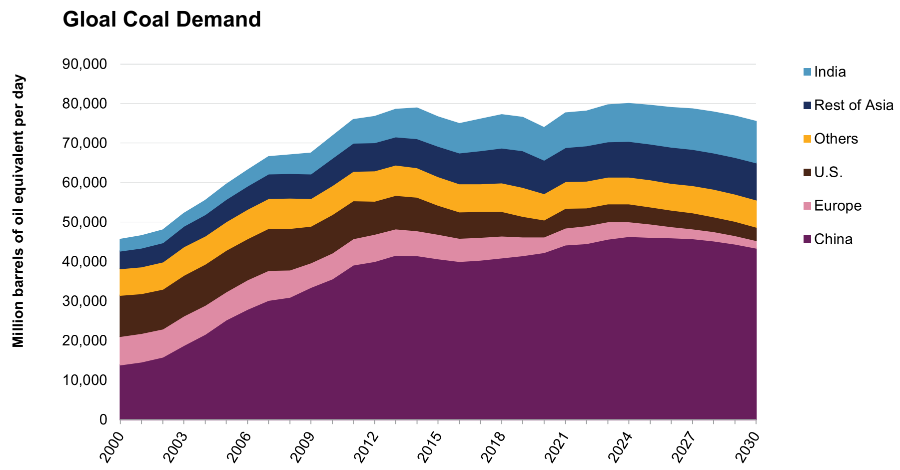


Chart 1.

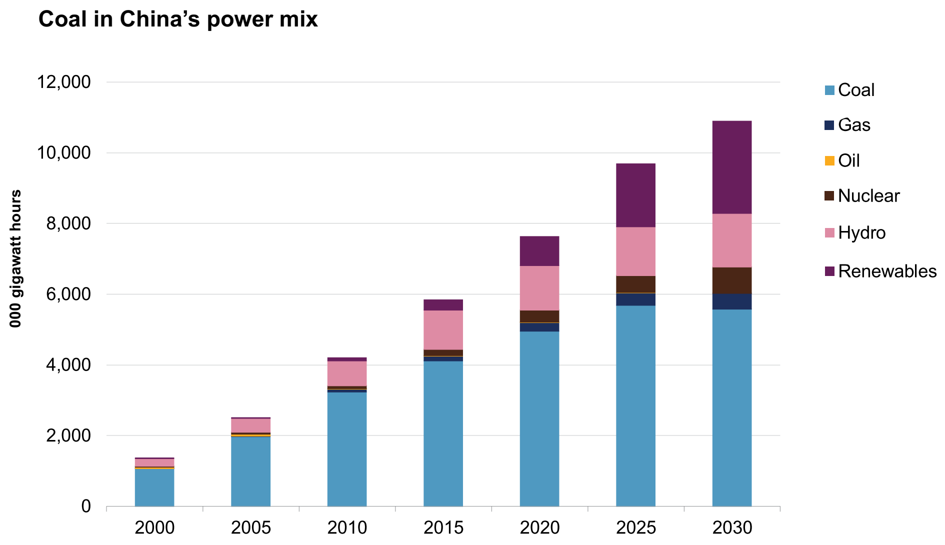


Chart 2.

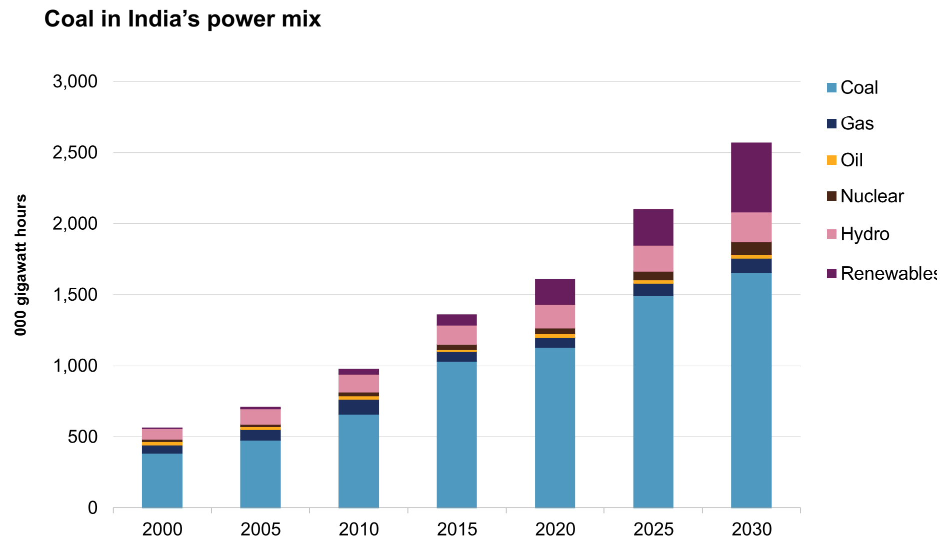


Chart 3.

Russian gas interruptions has however temporarily delayed the retirement of certain coal plants, with some destined to act as a reserve and therefore stay active for a short while longer than expected. The German government, for example, is considering setting up a 10 gigawatt (GW) coal-fired power generation capacity reserve, while many Eastern European countries are currently still high users of coal, with limited prospects for renewables development.

THE TRANSITION IS TAKING A DIFFERENT TRAJECTORY IN ASIA-PACIFIC

Economic realities in the Asia-Pacific region mean that any significant reduction of coal consumption will prove challenging. Large Asian economies are experiencing a strong rise in electricity demand, which is set to continue over the coming decades to sustain economic growth.

When it comes to meeting new demand, coal is still seen as the most affordable option for base-load power. At the 26th U.N. Climate Change Conference (COP26) in November 2021, China and India were the two major hold-outs on coal, agreeing only to phase down rather than phase out this fossil fuel. In China for instance, coal-fired generation will remain relatively flat and elevated this decade, although its share is set to reduce to 51% of power generation by 2030 from two-thirds today, with faster growth in renewables. In India, coal-fired generation will still expand substantially this decade to meet soaring demand. This is despite over 40 countries pledging to phase out coal at COP 26.

Asia's fairly new coal-fired generation fleet is another reason for its reluctance to turn away from coal. The average age of a coal plant in the U.S. and Europe is between 40 years and 50 years, and most are now approaching the natural end of their useful life spans. In Asia, much of the fleet has been built in the last 10 years, making significant plant closures unlikely before 2030 at the earliest.

The energy transition is also now more complex because of security of supply and geopolitical considerations, exacerbated by the ongoing Russia-Ukraine conflict. China, for instance, has declared that, although its decarbonisation efforts will continue, energy security is its first priority.

CARBON CAPTURE AND STORAGE MAY HOLD THE KEY TO LONG-TERM COAL USAGE IN CHINA

For now, without strong carbon pricing or policy mandates, CCUS technology is unlikely to be applied in power generation. That said, according to China's official "CCUS annual research report," carbon capture is China's indispensable "strategic choice" for reducing carbon-dioxide (CO_2) emissions and ensuring energy security in the future. China's emissions reduction from CCUS could be 0.6 billion tons-1.4 billion tons in 2050. The success of meeting net zero goals for countries like China, India, and Indonesia hinges significantly on the future economic and technical feasibility of CCUS technology.

According to the research report, CCUS technology would add Chinese renminbi (RMB) 0.26 per kilowatt hour (/kwh) to RMB0.4/kwh (roughly $40 per megawatt hour (/MWh) to $60/MWh) to the cost of coal-fired power generation. This is almost the same as China's historical coal-fired power tariff of RMB0.35/kwh-0.40/kwh, and compares to current power prices of RMB0.50/kwh-0.60/kwh. Put differently, for CCUS technology to be competitive, it would require a carbon price of $40 per ton-$60 per ton of CO2, whereas Chinese carbon prices currently trade at less than $10 per ton. For reference, according to the International Energy Association, the cost of CCUS technology varies widely between $40 per ton and $120 per ton of CO2.

POLICY APPROACHES DIFFER BETWEEN CHINA AND INDIA

China has pledged to achieve peak carbon emissions by 2030 and may well meet this target earlier, given its track record of overdelivering on its five-year renewables targets. Carbon emission growth in the country has started slowing since 2012, when larger rollouts of wind and solar capacity began. The lingering impact of COVID-19, which is still leading to lockdowns in Asia, could help make targets more attainable, since energy demand is currently somewhat lower than anticipated, although coal use has also rebounded faster than expected.

S&P Global Ratings believes that, India, on the other hand, will likely miss its 2022 renewable energy capacity targets, and its ambitious 2030 targets would be even harder to achieve with the country set to continue increasing coal use until 2050.

China's policy approach is multi-faceted, serving to discourage coal-fired generation while encouraging renewables. With the launch of China's carbon market in the summer of 2021, coal-fired power plants will need to comply with emissions targets. By contrast, India's policies are aimed at making renewables and other alternatives more attractive rather than penalizing coal use. In our view, India still lacks comprehensive energy transition policies and a clear commitment to phase out coal.

COAL-RELATED SECTORS FACE MOUNTING CREDIT RISKS AND FINANCING COSTS

Financial markets are independently taking action on the energy transition, and often ahead of policymakers. The pool of funding for coal projects is shrinking, with an increasing number of governments, financiers, and investors devoting more attention to climate risks. Although leading rich and developing nations have agreed to stop financing overseas coal-fired power plants, the current focus on energy security and higher energy prices is creating some hesitation.

Domestic bank funding is still available in China and India but, like all other funding channels, is steadily decreasing. With investor appetite diminishing, some coal projects are struggling to refinance, with access to capital – and not just its price – increasingly becoming an issue, heightening the risk that some assets may become stranded, or even default.

Charts: Source: S&P Global Commodity Insights – Global Integrated Energy Model.

ENERGY TRANSITION

Water management at mines – every drop counts

Water plays an essential role in most mining and extractive processes, and responsible water management is a critical business case for the mining sector at large. Managing mine impacted water often requires water treatment, but there is no one-size-fits-all approach when it comes to the design of water treatment plants, thus mines need to select a site-appropriate water treatment technology that meets their project specific needs. To this end, Multotec offers integrated fit-for-purpose water treatment systems that consider overall requirements of the site.

One of the greatest challenges facing mining operations is the development and management of water resources.

It is important that every operation prioritises the most efficient control and management of valuable water resources to maximise the efficient use and reuse of every drop of water that is involved with a mine site operation. This also minimises the long-term environmental liabilities that could result from the mismanagement of water resources.

Vincent Ridgard, Process Engineer, Multotec.

Reiterating the effect of mining practices on surrounding communities and the environment, Vincent Ridgard, process engineer at Multotec, quotes James Lyon, who, in an interview with the Mineral Policy Centre, said, “Water has been called mining’s most common casualty”.

According to Ridgard, mining affects fresh water through heavy use in processing ore, through pollution from discharged mine effluent and seepage from tailings and waste rock impoundments, commonly known as acid mine drainage (AMD)

He is of the view that water pollution from mine waste rock and tailings may need to be managed for decades, if not centuries, after closure, as the water sources continue to naturally produce sulphuric acid when sulphides in rocks are exposed to air and water. This results in oxidation and acidification processes, which continue to leach trace metals from the exposed rock face, and are discharged into the environment.

“Furthermore, chemicals used in leaching or flotation process, such as cyanide or sulphuric acid, enter the process water that is being recirculated within an operation, and some of these solvents remain in that water and, as it migrates, the toxic solvents are carried into the agricultural soils and into the water source of downstream communities,” explains Ridgard.

SIGNIFICANCE OF WATER IN MINING

Water, according to Ridgard, is arguably the second most valuable asset on a mine after the ore body itself. Strangely enough, he reasons, it is more often considered an “afterthought” for many design houses and mine owners.

WATER MANAGEMENT

The arsenic sludge from the HDS is dewatered by filter press while the solid cake is disposed of.

Mining uses water for mineral processing, including comminution practices, classification by screening and hydrocyclones, dust suppression, slurry transport and employees’ needs, among others. It is also used in some underground operations for hydro-powered equipment.

“Mining operations commonly seek water from groundwater, rivers and lakes, or through municipal water service suppliers. It plays an essential role in most mining and extractive processes, and today, responsible water use is a critical business issue for the mining sector as a whole,” adds Ridgard.

“Maintaining a constant water balance on your site is critical for both mining and mineral processing. For underground mining, you constantly need to dewater your shaft to allow for mining practices to continue. This water could now be contaminated by naturally leached components such as arsenic, and first needs to be treated before it can be discharged to the environment to maintain a water balance,” he says.

On the surface, the water needs of the processing plant must be balanced with what is now in the tailings facility. Any excess water needs to be treated and discharged from the tailings facility to maintain the water balance. Overcapacity can be catastrophic, with dam failures inevitable, explains Ridgard.

EFFECT OF CONTAMINANTS IN PROCESS WATER

Water quality can have a detrimental effect on process efficiency and recovery, but it is often the last place that mine operators look when experiencing a drop in recovery. Water hardness (high concentration of CaCO3 and MgCO3) in process waters can cause scaling of pipelines, which results in reduced throughput.

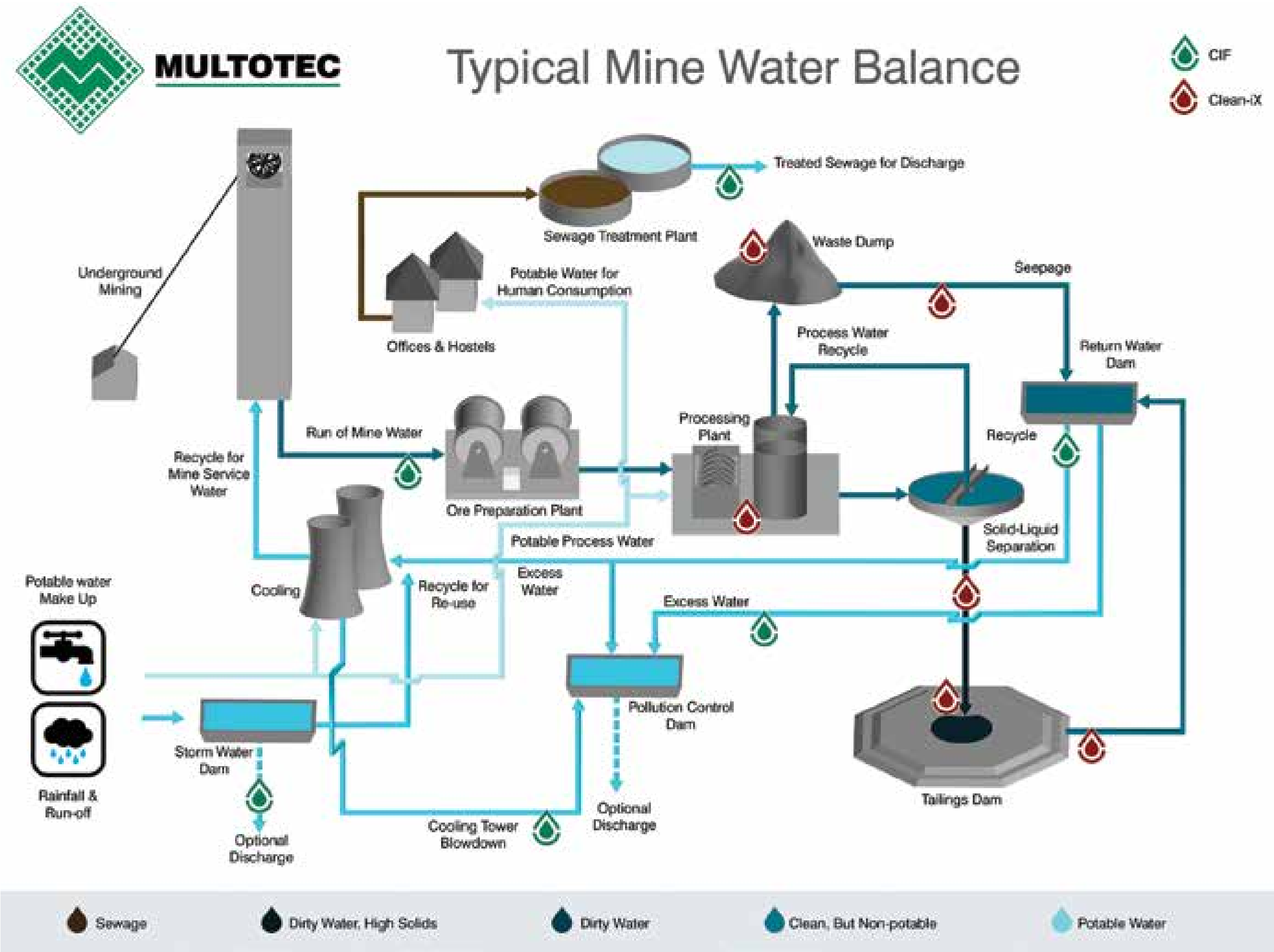
“Furthermore, it has been proven that contaminated waters can have a significant effect in recovery efficiency of hydrometallurgical processes. Compared to uncontaminated fresh water, lower recovery of target metals can be attributed to the presence of various metal ions in the process water,” explains Ridgard.

For gold operations, for example, the gangue minerals are insoluble in cyanide solution. Some metallic minerals, however, are soluble and deprive the solution of its oxygen and cyanide.

“Utilising completely clean water, however, does have its disadvantages in that residual reagents which carry over back into the process have been removed, and your operational cost increases to supplement this. Thus, it is critical to implement a fit-for-purpose water treatment system which removes target contaminants while allowing other elements to make up the necessary process water composition,” adds Ridgard.

HIGH RECOVERY WATER TREATMENT SYSTEMS

The cost of effluent treatment is significant, hence a high recovery system is essential. One of the common ways of treating effluent water is Reverse Osmosis (RO). RO was initially designed for sea water desalination to remove



Maintaining a constant water balance on your site is critical for both mining and processing.

monovalent salt molecules (NaCl). Due to its success in this application, it has since been introduced to other sectors such as industrial and mining.

"The problem is that sources of wastewaters also include a wide variety of other elements, such as divalent and trivalent elements which cause scaling of membranes. This means that when a standalone RO plant is utilised to treat these waters, it is operated at lower recoveries to enhance

Multotec has partnered with Australia-based Clean TeQ Water to provide the African mining market with continuous counter current ion exchange technology.

the lifespan of the membranes. It results in large volumes of highly concentrated brine streams, which are either recirculated within the system or require very expensive effluent treatment systems," says Ridgard.

Multotec offers fit-for-purpose, niche technologies specifically suited to the treatment of divalent and trivalent containing mining waters. To this end, the company has partnered with Australian based Clean TeQ Water to provide the African mining market with a continuous counter current ion exchange technology.

"The resin used in these systems is specifically manufactured to be more selective to the extraction of larger molecules and as a result provides the mining industry with a high recovery (>90%) system to provide fit-for-purpose process waters to be utilised within the water balance or discharged safely to the environment," explains Ridgard.

The utilisation of resin-based chemistry for the removal of target species has long been understood and respected globally in the industry, he says. It offers the selective extraction of contaminants by the exchanging of ionic functional groups, engineered on the resin beads, for target elements in the surrounding solution of like charge. The problem, however, has always been that there has not been a suitable technology to effectively facilitate the enormous advantages provided by the resin chemistry.

"The Continuous Counter Current Ion Exchange technology, engineered by Clean TeQ and supplied to the African market by Multotec Process Equipment, is a game-changing, moving bed technology," he says.

Contrary to the conventional fixed-bed systems, the use of resin transfer mechanisms allows the CIF (Continuous Ionic Filtration) to:

- Handle up to 150 ppm of solids (conventional systems need a 100% clean liquor), hence offering simultaneous removal of TSS (total suspended solids) and TDS (total dissolved solids);
- Offer optimised resin inventory (resin is the most expensive part of the plant and hence it is critical to ensure the longevity is maximised and the volume is minimised);
- Provide very high water recoveries;
- Handle in column precipitation;
- Offer low power consumption (given the limited power availability on isolated mine sites in Africa, this is another major advantage); and
- Produce valuable by-products and/or trace metal recovery.

Multotec offers fit-for-purpose, niche technologies specifically suited to the treatment of divalent and trivalent containing mining waters.

FIT-FOR-PURPOSE TREATMENT SYSTEMS

When designing its plants, Multotec considers the overall requirements of the site before building a complete fit-for-purpose solution based on the various effluent feed streams and the desired product water quality. "There is no one-size-fits-all approach when it comes to the design of these plants," says Ridgard.

If a certain quality of process water is required, then a system which produces the required qualities is specifically engineered, to treat specific elements which could potentially affect the overall process efficiency – such a system could potentially comprise of a combined HDS (High Density Sludge) and Continuous Counter Current IX system. If environmentally compliant dischargeable water is required, then a simple HDS system is perhaps the ideal solution.

"Even if the end goal is to change mine service water to potable drinking water, we design a high recovery system to meet these needs – this could potentially consist of an HDS, Continuous Counter Current IX and RO system," explains Ridgard.

Depending on the customer's ultimate water quality requirements, Continuous Counter Current IX is combined and fully integrated with RO to produce a high-recovery or Zero-Liquid-Discharge (ZLD) solution.

"Remember that RO was designed to remove monovalent ions, while IX is more selective to larger divalent and trivalent ions. Hence, by combining the two technologies and allowing the IX to firstly remove the elements which scale up the RO membranes, you allow the RO plant to do what is was designed to do, which is to remove monovalent salts at significantly higher recoveries. Furthermore, we can potentially provide a ZLD system by recirculating the concentrated sodium brine stream to regenerate the resin in the ion exchange plant."

PROVING CAPABILITIES

In one of the flagship Minimum Liquid Discharge (MLD) systems, Multotec designed and supplied a complete system to a mining operation that is extremely sensitive to water usage and waste production in the desert of the Middle East.

One of the major advantages of utilising ion exchange for the treatment of effluent and/or tailings streams, reasons Ridgard, is that in addition to being environmentally compliant, potentially increasing recoveries and reducing reagent consumption by providing a fit-for-purpose process water, ion exchange offers the possibility of recovering residual trace metals, which would have otherwise been lost to the mine owner.

"Mining operations spend millions of dollars to liberate and recover their target elements, but despite their best efforts, 100% recovery of these elements is simply not possible and large percentages end up in the tailings dams or is lost to the environment," says Ridgard.

"What the Clean-IX Continuous Counter Current Ion Exchange technology offers is the opportunity to recover what is lost from the processing plant and potentially provide an economic benefit which significantly offsets the cost of the water treatment plant. Depending on the concentration of the valuable metal and the total flowrate that is being treated, a complete payback within a matter of months could be possible," concludes Ridgard.

KEY TAKEAWAYS

- One of the greatest challenges facing mining operations is the development and management of water resources.
- Water is arguably the second most valuable asset on a mine after the ore body itself.
- Multotec offers fit-for-purpose, niche technologies specifically suited to the treatment of divalent and trivalent containing mining waters.
- Multotec has partnered with Australian based Clean TeQ Water to provide the African mining market with a continuous counter current ion exchange technology.
- Multotec provides the mining industry with a high recovery (>90%) system to provide fit-for-purpose process waters to be utilised within the water balance or discharged safely to the environment.
- *This article was, penned by Munesu Shoko*

Sustainable water management in mining, a global imperative

With an alarming prediction of global water scarcity in the very near future, organizations like the United Nations (UN), world governments, and other groups are putting increased pressure on industries that use water heavily, including mining, to be more sustainable. In their Sustainable Development Goals – the blueprint to achieving a more sustainable future – the UN identifies "clean water and sanitation" as the sixth goal to address the global water crisis. It includes a target to substantially increase water-use efficiency across all sectors by 2030.

The challenge: water is critical to the mining industry. Without water, mines don't function. The imperative for more sustainable water management is consequently crucial to the future of mining, driven by both social and economic needs.

With the global water shortage, there's greater pressure for mining companies to reduce their freshwater demand, particularly in dry areas where local authorities may restrict or oppose water use. But water scarcity isn't the only challenge facing mining operations. They must also manage flood risk to mitigate spilling, tailings dam failures and manage water quality to prevent pollution to the surrounding environment.

Environmental factors and climate contribute to the complexity of developing a sustainable mine water management system. In dry climates like the southwestern United States, northern Chile, southern Peru, and northern Africa, the key issue is a deficit in water supply. In these locales, water management should focus on conservation, like collecting, storing, and reusing contact water from the tailings storage facility, seepage, open pit, and/or underground mine. For wet regions like Colombia, Indonesia, and New Caledonia, the greatest challenge is managing flood events and eliminating the risks of spilling, erosion, and infrastructure failure. Finally, cold climate regions like Canada, Russia, and Finland must consider the large quantity of water generated from snow melt and ice thaw and manage the impacts of permafrost on drainage facilities. Each mine site requires a tailored and holistic solution.

MINE WATER TYPES AND USES

The mining industry uses large quantities of water for mineral processing and refining, dust suppression, slurry transport, tailings disposal, and potable and hygiene needs. Based on its quality, the water is classified into three categories:

1. **Raw water** is supplied from precipitation, groundwater, rivers, and lakes. It's used for employee needs, process make-up water, shaft and underground mine water demand, mobile fleet washing, fire water, etc.

2. **Compliant flow** (non-contact water) is clean surface runoff, or water that's compliant with the applicable legislation requirements that can be directly released to the environment without treatment. This water is normally segregated from the contaminated mine areas to reduce the treatment requirement and the facility sizes for non-compliant water management.

3. **Non-compliant flow** (contact water) is water that has contact with mining, mineral processing, and tailings disposal and, as such, is not suitable for direct release into the environment. Normally, this type of water is collected and reused on site (i.e., for process use, dust suppression, or soil conditioning, etc.) to the maximum extent to minimise the freshwater consumption. Any excess non-compliant water from the site will need to be treated to meet the effluent discharge criteria.

WATER MANAGEMENT IN A TAILINGS FACILITY

In the past thirty years, there have been more than one hundred tailings dam failure incidents reported in the world. The spillage and/or release of large quantities of mine waste and water can have catastrophic impacts on the surrounding community and environment – and the costs and clean-up work for the operating company are severe.

Several factors must be considered in mitigating the risk of a tailings dam failure and designing a safe water management system:

- **Safe operation:** during normal operation, the water pond within the tailings basin should be maintained at a small size or eliminated and kept a safe distance away from the tailings dam. Constant monitoring of pond levels, early warning systems, and vigorous reporting are critical factors to operating safely.

- **Water storage and decant capacity:** tailings dams must provide sufficient storage capacity to retain the Environmental Design Flood (EDF) without releasing untreated water to the environment, and it must have sufficient decant capacity to draw down the pond after the storm event.

- Extreme flood management: an emergency spillway should be provided at the tailings dam to safely pass an extreme flood event without overtopping the dams, and to safely release the water along a designated flow path that has less impact and damage to the surrounding environment.

Understanding effective water recovery can significantly reduce the cost of the project and subsequent operations. Involving specialised water experts who have experience with conceptual and detailed operational engineering design, water balance modeling, and water cycle optimization is key. Our approach to water management goes beyond the conventional to provide sustainable results by optimizing the entire system.

SOLUTIONS FOR A SUSTAINABLE FUTURE

Tailings disposal methods have a significant impact on water management and conservation. Advances in technology have helped move us away from the conventional un-thickened slurry tailing deposition to dry stacking and paste disposal. These methods have important benefits for the facility, including reduced water consumption, reduced facility footprint, less seepage and contact water for treatment and discharge, and reduced consequential risks of dam failure.

Digital solutions have also allowed us to develop site-specific, real-time monitoring systems, as well as improved forecasting and reporting tools. Water balance models can be used to simulate water quantity and contaminant loadings at selected locations and assess the performance of the water management system under different climatic conditions and statistical storm events. With improved data collection and reporting, operations can reduce the risk of flooding and environmental contaminations.

Our project experience, combined with our unique, world-class multidisciplinary technical teams, enables us to fully understand the full scope of a project, identify gaps and risks, and develop strategic plans and solutions for compliance with current and likely future regulatory requirements.

To support the industry's efforts, the International Council on Mining & Metals has developed a "Water Stewardship Framework" that provides high-level guidance on responsible water management. More comprehensive guidelines have also been developed by international technical associations to provide instructions on mine water management design and dam safety, including the International Commission on Large Dams and its affiliates.

Good water management practices can reduce water consumption and secure water supply, increase operation efficiency, mitigate water-related risks and liabilities, and improve collaboration from all stakeholders – making it a key focus of many mining companies' sustainable development plans.

Jie Yang
Technical Director, Mine Hydrology

A review on underground mine ventilation systems

To support and improve miner's health, ventilation is a major aspect of underground mining. As a result, there is an increase in productivity and efficiency. To reduce the number of toxic gases in the air to a safe level. The ventilation system is a method of bringing fresh air into the mine. It is necessary to develop techniques for maintaining the quality of the ventilation. For ventilating in the working faces, the proper controlling devices were used for controlling air and sufficient ventilation survey techniques are to be developed to maintain the quality and quantity of air. This present paper shows a detailed view of the underground mine ventilation system, ventilation survey instruments and different parameters that contribute to provide ventilation effectively.

Mining is a process of extracting the economically valuable minerals from the Earth. Personnel and machines require good quality air to breathe, to dilute both natural and introduced (e.g., diesel exhaust) gases, to dilute or carry away dust, and to provide cooling. In surface mines if any toxic gases were release then they will be mixed with the environment gases those won't affect workers in the mine. In underground mines there is no way for gases to go outside, the only way through ventilation.

In mine ventilation there will be mainly two types,

1) Natural ventilation
2) Artificial ventilation

In mines the air will enter from the surface through shaft or adit. The main purpose of underground mine ventilation is,

- To dilute and remove dangerous gases
- To remove dust
- To remove heat
- To supply oxygen for breathing

The primary sources that release gases will be

a. Vehicles
b. Human beings
c. Blasting and Drilling
d. Naturally generating gases.

OBJECTIVES

To review about various underground mine ventilation systems and ventilation monitoring instruments.

LITERATUR

Ventilation systems in mines can be classified as boundary or unidirectional, central or bi directional, combined, depending on the relative position of intake and return airways.

Boundary Ventilation System

The boundary ventilation system, in which air flows unidirectional from the intake to the return via the working, is by far the most efficient, requiring the least amount of ventilation control devices and resulting in high volumetric ventilation efficiency (70-80%). In its most basic form, it is used in metal mines that work steep lodes, with the intake and return shafts positioned at the mine's strike limits. Lateral extent, a central input shaft with two return shafts or winzes at either end is desirable. Two exhaust fans are installed in the property.

On the top of the intake shaft, a single forcing fan is sometimes utilised. However, this needs an air lock on the hoisting shaft, which is not ideal. When the mine is large enough on the strike, it can be split into multiple lateral parts, each with its own fan. Separate exhaust fans are usually installed on each parallel lodes in mines with several parallel lodes, but there may be a shared intake. A single forced fan is a less attractive option.

Advantages

- The usage of ventilation control devices is limited by the boundary ventilation system.
- This lowers leakage and results in a high volumetric efficiency.
- In addition to conserving the capital spent in them as well as the cost of operation and maintenance.
- Separate fans can be used to air two distinct areas of the mine. As a result, the overall flow handled by a single fan is reduced, lowering the fan's head demand.
- Leakage is reduced to a lower head. The flow can be handled by narrower cross-sectioned airways.
- Each portion's ventilation may be regulated individually, and a section can be separated quickly in an emergency.
- Because there are more exits to the surface, there is more safety.
- The mine characteristic remains almost constant throughout the mine's life, resulting in the fan's operation being consistently efficient.
- The mine resistance, on the other hand, is constantly changing as the workings proceed.
- The property line in the central ventilation system, where the fan must navigate a larger range of mine characteristics.

Disadvantages

- The reversal of air flow is more difficult.
- The cost of operation, management, and maintenance of separate fan systems rises.

Central Or Bi Directional

Ventilation system that is either central or bidirectional is used. In-the-seam coal mines, where both the intake and return shafts are close by at the property's centre, the system is commonly used. In any district, intake and return air travels in opposite directions through parallel roadways, which are usually separated by stopping erected in the cross section between them. In order to join the main return, return air from a district must also pass the intake. Obviously, the central ventilation system permits a significant amount of leakage due to the number of stopping and air crossing points employed, resulting in a volumetric efficiency of just 40- 50%.

Advantages

After a brief development period, the deposit may be exploited, allowing for a speedier start to production. Because long development headings aren't required, there's no need to worry about ventilation. Mineral loss in shaft pillars is reduced in central pits. The expense of digging deep pits nearer is reduced since some common amenities may be shared by the pits. On the other hand, boundary pits that are located far away from the sinking site need the construction of a road, the expansion of power lines, and other costs. Although both central shafts can be used for hoisting, boundary shafts are rarely employed since this would need the extension of surface transport to these pits. If they're on the rising side, they can also be used as stowing pits (with hydraulic stowing pipes attached).

Disadvantages

- The central mine ventilation method slows substantial leakage due to stopping and air crossing.
- With this system the loss of volumetric efficiency is 40% to 50%
  - i) **Ascensional Ventilation**
    In this ventilation system fresh air is taken down to the bottom faces of a working district and is allowed to reach up the dip along the faces collecting heat from the freshly exposed rock at the face, this can lead to the development NVP that aids the fan pressure.
  - ii) **Descensional Ventilation**
    It implicit, taking the air to bottom faces from the rise side of a district to the bottom levels along with the working places and return are at the lower end of the working place. It has been asserted to reduce the quality of heat added to the air in workings, apart from making the workings less dusty.
  - iii) **Antitropal Ventilation**
    When air and mineral flow in different directions then the ventilation is known as antitropal ventilation.
  - iv) **Homotropal Ventilation**
    When the direction of air and mineral flow is same then it is known as homotropal ventilation

VENTILATION ENTAILS A VARIETY OF TASKS

Planning: Calculating the quantity of air required in the mine and how that volume will be transported to each region of the U/G workings, both now and in the future, for example, if the mine expands, produces more, or introduces new equipment, particularly mechanised, mobile equipment. Implementation includes planning and building intake and upcast airways, as well as choosing, installing, and maintaining equipment to provide the needed air volumes.

Temperature, dust levels, airflow, and pressure are measured on a regular basis in all working areas of the mine; Ventilation equipment and installations are inspected; Reports and suggestions on ventilation requirements are made. Mine air travels through vent columns (also known as vent ducts), which are pipelines with a relatively high diameter, or through excavations, which include tunnels and stopes, in U/G mines. Any of these might be an airway. Airflow happens only when a force or pressure is applied to it. A difference in pressure at the airways ends causes airflow in a mine or any other airway. Similar to an electrical circuit, friction along the sides of an airway or from obstacles in it, as well as the inertia (dead weight) of the air, create resistance to air movement. Similarly, to electrical conductors, the less resistance, the greater the cross-sectional area of an airway. An input airway, sometimes referred to as the downcast shaft, and an upcast or return airway, where polluted air is expelled to the surface, are both present in U/G mines.

Natural ventilation is created in small-scale U/G mines when there is a significant difference in natural pressure between two exits to the surface to produce an airflow through the mine. It's unreliable since the pressure differential might be tiny, and it could change from night to day or season to season, resulting in severe flow reversals. Building a fire in the exhaust part of the airway can help with airflow. Electric fans are utilised in most situations, especially in large, deep mines. A pressure differential is generated in mechanical ventilation by running one or more fans in an airway. As air flows down the airway against resistance, each fan creates a particular amount of pressure, which eventually decreases. The majority of miners follow one of two main strategies. Axial-flow fans have a set of blades inside a circular housing, similar to a household fan, with air flowing directly through the centre, propelled by the blades rotation at an angle or pitch.

The air stream changes direction as it travels through the centrifugal fan, which has an impeller that is supplied tangentially from the side. Force fans push air into an airway ahead of them, whereas exhaust fans physically suck air out of an airway, allowing new air to enter at the intake end. Mine fans are not self-contained like domestic fans in houses, workplaces, and other buildings. Domestic fans do little more than circulate air at a high velocity in order to keep people cool. Mine fans are attached to an airway through a duct (pipe) or a tunnel wall. Enormous U/G mines feature a main ventilation system that uses large fans, either axial-flow or centrifugal, to pull air out of a return route, allowing new air to flow in via another aperture.

Although radial booster fans may also be placed U/G to counteract pressure loss, primary ventilation systems are typically exhaust systems with main exhaust fans situated on the surface. Mines frequently feature several intakes and return airways running in tandem.

The secondary ventilation system distributes air to various sections of the mine as needed, helped by barriers and regulators that prevent air from escaping into places where restricted or zero quantities are necessary.

Erecting hessian screens and spraying them with concrete to form a seal, is a simple and inexpensive technique to make vent walls. Temporary barriers are sometimes necessary. Inflatable bags, which are easy to travel and can be set up in minutes to close an airway, can be utilised. Where access to a level is still necessary, doors are erected to block it off. This might be a tiny door in a vent wall allowing man access or a huge steel door that opens to enable rolling stock and vehicles access. Workers must be taught how to keep doors shut. A counterbalance is commonly used to close doors automatically. Pressure loss is reduced in lengthy airways, particularly ventilation columns (ducts), by connecting fans in series. Long tunnels are being built with overlapping force and exhaust columns for ventilation. By connecting two or more fans in parallel, volume may be enhanced.

VENTILATION CONTROL DEVICES

There are several ways to get a mines air supply to the operating area. Signs indicate the location of air in a mine. To control the ventilation, devices can be used in the underground mine ventilation. Some Among the control devices are the following ones:

Stoppings

To halt the airflow between intake and return when they are no longer needed for a ventilation. This will prevent the airflow from being short-circuited. These may be made from brick, stone, or concrete. Concrete blocks, or fireproofed timber blocks, can be used to build a structure. They should be securely anchored in the roof, floor and wall. especially if the strata are weak or unstable. Inflammability of coal mining

Air Crossings

Air crossings must be used where intake and return airways must cross over each other in order to prevent leakage between them. Air crossing erected upon the site of an existing crossing, has a decent level of rock-free terrain movement.

Regulators

This is a device that creates a shock loss to limit airflow via a respiratory tract. stoppings. The air amount may be changed by adjusting the pressure differential. The aperture's size can be altered. There are a number of regulators in the return airway to minimise the traffic

Figure. 1: Ventilation stopping.

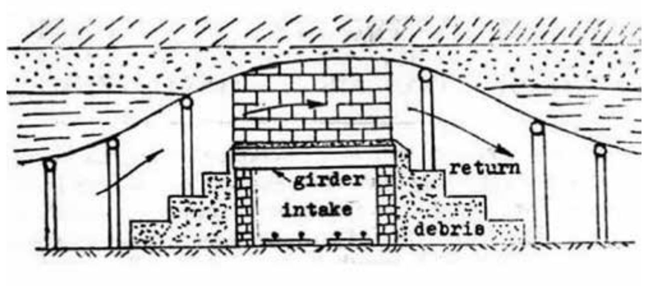


Figure 2: Air Crossings.

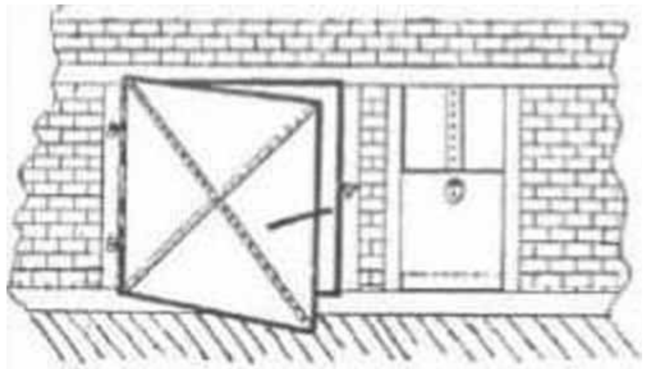


Figure 3: Regulators.

Figure 4: Brattice Cloth.

interference. Locating the source of the problem at the intersection with other splits of a road. Leakage of air will be kept to a minimum.

Brattice Cloth

It consists of a canvas sheet or sheets of canvas hanging on a strut to separate the aperture into intake and return airways. To prevent a short circuit of air from occurring, props and boards were used. Ventilation air is forced to return to the intake.

INSTRUMENTS

The instruments that were used in the underground mining to know the parameters are,

Barometer

A barometer is a device that is used to detect atmospheric pressure. The use of a barometer is beneficial in the operation of a mine because it displays changes in air pressure as they occur. A detailed examination of these pressure variations in relation to the gaseous state of the mine workings allows for more intelligent ventilation design and management, and may frequently predict a dangerous gaseous condition in the mine due to a fast drop in the barometer. Regular barometer readings are important in mining operations because they indicate the expansive effect caused by a sudden drop in barometer or decrease in atmospheric pressure. As a result, air and gases confined in a large abandoned area are forced out into the live workings, significantly increasing the explosive condition of the mine air.

Mine water gauge

A water gauge is a partly filled glass U-tube that is open at both ends and graded in inches. In Mine Ventilation, a water gauge is used to calculate the amount of power in the air. As a result, it should be mounted on the fan drift to account for the full resistance of the shaft and mine, which the ventilation fan must overcome. When the water gauge is in this position, the reading reflects the pressure created by the fan, which is either above or below atmospheric pressure, depending on whether the fan is blowing air into or expelling air from the mine. The change in the level of the water column of one inch is 5.2 lbs. per square foot.

Thermometer

A device for measuring temperature that is used to assess the relative humidity of mine air and to measure temperatures in sealed areas. Regular temperature readings within and outside the mine are critical for determining if the air has a higher or lesser capability for transporting moisture or absorbing moisture from the mine. In a dry and dusty mine, hygrometer readings are most useful.

Anemometer

Anemometers are commonly used in coal mining and consist of a metal ring with a revolving propeller of blades. The air stream striking the inclined blade rotates the bane, with a series of gears recording the number of rotations on the dial's face. The device is used to calculate the air current velocity in mine airways, which is given in feet. When taking a reading, choose a spot where the air is travelling straight and won't be diverted unequally to either side, then measure the area of the airway. Hold the anemometer at arm's length so that the blades move in a plane perpendicular to the air current, then use the anemometer's reset lever to reset all dial hands to zero, then release the brake lever near the handle. The anemometer is exposed to the air current for one minute, moving about to acquire an average reading for the airway's enter sectional area, following which the anemometer is removed. Brake lever is released and the anemometer is exposed to the air current the amount of air moving in cubic feet per minute is calculated by multiplying the anemometer measurement by the square footage of the airway.

CLASSIFICATION OF MECHANICAL VENTILATION

All powered machinery used to generate air flow through mine entrances or ducts are considered mechanical ventilation devices. Fans are the most important and most common of these but compressors and injectors also have application to ventilation.

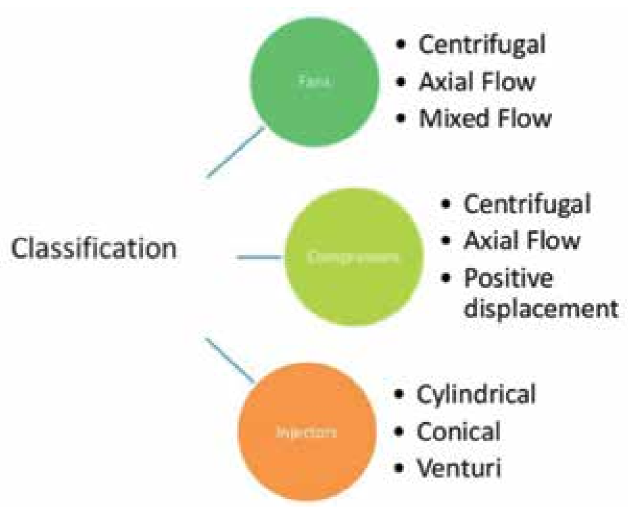


Figure 5: Classification of mechanical ventilation.

Figure 7: Axial Air Flow fan.

Fans

A fan is an air pump, a mechanism that generates air flow by creating a pressure differential in a duct or airway. The air pump or pressure source collects air at a certain input pressure and releases it at a higher pressure in a constant flow operation. The fan is an energy converter (from mechanical to fluid).

Centrifugal Fan

Centrifugal Fans: Air is sucked into a revolving impeller and released radially into an expanding scroll casing in centrifugal fans. It's further broken down into:

1) A plate of steel
2) There are many blades

Axial Air Flow Fan

Axial Air Flow Fans are divided into two kinds, both of which employ an impeller in a cylindrical housing with a mounting disc or air foil shaped blades to provide axial air flow. Axial flow mining fans with a diameter of 209 inches and a power rating of 5000 horsepower are used.

The Mixed Flow Type

The mixed flow type resembles a cross between centrifugal and axial flow types, with an axial flow fan flaring in the direction of air flow and blades on the impeller that resemble a cross between centrifugal and axial flow types. This kind is rarely used.

Compressors

Because they also function as air pumps in the ventilation system, compressors for ventilation can be thought of as high-pressure fans.

Centrifugal and Axial Flow Compressors:

Centrifugal and axial flow compressors look similar to fans of the same type. They operate at considerably greater pressures than fans and handle lesser quantities of air.

Positive Blowers:

Positive blowers feature two spinning impeller that mesh in such a way that a virtually constant amount of air is displaced (in all other mechanical ventilation devices, the volume of air discharge varies with the pressure).

Injectors

Injectors use compressed air's kinetic energy to en-train ambient air, giving mostly kinetic energy to it. Injectors force a jet of compressed air into the open end of a short pipe segment or ventilation duct, en training the ambient air and establishing a flow. The injector's characteristics are determined by the geometry of the pipe or duct input.

Figure 6: Centrifugal fan.

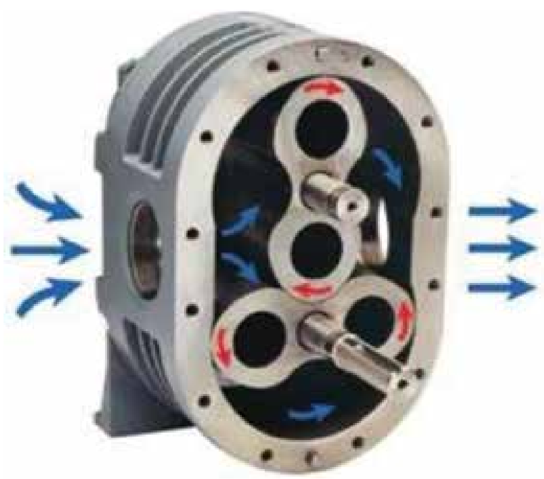


Figure 8: Positive Blowers.

CONCLUSION

Ventilation is one of the major aspects that needs to be focused in underground. The study was focused on reviewing various underground ventilation systems were studied along with the instruments used for monitoring ventilation and for performing ventilation survey. Also, various ventilation stopping were studied which were useful in minimizing the losses so as to improve the ventilation to an underground mine.

REFERENCES

- Gladyszewska-Fiedoruk, K., & Gajewski, A. (2012). Effect of wind on stack ventilation performance. *Energy and Buildings*, 51, **242-247**.
- Koushan, K., Spence, S. J., & Hamstad, T. (2009, June). Experimental investigation of the effect of waves and ventilation on thruster loading's. In Proceedings of the 1st International Symposium on Marine Propulsors (SMP'09).
- Monnet, X., & Teboul, J. L. (2013). Assessment of volume responsiveness during mechanical ventilation: recent advances. *Critical Care*, 17(2), **1-7**.
- Zhou, L., & Haghighat, F. (2009). Optimization of ventilation system design and operation in office environment, Part I: Methodology. *Building and Environment*, 44(4), **651-656**.
- Munjal, M. L. (1987). Acoustics of ducts and mufflers with application to exhaust and ventilation system design. John Wiley & Sons.
- Mundt, E., Mathisen, H. M., Nielsen, P. V., & Moser, A. (2004). Ventilation effectiveness. Rehva.
- Su, S., Chen, H., Teakle, P., & Xue, S. (2008). Characteristics of coal mine ventilation air flows. *Journal of environmental management*, 86(1), **44-62**.
- Karakurt, I., Aydin, G., & Aydiner, K. (2011). Mine ventilation air methane as a sustainable energy source. *Renewable and Sustainable Energy Reviews*, 15(2), **1042-1049**.
- Eck, B. (1973). Fans. 1st English ed., Pergamon Press, Oxford, **139-153**
- Acuna, E. I., & Lowndes, I. S. (2014). A review of primary mine ventilation system optimization. *Interfaces*, 44(2), **163- 175**.

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Seaborne Coal Exports Effectively Halted by EU Ban

Russian coal exports were effectively halted by a European Union ban on entities within the 27-nation bloc servicing shipments of the fuel to anywhere in the world.

Suek JSC, Russia's largest thermal coal miner, was unable to ship the fuel since mid-August, according to people familiar with the situation who asked not to be named because the matter is private. The insurance and reinsurance markets are dominated by EU, UK and Swiss companies, making it hard for shipowners to find cover, the people said.

An EU ban on imports of Russian coal and other goods into the bloc started on Aug. 10, following a wind-down period of four months. In a clarification earlier this month, the European Commission said the sanctions also prohibit EU operators from providing services – such as financing and insurance – to all shipments of such products originating in Russia.

While Russian coal miners started re-directing volumes to Asia long before the ban came into force, the shipowners typically reinsure their risks with bigger providers that can no longer cover such exports. The companies are looking at other options, but those will be costly and take time to implement, the people said. That will drive prices even higher, they said.

Russia is one of the world's top three coal exporters, controlling about 17% of the global shipments. The coal industry accounts for only about 1% of the Russian economy.

As Russia re-directed its coal to Asia, including India, exporters like Australia have replaced the volumes in Europe. That's fueled higher prices, which have already gained 10-fold over the past year.

The EU clarification also included some types of fertilisers. However, because the EU permits the import of set quota-based volumes of certain Russian fertilisers, it didn't affect the situation much, people said. Still, even before August, it was more difficult find a ship or insurer for such cargoes, they said.

Suek's press service as well as biggest Russian fertiliser makers declined to comment.

Germany's Russian gas crisis sparks coal rush

"A rush like this in the summertime, it's unheard of – everybody wants coal," says Frithjof Engelke, a supplier of the briquettes which have become a hot commodity in the German capital.

A looming shortage of Russian gas in the wake of the Ukraine war has reignited enthusiasm for this method of heating private homes despite its sooty residue and heavy carbon footprint.

Engelke, 46, head of the century-old Berlin business Hans Engelke Energie, says it's brought a bonanza for his family business: "My holidays will have to wait."

He and his team are frenziedly taking orders, organising deliveries by truck – now booked out until October, and getting supplies ready for those who come directly to pick up coal from his warehouse.

On a hot summer's day, he weighs and bags loose coal amid the dust and din of his filling machine, then arranges the bags on pallets, awaiting customers.

In Berlin, 5-6,000 homes still heat with coal – only a fraction of the city's 1.9 million homes, say municipal authorities.

Engelke's customers are often elderly people, sometimes entirely dependent on coal and living in old dwellings that have never been renovated.

Others are lovers of the "cosy" heat emanating from often ornate old ceramic stoves.

But this year, new customers have arrived "en masse", says Engelke, whose medium-sized company has also diversified into wood pellets and fuel oil.

"Those who heat with gas but who still have a stove at home now all want to have coal," he said, citing a phenomenon seen throughout Germany as winter approaches.

'Better than being cold'

Jean Blum is one of the new converts.

The 55-year-old man with tousled hair and a bushy white beard loads 25-kilogram (55-pound) bags filled with precious black briquettes in his trailer.

"I'm buying coal for the first time in years," he tells AFP.

Since his home is equipped with gas heating, he sometimes lights his stove, but only with wood.

With the jump in gas prices, which will be exacerbated this autumn when operators will be able to pass on the increase in energy levies to the consumer, Blum wants to make sure he has a safety net.

"Even if it's bad for your health, it's still better than being cold," he says.

Although coal prices have soared 30% this season, it remains cheaper than wood, whose price has more than doubled.

"I worry when I wonder if there will be enough gas for everyone," he adds, noting that Russian President Vladimir Putin has already partially closed the gas tap on Germany after Western nations imposed new sanctions on Moscow.

– 'Renaissance' –

The black fuel is experiencing a comeback on several fronts in Europe's top economy.

The German government had already resolved to increase the use of coal-fuelled power plants to satisfy the enormous appetites of several industries.

However Berlin insists it will keep its pledge to phase out the heavily polluting energy source by 2030 and rules out a "renaissance of fossil fuels, in particular coal," as Chancellor Olaf Scholz recently vowed.

However with new private customers coming out of the woodwork, production has a hard time keeping up, and many small coal merchants in the capital are running out of supplies.

"We produce at full capacity during the summer, with three shifts, seven days a week," Thoralf Schirmer, spokesman for LEAG, a mining site in the Lusatia basin, told AFP.

The company supplies DIY stores and fuel sellers with coal briquettes.

Production has jumped 40% since January, he said, but demand is strong everywhere and the situation is expected to remain tense at least until this winter.

Adding to the pressure is the fact that the other factory supplying the market in Germany, based in the Rhine valley, will cease production at the end of the year, reducing supply.

"I dread the winter a bit," Engelke, the coal seller, admits.

Currently, people are relatively relaxed when they learn that they will have to wait at least two months before getting deliveries, he says.

"Things will be radically different when it starts to get cold outside.

Innovation in the mining industry: Technological trends and a case study of the challenges of disruptive innovation

Innovation plays a critical role in the mining industry as a tool to improve the efficiency of its processes, to reduce costs, but also to meet the increasing social and environmental concerns among communities and authorities. Technological progress has also been crucial to allow the exploitation of new deposits in more complex scenarios: lower ore grades, extreme weather conditions, deeper deposits, harder rock mass, and high-stress environments. This paper discusses the importance of innovation for the mining industry and describes the mechanisms by which it is carried out. It includes a review of the drivers and actors involved and current trends. The digital transformation process that the industry is going through is analyzed, along with other relevant trends that are likely to shape the mining of the future. Additionally, a case study is presented to illustrate the technical and economic implications of developing a disruptive innovation project.

Over the past decades, the mining industry has had to face a challenging scenario for its operation. Improving productivity to overcome natural factors such as decreasing ore grades, deeper deposits, and harder rock mass, combined with an increasing environmental and social awareness, has boost the industry to constantly work to enhance their processes along the whole value chain. In this, innovation plays a crucial role by providing suitable solutions to surpass these difficulties, ensuring the continuity and sustainability of the mining activity.

There has been a historical debate whether mining is indeed an innovative industry or not. It is often perceived as a conservative sector, where innovation takes only a secondary position in the concerns of companies. But at the same time, many argue that mining is more likely to be comparable with high-tech industries, considering that it utilises vanguard technologies in its processes, such as automated or remote-controlled machinery, and advanced monitoring systems for the collection and analysis of large amounts of data[1].

Nowadays, many relevant actors of the industry claim that mining is going through the first stages of a deep

INNOVATION IN MINING

changeover from the hand of digital transformation. It is said that this process could change how mining is done, passing from human-run operations to autonomous or semi-autonomous remote-controlled mines. Independent if fully automated operations are achieved in the near future or not, the digital transformation is already impacting the industry and will continue doing so.

This article aims to characterise the innovation environment in the mining industry, specifically:

- Importance of innovation for the mining industry: relation between labor productivity and innovation
- Dynamics of innovation in the industry: drivers and actors
- Current trends and future of the mining industry

It will contribute to improve the understanding of the dynamics and mechanisms involved in the innovation processes, along with analysing the current status and expected future of the mining industry, in terms of technological advance.

The scope of this paper covers the mining industry in general and its entire value chain (exploration, extraction, processing, and smelting and refining). However, by the nature of the topic, artisanal and small-scale mining have been mostly excluded from the analysis, considering the historical low degree of technological specialisation in this sector. Also, for the illustration and exemplification of certain points made in this document, a special focus has been put in the large-scale copper mining sector and the main copper producer countries.

INNOVATION IN THE MINING INDUSTRY

Cambridge Dictionary defines innovation as a new idea, method, design, or product, as well as its development or use[2]. In general, innovation can be understood as a process of change, through which a new idea or solution is applied in a good, service, or productive procedure to create value and meet new requirements from customers and higher safety or environmental standards, among other goals.

In this section, the importance of innovation for the mining industry is discussed. Firstly, the relation between innovation and labor productivity is examined. Then, a general view regarding the innovation dynamics within the industry is provided, exploring the main drivers and actors involved.

Innovation and Labor Productivity

A first approach to understand the relevance of innovation within the industry can be made through the analysis of labor productivity. Technological advances usually have an impact on the output, allowing larger production rates while maintaining a similar workforce, or directly reducing the needed personnel by the automation of processes. Nevertheless, changes in labor productivity of a mine may be caused by a series of other reasons. Natural factors, such as decreasing ore grade and deepening of deposits, mean that a larger amount of material in more complex situations must be removed to obtain the same final metallic output, thus impacting negatively on labor productivity, while, in an aggregated view (e.g., when analysing the mining industry of an specific country), the discovery and exploitation of new and better deposits can also positively impact the overall labor productivity[3]. On the other hand, in a high-price mineral commodities scenario, companies are willing to compromise their costs in order to increase production (because it is profitable) and, therefore, reduce their labor productivity[4].

Several authors have analysed the behavior of labor productivity in specific mining industries in an attempt to isolate the effect of innovation. Tilton et al. [5] first introduced the importance of innovation and new technologies in the growth of labor productivity while studying the decline and recovery of the US copper industry during the 1970s, 1980s, and 1990s. The authors attributed most of the labor productivity increase in this period to the incorporation of the solver extraction and electrowinning technology (SX-EW), along with the use of larger trucks, shovels and drills, in-pit mobile crushers and conveyor belt systems, computerised scheduling of trucks, and real-time process controls.

In a later study, more concrete evidence regarding the previously mentioned was provided [6]. Since the exploitation of new deposits can have an impact on the aggregated labor productivity, the authors built two scenarios to analyse this index between 1975 and 1995: one, considering only the mines operating at the beginning of the studied period, and therefore, excluding the effect of new mines, and two, the actual situation, including both old and new operations. In **Figure 1**, the adjusted curve represents what labor productivity would have been if no new mines would have entered in operation in this period of time. As shown, adjusted and actual labor productivity resulted to be not so far different; thus, approximately 75% of the productivity growth in the US copper industry over those years came from productivity improvements at individual mines (i.e., innovation and technological advances), despite the exploitation of new deposits.

Under a similar methodology, the labor productivity growth in the Chilean copper industry during the 1978-1997 period was analysed (**Figure 2**)[7]. Their findings, though

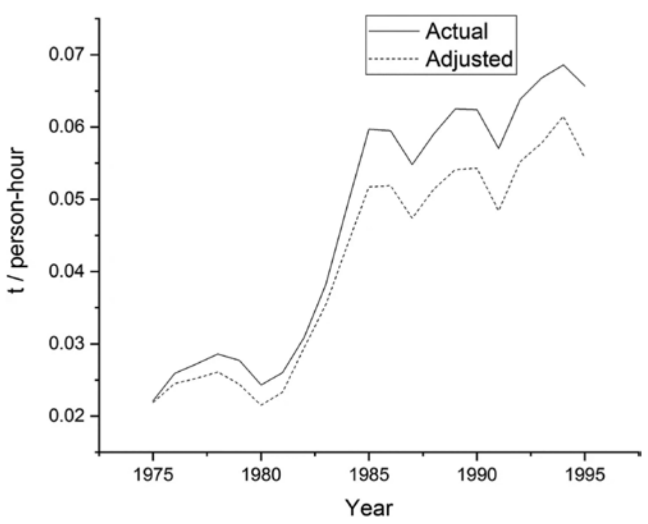


Figure 1: Labor productivity in the US copper mining industry, actual and adjusted to exclude the effects of changing location of output , 1975-1995. Modified from[6].

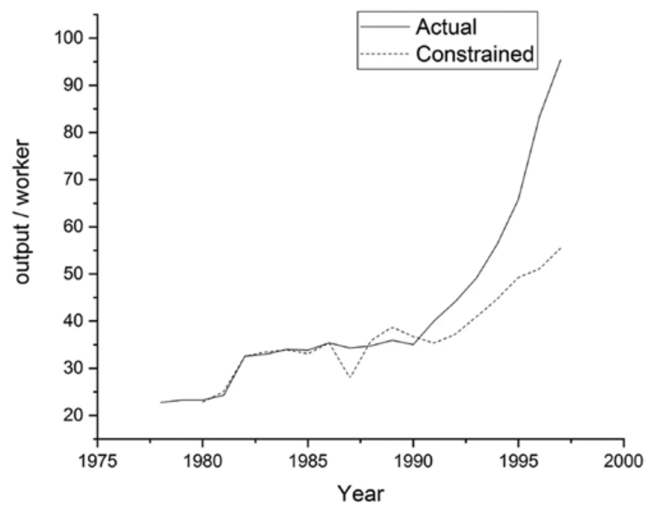


Figure 2: Labor productivity for the Chilean copper industry, actual and constrained (or adjusted) assuming no change in the location of mine output 1978–1997 (tons of copper contained in mine output per copper company employee). Modified after[7].

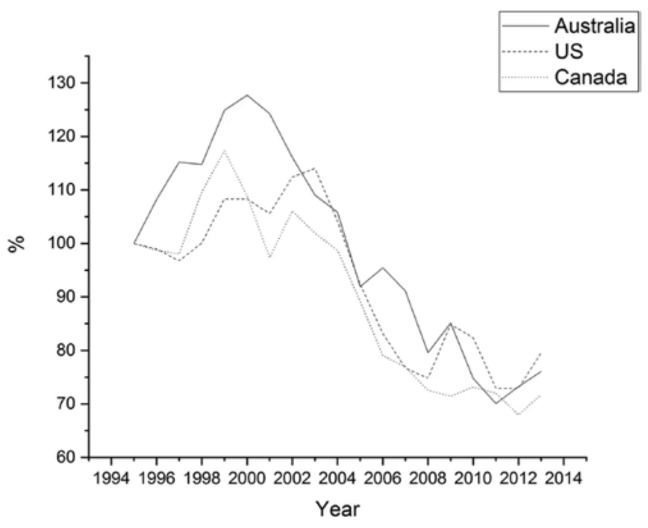
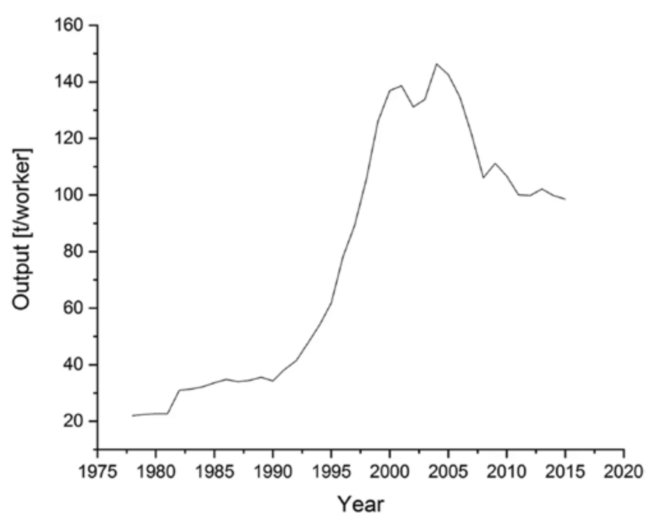


Figure 4: Labor productivity of the mining sector of selected countries, for the period 1995–2013. Annual value presented as a percentage of labor productivity in 1995 (100%). Modified after[4].

not as dramatic as in the US copper industry, showed that innovation and the introduction of new technologies were responsible for approximately a third of the productivity growth in the total period. Specifically, during the years prior to 1990, this factor accounted for the total growth, while in the 1990s, the development of new world-class mines (e.g., Escondida) turned over the scenario. Nevertheless, these results were coherent with the findings of previous studies on the US copper industry, regarding the role of innovation in improving the competitiveness of the mining industry.

More recent research on the copper industry of Chile and Peru has presented additional supporting evidence that, though not the only factor, innovation, including the adoption of new technologies and managerial changes, remains as a key element for the improvement of labor productivity[3].

When looking at the following time period (late 1990s to early 2010s), the situation presents a dramatic change.



Fgure 3: Average labor productivity of Chilean mines for the period 1978–2015, measured as tons of mine production per worker. Modified after[4].

From 2005 onward, the average labor productivity of Chilean mines suffered a sharp decline, as shown in **Figure 3**. The same situation can be observed in other main mining countries, like Australia, Canada, and the USA (**Figure 4**). Labor productivity in these countries started falling in the first years of the 2000s. This decline can be attributed to a combination of natural and economic factors. On one side, while reserves are depleted, ore grades tend to decrease and the operation advances to deeper locations, increasing hauling distances, stripping ratio, and geotechnical difficulties, all of which have a negative impact on labor productivity. On the other side, in a period of high mineral commodity prices, like the one that the industry went through during the second half of the 2000s and the beginning of the following decade, mining companies will favor production growth despite productivity[4].

As presented, labor productivity is affected by a series of factors, mainly by natural characteristics of mineral deposits, market conditions, and innovation. While in periods of labor productivity growth it has been possible to isolate the positive effect of innovation, during declining cycles, this task turns more complicated. However, the fall in these periods is attributed mainly to natural and economic factors. In the meantime, innovation remains crucial to maintain the competitiveness of the industry, to the extent possible, providing the methods and tools to overcome the natural challenges faced by modern mines and exploit new and more complex deposits. In other words, while declining labor productivity may be inevitable during certain periods of time, the development and adoption of new technologies, along with innovation at a managerial level, are essential to maintain mining's competitiveness through the different cycles.

Drivers for Innovation and Actors

As discussed in the previous section, innovation constitutes an important factor affecting the productivity of mining operations. Examples of technologies developed to improve the efficiency of processes, reduce costs, and in consequence enhance productivity are easily found. Hydrometallurgical production method SX-EW has been identified as a major contributor for productivity growth in the US copper industry over the last decades of the twentieth century[6]. Likewise, continuous mining equipment in underground coal mining, along with draglines and bucket wheel excavators in surface coal mining, were key advances to reach new levels of productivity in coal production. In smelting processes, the development of flash, and, more recently, bottom blowing furnaces, has had a great impact in reducing energy consumption and OPEX.

Besides boosting productivity, through innovation, it has been possible to unlock the potential of deposits that were technically infeasible to exploit by traditional methods. For example, preconditioning of the rock mass through hydraulic fracturing, confined blasting, or a mix of both has allowed the exploitation of deeper ore bodies, in high-stress environments.

Addressing safety and environmental concerns has been also a major driver for innovation. Over the recent decades, focus has been put on removing workers from critical activities through the automation of processes and the use of autonomous and semi-autonomous (remote-controlled) equipment.

Meeting more rigorous environmental regulations and attending the concerns of local communities are minimal requirements for maintaining the social license to operate. Therefore, innovation has been also aimed at developing cleaner and more environmentally friendly solutions in the whole value chain of the business, and not only to improve the efficiency and reliability of its processes[8]. Examples of these are the new tailings disposal methods that have been implemented to reduce the impact of mining on the environment, such as the thickened and paste tailings disposal. These methods improve water efficiency in their processes, reduce the requirement of surface for their disposition, and minimise risks of collapse, among other advantages over traditional methods.

Regardless, extractive firms have historically shown low levels of expenditure in research and development (R&D), often perceived as the main innovation-related index[8]. During the decades of the 1990s and 2000s, R&D intensity of relevant mining and mineral companies, understood as the R&D expenditure as a percentage of total revenues, was on average only approximately 0.5%[9].

Figure 5 shows the average R&D intensity for some of the largest mining companies, as revenue level refers, during the 2011-2018 period. Though presenting variation during the period, on average, this index has remained around 0.4%. These levels of R&D intensity are considerably low compared with other industries. For example, in 2015, pharmaceuticals and information and communications technology (ICT) equipment, the most R&D-intensive industries, reached levels of 25.1% and 24.7%, respectively. Moreover, the average R&D intensity in 2015, across all industries in OECD countries, was 5%, more than ten times the level of the selected mining companies[10].'

Measuring the level of innovativeness of an industry by only examining R&D intensity, however, can lead

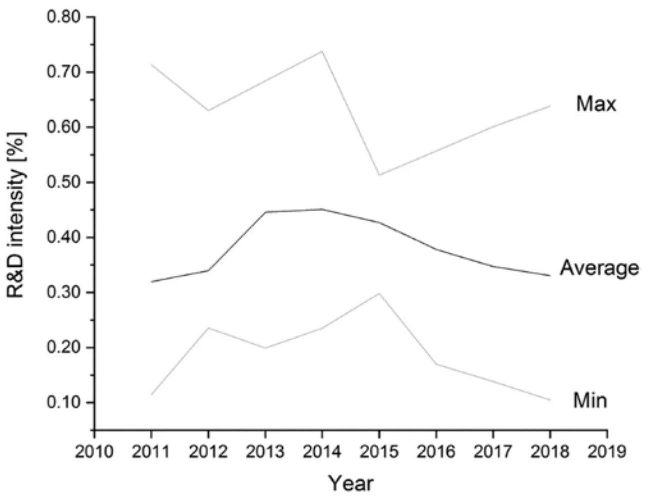


Figure 5: R&D intensity of five of the largest mining companies, based on 2018 revenues (companies selected according to availability of information i.e. R&D expenditure informed in annual reports, individualised and separated from exploration expenses). R&D intensity calculated as a percentage of total annual revenues for the 2011–2018 period (in the case of Zijin Mining, R&D intensity was calculated as a percentage of total operating income, according to data reported by the company). Data retrieved from annual reporting of companies Anglo American (available in: https://www.angloamerican.com/investors/annual-reporting), China Shenhua Energy Company (available in: http://www.csec.com/shenhuaChinaEn/1382683238772/dqbg.shtml), Codelco (available in: https://www.codelco.com/prontus_codelco/site/edic/base/port/memorias.html), Rio Tinto (available in: https://www.riotinto.com/investors/results-and-reports-2146.aspx), and Zijin Mining (available in: http://www.zijinmining.com/investors/Annual-Reports.jsp).

to misinterpretation. Some authors argue that R&D expenditure fails to consider other activities that could be related to innovation efforts, such as engineering development, plant experimentation, and exploration of new markets. Also, R&D expenditure in general does not include mineral exploration expenses[8]. While these arguments may be reasonable, it is necessary to analyse in more detail how and by whom innovation is done in mining.

Whereas in the past mining companies would have tended to develop technology solutions in-house, over the last decades of the twentieth century the tendency changed. Economies of scale from using larger loading and hauling equipment had an important impact in improving productivity and reducing costs. Yet, these solutions came from equipment manufacturers, not from mining companies[1]. This is how outsourcing became a tendency among large producer firms, resulting in higher degrees of vertical disintegration[11]. Companies would focus on their core business, while relying on suppliers for the development of technological solutions, therefore avoiding the risks associated with the large investments involved. At the same time, in many cases, suppliers of such are also subcontractors for mining companies, handling construction and mining activities in projects and operations. These include the development of methods, techniques, and technologies to accomplish these tasks and therefore liberating their clients, the mining companies, from the technological concerns.

INNOVATION IN MINING

Leading technology suppliers, such as Sandvik, Epiroc, and Caterpillar, among others, have not only focused in the development of new equipment according to the technological and sustainability trends (currently, on automation and electromobility), but they have also put effort in the development of the proper digital systems for the operation and coordination of these machinery within the operations (e.g., AutoMine® from Sandvik).

Though large global suppliers are important actors for the development of new technologies, the outsourcing tendency previously mentioned has also opened the opportunity for the emergence of local knowledge intensive mining suppliers. These firms hold specific local knowledge that allows them to provide customised solutions for mining companies in niches that cannot be covered by the standardised products offered by large global suppliers[12].

Also, this outsourcing trend has promoted the creation of collaboration initiatives between large mining companies, local suppliers, and governmental and academic institutions for the development of technological solutions. Instances like these can be found in Australia, Chile, and Brazil[11]. In Chile, for example, the World-Class Supplier Program, a public-private partnership between the mining companies BHP, Codelco, and Antofagasta Minerals; Fundación Chile and other governmental institutions; and more than 75 local suppliers has already developed over a hundred innovation initiatives since it was launched in 2009. Though the program has had a positive impact in the development of the knowledge-intensive mining supplier sector in Chile, certain challenges need to be faced to bring this sector to the next level of progress. Among these challenges, it is necessary to escalate the program, promoting high-impact and long-term innovation projects, despite the usual incremental technological solutions developed until now[13].

Unlike most mining companies, the supplier sector holds in high priority the innovation agenda. A survey conducted on 432 firms from the Mining Equipment, Technology and Services (METS) sector in Australia, in 2015, revealed that for 63% of these companies innovation was core to their business strategy, driven mainly by a customer-focused vision, the necessity of staying ahead of the competition and direct solutions requirements from their customers[14].

A similar view is shared by the mining supplier sector in Chile. One hundred five of these companies were surveyed in 2019, revealing a high level of innovation-aimed expenditure. On average, they reported innovation expenses for 14.3% of 2018 revenues, reaching levels of 28.7% and 22.3% in the medium- and small-scale suppliers, respectively. Likewise, their innovation projects were driven mainly by direct solutions requirements from their customers, the necessity of staying ahead of the competition and by having innovation as core to their business strategy[15].

Besides the dynamics involved in the development of technologies, either by mining companies themselves or their suppliers, the mining industry is also recognised for its capacity to adopt technologies from other industries. ICTs have facilitated the introduction of important improvements in exploration techniques, mining, and processing. Simulations, sensor systems, automation and remote-controlled operations are some examples[8].

Nowadays, ICTs offer a new level of technological advance from the hand of digital transformation. The extractive industry finds itself in the early stages of adopting these new technologies. The full potential of their applicability for mining processes is yet to be unlocked. The implications of the current trends of Industry 4.0 for the mining industry are discussed and analysed in the following section.

CURRENT TRENDS AND MINING OF THE FUTURE

Defining a future view for an industry is not a simple task. Nowadays, the world is changing faster than ever before. New technologies are developed every day, impacting the way people live. The phrase "we live in a different world than the one where our parents grew up" does not completely cover the reality of the past few decades. For example, in current days, most people would not conceive their lives without their smartphones, and even though the first ones were commercialised in 1992, the massification of these devices came only a little more than a decade ago (e.g., the first iPhone was developed in 2007).

Nevertheless, in the case of the mining industry, it is possible to identify certain trends that can be of help to outline this future scenario. First and most evident, it is the major technological shift occurring across all industries: the so-called Fourth Industrial Revolution, or simply Industry 4.0, as the transition to the digital era. Then, social and environmental concerns are already compelling mining to look for safer, more efficient, and sustainable ways of conducting the business. Reduction of energy and water consumption, lower emissions, and waste generation are all factors that will be in the core of the "mine of the future."

Digital Transformation in Mining

Over recent history and since the beginning of industrialisation, several changes in production paradigms have taken place, promoted by the surge and application of novel technologies. As shown in **Figure 6**, the world has already seen three paradigm shifts, better known as industrial revolutions. Currently, a new transformation is in progress from the hand of cyber-physical systems and a set of new technology developments, e.g., automation, internet of things, and analytics[16,17].

The Fourth Industrial Revolution brings a new concept of industry, also called Industry 4.0. This concept is based on an advanced digitisation of production processes and the combination of internet-oriented technologies, allowing the connection between smart sensors, machines, and IT systems across the value chain. The implementation of these cyber-physical systems should bring a series of benefits, such as productivity increase by the automation of production and decision-making processes, reduction of waste, improvement of equipment utilisation, and maintenance costs reduction. However, Industry 4.0 is not only about the adoption of new technologies, but it will also demand organisational changes, specialised knowledge, and expertise[16,17].

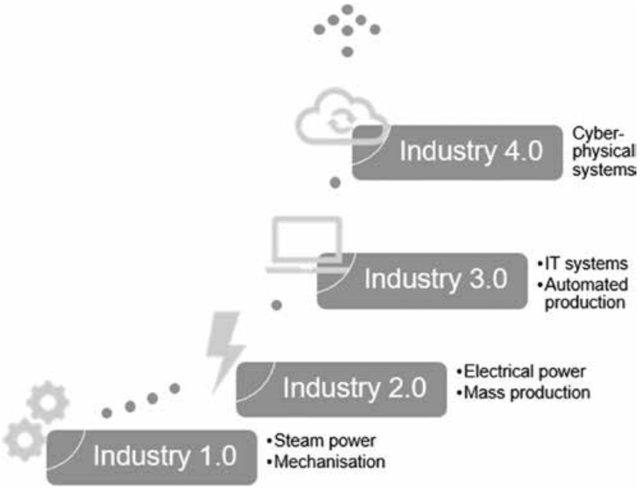


Figure 6: Industrial revolutions.

To achieve the scenario set by Industry 4.0, companies from all sectors, though at different speeds, are implementing the necessary changes at a technological and organisation level. These changes constitute the process of digital transformation.

What Is Digital Transformation?

Though the term digital transformation (DT) has been extensively used in recent years, mainly to describe the adaptation process of organisations to new digital technologies, there is not a unique definition for it. On the contrary, there are many. Acknowledging this situation, and after an exhaustive review of DT-related literature[18], offers the following definition: "a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies."

The reason for the existence of various acceptations for DT may lie in the differences among industries: each sector operates in particular ways; therefore, each digital technology will have a different impact, depending on the industrial sector adopting it.

The specific information, computing, communication, and connectivity technologies involved in DT also vary from one industry to another. In the case of mining, however, it is possible to identify a set of tools that will and are already affecting the processes not only at the mine site but across the operational and corporate units within a firm.

Key Technologies in the Digital Mine

DT is a transversal process of change across the complete value chain of the mining industry, from the exploration to the production of final products, their commercialisation, and even the closure of operation sites. Experts, companies, and government agencies have been discussing how the "digital mine" should look like while advancing forward in the DT process. **Figure 7** shows how modern digital technologies are and will keep affecting the different areas of the business.

As shown, novel technologies are producing operational changes across the value chain, and their use is not necessarily exclusive for a specific activity. For example, intelligent operation centers are being implemented for both extraction and processing operations. Likewise, augmented and virtual reality, along with digital twinning, are tools that will enhance the design and construction of mining projects ("Establish" in **Figure 7**), and the extraction and processing operations.

While the view of the "digital mine" may vary among firms and organisations, it is possible to define a set of core technologies that represent the pillars of the DT in the mining industry[19-27]. These key elements are described below.

Automation, Robotics, and Remote Operation

These technologies might hold the highest level of implementation among the tools offered by DT. The first and more clear benefit of the automation of processes, use of robots in critical activities, and remote operation centers (ROC) is the improving of safety, by reducing the number of operators required in hazardous sites[25].

ROCs can also significantly reduce OPEX and CAPEX of mining operations. Since less workforce is needed at the mine site, fewer or none supporting infrastructure is required, such as housing installations, hospitals, or schools. Also, other expenses are reduced, such as transportation of operators. The impact on costs is larger as the location of the mine is more remote, distant, and isolated[25].

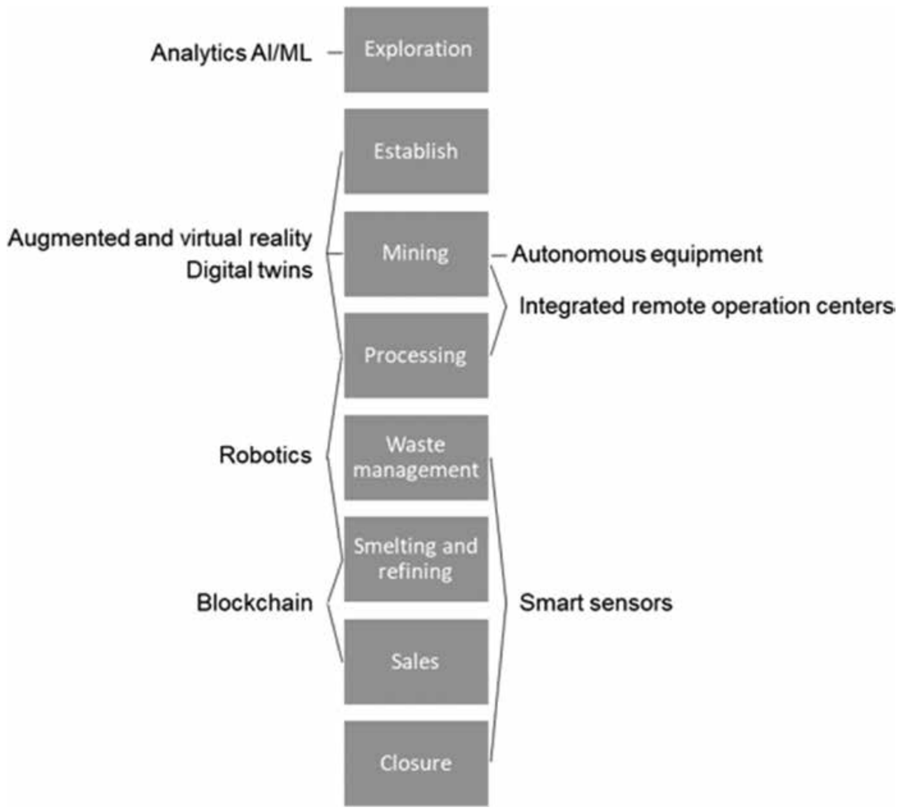


Figure 7: DT technologies in the different stages of the mining value chain. Based on[19,20].

The use of autonomous equipment, such as hauling trucks, LHDs, and drillers, is expanding rapidly. For example, global equipment manufacturer Caterpillar has already provided more than 239 autonomous trucks for large-scale mining operations in Australia, Brazil, Canada, and the USA[28].

Similarly, Komatsu holds a total fleet of 141 autonomous trucks distributed in Australia, Canada, Chile, Japan, and the USA. In Chile, these vehicles operate in Codelco's mine Gabriela Mistral. Over the 10 years of operation of the mine, the use of autonomous trucks has allowed a significant collision risk reduction and high levels of productivity and tires performance[29].

By February 2020, a total of 459 autonomous haul trucks were accounted as active in mining operations around the world[30]. Though these equipment still represent less than 1% compared with the total of manual trucks currently operating,* they are characterised as high year-to-year growth: 32% in the 2019-2020 period and higher rates are expected for the next years, from the hand of significant investments made by major companies such as BHP, Fortescue Metals Group, Rio Tinto, and Hancock Prospecting in Australia and Suncor Energy and Canadian Natural resources in Canada.

In general terms, besides the benefits in safety, autonomous equipment enhance productivity and reduce operational costs, by increasing equipment's utilisation (due to the continuous operation), reducing variability in the production outcome, and improving tires and components performances[20,29].

Internet of Things (IoT), Smart Sensors/Real-Time Data Capture

IoT is understood as a network of physical objects, such as sensors, equipment, machinery, and other sources of data. The elements connected to this network can then interact, exchange information, and act in a coordinated way[31]. Thanks to advances in IoT technology, nowadays, it is possible to establish low-cost networks. Additionally, the development of smart sensors allows real-time capture of data from machines and equipment across the operation. This generation of data is the base to conduct an integrated planning and control, considering the different units within the operation, and support the decision-making process[20].

Analytics, Artificial Intelligence (AI)/Machine Learning (ML)

Due to the digitisation of processes, advances in IoT, and real-time data capture, mining operations have enormous amounts of data available regarding production, processes, and performance of machines, among others. Through advanced analytics methods, it is possible to transform this information allowing its use for a better planning of activities and to support fast and effective decision-making processes for the operation. Predictive models can also be developed to enhance maintenance of equipment, therefore improving productivity[21].

AI/ML methods are also being applied for mineral prospecting[32-34]. It is expected that these methods will optimise the prospection and exploration activities, reducing costs and improving their accuracy.

Digital Twinning

The concept of digital twinning refers to the construction of a digital model of the physical operation. This is possible using the geological and engineering information of the site, but more importantly, thanks to the real-time data generated from the sensors connected across the operation. With the digital twin of the mine, it is possible to perform simulations and predict potential failures or downturns in equipment performance. Thus, the digital twin constitutes a useful tool to improve operational planning and reduce operational costs, by avoiding unexpected interruption in production processes and optimising the maintenance of equipment[20,21].

Current Status of DT in the Mining Industry

In its study of 2017, the World Economic Forum and Accenture estimated a potential benefit for the mining industry, as a consequence of DT, of US$ 190 billion over the period 2016-2025, equivalent to approximately 9% of the industry's profit[26]. Correspondingly, in the USA, the mining industry has been included among the group of sectors with potential to increase productivity from the further digitisation of its assets, customer relations processes, and transformations in its workforce[35]. These expectations are aligned with the results of a survey conducted by Accenture in 2014 among executives from 151 mining companies around the world. In this, 85% of the surveyed executives reported that their companies were strongly supporting internal DT initiatives and 90% that the DT programs were already elevated into strategies and high-level decision-making[25].

However, the level of overall digitisation of mining is still low, when compared with other industries. By 2014, though DT was mentioned in six out of ten of some of the largest (by market value) global mining companies' annual reports**, qualitative benefits from DT were reported only by three of them and only one presented actual quantitative gains[25]. This confirms that, though DT has claimed a relevant position among mining companies' concerns, on average, the industry is still in the early stages of this transformation, and most of the potential benefits are still to be unlocked.

Correspondingly, a survey conducted on 105 companies from the mining supplier sector in Chile in 2019 revealed that 59% of them perceived a medium level of interest from the mining companies to incorporate DT-related technologies and 32% a low level of interest. Only 9% of the surveyed firms perceived a high level of interest from mining companies to incorporate these technologies in their operations (**Figure 8**). Regardless, most of these suppliers are already developing or will

* According to data from The Parker Bay Company. Available in: https:// parkerbaymining.com/mining-equipment/mining-trucks.htm

** Companies in this analysis: Rio Tinto, BHP, Vale, Glencore, Anglo American, Codelco, Fortescue Metals Group, OCP Group, Freeport-McMoRan, and Nornickel develop in the next 5 years products or services incorporating technologies 4.0, being remotisation, automation, smart sensors, and analytics the most frequent ones[15]

In general terms, though DT is frequently mentioned as one of the main concerns among most large-scale mining companies, which over the years has generated great expectations regarding its benefits, the overall level of digitisation of the industry remains low. Nevertheless, there are several cases of mining operations where a high level of digitisation and automation of its processes has been achieved. LKAB's iron ore mines, Kiruna and Malmberget, located in northern Sweden, are operated under a combination of remote-controlled and fully automated equipment for drilling, blasting, and hauling processes. Moreover, full automation and electrification are core elements in the future plans for deeper levels, for which development KLAB has been working in close collaboration with high-tech companies, such as ABB, Epiroc, and the Volvo group[36]. Similarly, the Syama underground gold mine in Mali, owned by Resolute, constitutes the first fully automated mine, incorporating an automated haulage system, automated rehandle level, and mine digitisation[37,38].

Likewise, some technologies present a greater level of adoption across the mining industry than others. For example, autonomous and semi-autonomous equipment, such as trucks, LHDs, drills, and trains, started to be tested more than a decade ago (in some cases, even before); some have been successfully operating for several years now and are rapidly spreading[28,29,39]. In the same way, many companies have implemented ROCs to control their operations remotely. In Chile, for example, Codelco has a ROC for its mine Ministro Hales and it is developing centers for three more of its divisions[40]. BHP has also implemented its Centre of Integrated Operations (CIO) in Santiago, Chile, from which it will coordinate all its operations in the region.

Smart sensors and monitoring systems are also already generating large amounts of data. However, the wide and successful application of advanced analytics to support and gradually automate the operational decision-making processes is still to come. Today, its use remains mainly in the construction of predictive models for maintenance purposes and the visualisation of data to support human decision-making.

Challenges in the Implementation of DT

For the period 2019-2020, the "digital effectiveness" has been identified as the second most relevant risk for the mining industry[41]. It highlights the importance of advancing in digitisation, as a necessity for companies to remain competitive. The main risk lies then on the fact that DT is often perceived as a task exclusive of the information technology (IT) area. Nonetheless, to achieve a truly effective and value-creative transformation, it must be carried out as a joint task across the organisation, with a shared view of the business goals and a strong commitment from the top management. Otherwise, DT initiatives will remain as isolated IT projects, with no significant benefits considering the investments involved[22-41].

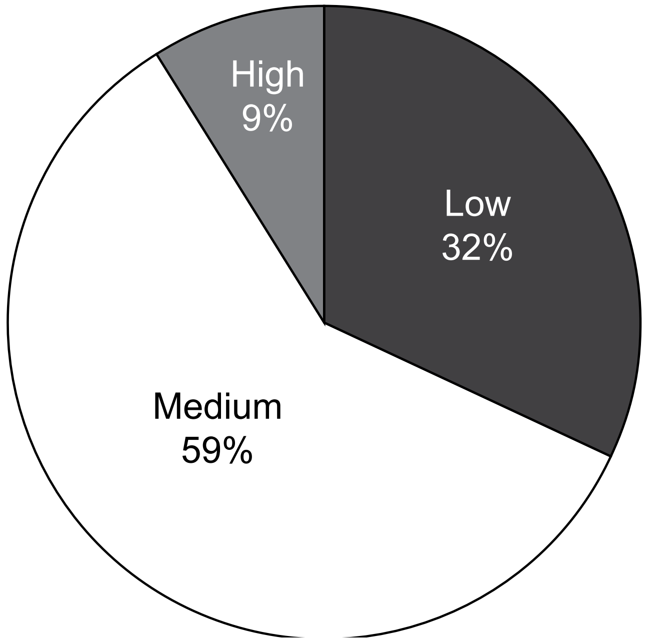


Figure 8: Level of interest of mining companies in Chile in 2019, perceived by the mining supplier sector, regarding the incorporation of DT-related technologies in their operations. Based on[15].

Ensuring the convergence of IT and OT (operational technology) is also key for a successful DT. These areas have traditionally worked by different paths: IT closely to corporate and support systems, while OT running core processes at the operation site. However, the automation of processes requires an integrated IT/OT management[20].

DT is a process of change that goes beyond technology. As mentioned in the first paragraph of this section, it requires coordination across the whole company. But it is also important to understand what this transformation will mean at an organisational level[22]. Structures will suffer changes by the automation of processes and introduction of new technologies and methods. For example, a recent study revealed that around 80% of the current labor competences in the mining sector in Chile will potentially change in the middle and long term as a consequence of the technological progress. Even more, at least 40% of them have a high probability of being replaced by automated processes[42]. This situation must be considered and evaluated. The new structures must be designed in advance and action must be taken to prepare the employees for these new arrangements. New knowledge and skills will be required, so the firms should also invest in the proper training programs to face DT.

Finally, in an increasing digital environment, a special focus must be put in cybersecurity. DT brings a wider connectivity among equipment and sensors but also between different business units. The company could then be exposed to greater risks of security breaches. For this reason, cybersecurity constitutes a fundamental element in DT[20,25]. In fact[41], also classified this issue as the fourth most important risk for the mining industry in 2019-2020. To overcome this risk, a solid "cybersecurity culture" must be promoted in every level of the organisation, incorporating new security-related practices in the daily responsibilities of the employees, along with the

measurement of relevant KPIs and a periodical revision of the adopted strategies to evaluate their effectiveness and generate improvements, if necessary[41].

Mining beyond DT

In parallel with the technological wave brought by the digital transformation, a series of other trends have been gaining relevance in the mining industry over recent years. Driven by safety and environmental concerns, cost reduction, enhancement of efficiency, and productivity in the operation, or a mix of these motives, these trends are complementary to the technologies 4.0 and offer an idea of the future paths that mining might follow.

Electromobility

Electromobility, as the development and use of electric-powered vehicles, is a technological trend across industries. From personal-use cars and public transportation vehicles, to heavy machinery, electromobility offers an economical and more environmentally friendly alternative to the use of fossil fuels.

Mining is especially affected by this paradigm change. Most mobile equipment in mining operations has been historically powered by internal combustion engines (ICEs), using diesel fuel. While the impact of the negative aspects of these engines might be bearable in open pit operations, in underground mines, where ventilation can account for up to 25-40% of the total energy costs, the situation is different[43]. Diesel ICEs emit exhaust gases containing a series of pollutants, such as unburned hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and diesel particulate matter (DPM). Additionally, a large amount of heat is also produced. All these elements increase the demand for fresh air flow in order to ensure a proper working environment for operators and equipment, having a significant impact on costs[44].

Moreover, due to the increasing environmental and safety awareness in the industry, regulations regarding the admissible levels of pollutants have become stricter in the past decades and are likely to become even stricter in the future. At the same time, after exhausting shallow deposits, mining is moving to deeper locations, aggravating the temperature conditions[45].

Even though some methods to provide electric power have been used for a long time already (e.g., trolley assist), today there are more incentives to look for electric-powered alternatives to replace the mobile equipment that have been predominantly running with diesel ICEs, like LHDs and haul trucks. According to the method used to supply the motor with electric energy, this equipment can be classified into five categories[45]:

- Trolley powered
- Battery powered
- Cable powered
- Hybrid ICE/electric equipment
- Hydrogen fuel cell powered

In **Table 1**, a summary of the differences among diesel-powered equipment and the categories mentioned of electric-powered equipment, according to key operational, environmental, and economic parameters, is presented.

In general terms, the main advantages of electric-powered over diesel-powered equipment are higher energy efficiency, higher service life (and, therefore, lower fleet requirements along the life of the mine), lower maintenance requirements, reduced generation of pollutants, heat and noise, and overall lower operating costs. The lower ventilation requirements can also have an impact on the CAPEX of the mining project, by reducing the size of ventilation adits and fans. On the downside, electric-powered equipment usually presents higher CAPEX and, depending on the type, can present some other disadvantages (**Table 1**). Also, the specific conditions of the operation can affect the preference for one specific technology, e.g., open pit vs. underground,

Table 1: Comparison between diesel-powered and electric-powered equipment. Compiled from[44-46].

Parameter	Diesel	Battery	Cable	Trolley	Hybrid	Hydrogen
Flexibility	High	High	Low	Low	High	High
Autonomy	High	Low	High	High	Medium	High
Specific energy	High	Low	High	High	Medium	High
Energy efficiency	Low	High	High	High	High	High
Overload capacity	Low	High	High	High	High	High
Additional infrastructure	No	No	Yes	Yes	No	Yes
CAPEX	Low	High	High	High	High	High
OPEX	High	Low	Low	Low	Low	Low
Maintenance requirements	High	Low	High	Low	Low	Low
Service life	Low	High	High	High	High	High
Refueling/recharging	Fast	Slow	None	Fast	Slow	Slow
Pollutants emission	High	None	None	Low	Low	Low
Heat generation	High	Low	Low	Low	Low	Low
Noise and vibration	High	Low	Low	Low	Low	Low

haulage distances, deepness and rock temperature, regulations of the country, and diesel and electricity prices. For these reasons, an integral techno-economic evaluation must be conducted in each case.

Nevertheless, a lot of effort is currently being put in R&D regarding electric-powered equipment, especially battery and hydrogen fuel cell-powered. These show the greater potential to replace diesel equipment, due to their high flexibility, besides the safety and environmental advantages already mentioned[43].

Main mining equipment manufacturers have already developed several models of battery-powered vehicles. The Epiroc's "zero-emission fleet" for underground operations includes the Minetruck MT42 Battery (articulated low-profile truck), Boomer E2 Battery (drill rig), and the Scooptram ST14 Battery (LHD)[47]. In the meantime, Caterpillar continues to develop its R1700 XE battery-powered LHD[48] and Sandvik works on its LH514BE battery-assisted LHD (as a combination of battery and tethered cable)[49].

Though the transition to electric mining equipment has been relatively slow, it is difficult to think of a mining industry of the future still depending on fossil fuels. The shift to cleaner sources of energy is global: industries and governments across the world are implementing renewable energy sources strategies and policies, regulations are becoming stricter and social scrutiny harder. Electromobility has arrived to stay and the mining industry is not excluded from its influence.

Invisible Zero-Waste Mining

The concept of a mining with no impact on the surface is not new. Underground operations have been using their waste material to backfill open cavities left after ore extraction, mainly for stability reasons and as a mean to reduce haulage costs. At the same time, this practice reduces subsidence effect and, therefore, the impact on the surface above the underground mine. However, it is not possible to use all the waste extracted due to interference with the operation (e.g., during early development stages). Also, not every mining method allows backfilling application (e.g., caving operations). Therefore, it is certain that impact on the surface can be significantly reduced, but most of the time it is unavoidable.

In this regard, in situ leaching (ISL), also referred to as in situ recovery (ISR), constitutes an alternative that minimises the effect on surface and generates practically zero waste. This method is understood as the in-place leaching of the ore, recovery of the enriched solutions, and their transportation to the surface for further processing.

ISL has been mainly applied in uranium mining (since it was first introduced in 1959 in the U.S.). There is also a record of successful cases of ISL applied in copper and gold deposits, though in relatively small scales. Besides typical characteristics of deposits (e.g., shape, dimensions, mineralisation, grade distribution), the most critical factors restricting its applicability are permeability, hydrogeological conditions in site, and the possibility of achieving selective leachability of the ore body[50]. Containment of the leaching solutions within the zone of interest to prevent the contamination of groundwater might be the greatest environmental risk regarding ISL[51].

From an economic point of view, ISL presents obvious advantages over traditional mining methods. Energy consumption is reduced, thus lower OPEX needs to be met. ISL also requires lower CAPEX for infrastructure and mine developments. Additionally, this mining method admits a high production flexibility and can be developed as a modular project, if desired[50].

Future widespread application of ISL depends greatly on the technological advance regarding permeability enhancement and hydrogeological management. Findings in preconditioning techniques used in caving operations are likely to be adapted and applied in ISL mining for permeability improvement. Pilot tests of in situ bioleaching have shown that it is possible to enhance permeability within the orebody after the application of conditioning methods, such as hydraulic fracturing and water pressure blasting[52], whereas the use of barriers, such as the gel barriers widely used in the oil and gas industry to control the flow of sweep and production, are also potentially applicable for this mining method as a tool for proper leaching solutions containment[53]. For these reasons, R&D efforts should be mainly aimed at the adaptation and improvement of existing technologies.

Besides environmental benefits of this method, if the restrictions mentioned can be overcome, ISL opens the possibility to exploit very deep low-grade deposits, currently uneconomic or technically infeasible to mine.

Continuous Mining

Continuous extraction and material handling systems have been used for many years in the coal mining industry. In surface operations, this has been carried out combining the action of bucket wheels excavators for the extraction and conveyor belt systems for the transport of coal and waste. Meanwhile, underground methods such as longwall mining and room and pillar (by using continuous miner equipment) have also offered continuous flows of material. However, due to rock strength, most metallic ore deposits do not allow mechanical extraction methods, making necessary the use of drill and blasting, therefore, impeding continuous operation.

Traditional mining methods combining drill and blasting, excavators for loading and mobile equipment for hauling (or LHD for loading and hauling, in underground mining), have high levels of operational inefficiency and low equipment utilisation: significant hauling cycles, in which at least half of the time the mobile equipment is empty, along with queues and waiting times at loading and dumping site, are some of the inefficiencies of these processes.

As discussed in the previous sections, increasing productivity and enhancing efficiency of operations are the main drivers for innovation. Then, the development of continuous extraction and material handling systems, outside the coal sector, are trends that will likely gain importance in the future.

Indeed, efforts in this matter have already been done in recent years. One example is the S11D iron mine of Vale in Brazil. This mine operates in four independent truckless systems. Each system consists of an excavator, a mobile sizer rig (MSR), and a mobile belt wagon (MBW) that connects to a belt conveyor (BC). Due to its continuous truckless design, the project has reported high operating productivity rates (about four times higher than Vale's typical rates in the region) and lower operating costs (approximately three times lower than Vale's traditional cost levels in the region)[54].

Initiatives in underground mining have also been developed. Such is the case of the Continuous Mining System (CMS) for caving operations, introduced by Codelco in Chile. This design considered the continuous and simultaneous extraction of broken ore from active drawpoints in a block or panel caving mine, by the combined action of feeders (located at the drawpoints), heavy weight conveyors, and primary crushers[55].

After almost 20 years of research and testing, the project was finally dismissed as a consequence of difficulties faced in the construction phase for its industrial validation[56]. Thus, the design did not get to be tested at an industrial level, and therefore, its real potential and applicability remained unclear. However, previous tests and studies suggested that great benefits in terms of productivity, costs, workforce requirements, and ramp-up duration can be achieved through the implementation of the CMS[57].

CASE STUDY: A CONTINUOUS MINING SYSTEM FOR CAVING OPERATIONS

The Continuous Mining System (CMS) was an innovation project developed by Codelco, in Chile, that intended to create a continuous material handling system for block and panel caving operations. With the objective of illustrating the impacts and implications of implementing a disruptive innovation project, the CMS initiative is below described and analysed.

Codelco

Codelco is a Chilean state-owned mining company, first copper and second molybdenum worldwide producer. It is divided into eight operating divisions located in the central and north of Chile. In total, Codelco possesses seven mining operations, four smelters and three refineries[58].

Divisions Andina, El Teniente, and Salvador include panel caving operations, thus the importance of projects such as CSM for the corporation. Moreover, Chuquicamata Underground Mine has been recently commissioned, a block caving operation that required over US$ 5.5 billion for its construction and will extend the life of Chuquicamata Division for at least 40 years.***

*** Information available in https://www.codelco.com/

General Description of the Project

The concept of continuous mining for caving operations was first introduced by Codelco and its Institute for Innovation in Mining and Metallurgy, IM2, in 1998. It was conceived as a tool to face the future challenges of underground mining, specifically the necessity of increasing extraction rates and improving safety[59].

This mining design was based on the following key elements[59,60]:

- Application of preconditioning to ensure a proper fragmentation of the rock mass and an uneventful flow of broken ore through drawpoints
- Continuous and simultaneous extraction from active drawpoints by dozer feeders, increasing extraction rate and utilisation
- Continuous transport of material by panzers
- Early size reduction of ore by sizer crushers
- Remote operation of the system, reducing the exposition of workers, and increasing productivity

The CMS comprised dozer feeders at the drawpoints, panzers to collect and transport the broken ore from the dozers to the sizer crushers, and finally the sizers themselves. Changing the operation of LHDs for a continuous material handling system also requires a reorganisation of the layout of the extraction level. The basic differences between the El Teniente layout (typically used by Codelco in its caving operations) and the CMS layout are presented in **Figure 9**.

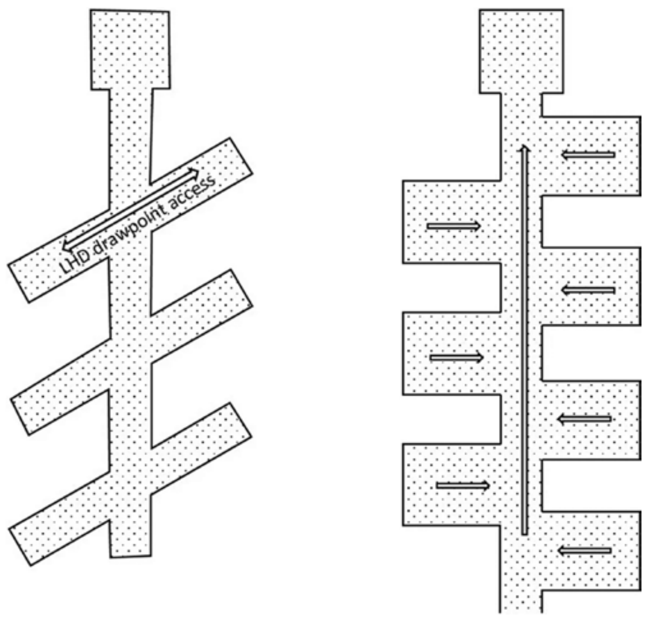


Figure 9: El Teniente layout (left) vs. CMS layout (right). Modified after[57]. Left layout dedicated to LHD access to drawpoints, whereas right layout with perpendicular arrangement dedicated to continuous material flow with panzers (flow direction indicated by arrows).

Process Validation of CMS

After years of research since the concept was first introduced in 1998, the process validation for the CMS design was carried out in three phases.

Phase I (2005): Dozer Feeder

The first phase took place in Codelco's Salvador Mine, in 2005. It was focused on the validation at a pilot level of the concept of continuous extraction. For this, the extraction of ore from one drawpoint by a prototype of a dozer feeder was tested.

The test showed the capacity of the dozer feeder to extract the ore from the drawpoint at a reasonable rate (200 t/h on average), allowing a proper flow within the ore column[55]. With these positive results, the process validation moved forward to Phase II.

Phase II (2006-2008): Module CMS

The second phase in the process validation of CMS was also executed in Salvador Mine. This time, a prototype of a modular system of continuous extraction, haulage, and crushing was tested. The module considered one haulage drift with four drawpoints, each one of them with a dozer feeding the panzer, which transported the ore to a roller impact crusher[57]. The module was built between 2006 and 2007 and the test itself carried out between 2007 and 2008. During this period, approximately 200,000 t were extracted in total. The results achieved in Phase II were satisfactory, in terms of the performance of the different equipment and their interaction, though the roller impact crusher was dismissed for further tests due to its low availability and high components wear. In its place, a sizer crusher was incorporated afterwards[60].

Phase III (2012-2016): Industrial Validation of CMS

Due to the promising results in previous phases of validation, the company decided to move forward to Phase III, to validate at an industrial level the CMS method. This test aimed to evaluate the performance of the CMS method under real operating conditions, in Andina Division of Codelco. The design considered a sector of four haulage drifts (equipped with panzers) and eight drawpoints per drift (each one of them equipped with a dozer feeder), and a total test period of 38 months[57].

Phase III was defined as the validation test of CMS for its application in the Chuquicamata Underground Mine Project, which commissioning was planned for the first semester of 2019. In this sense, the main expected benefits from its applicability in the Chuquicamata Underground Mine originally were[57]:

- Instant production rate: 3 t/m2-day
- OPEX: 20% lower
- Workforce requirements: 30% lower
- Ramp-up period: 25% shorter
- Improvements in safety and energy efficiency
- Net present value for its application in Chuquicamata: US$ 1000 million

The construction of the test module started in 2012. However, due to significant deviations in the execution period and budget, the works were stopped in December 2015. After more than 2 years of being paralysed, and in the light of new studies and re-evaluations performed by Codelco, the project was finally cancelled in 2018, totaling US$ 138.1 million of loss[56].

Analysis and Discussion

From Codelco's experience in the process validation of the CMS innovation project, several key elements can be identified, and lessons can be learned:

Time required for Process Validation

Developing an innovation project for a technological breakthrough often requires long periods of time. Since the idea is conceived, conceptual studies must be carried out before initiating pilot and industrial validation tests. In the case of Codelco's CMS, over 20 years passed since the concept was first introduced until the industrial validation project was finally cancelled. During this time, other technologies are developed, which can be incorporated in the innovation project being tested, changing its potential value and future impact of its application. Specifically, during the process validation of CMS, significant advances were made in preconditioning techniques and digital technologies (e.g., automation, robotics). The project team must evaluate the impacts of new technologies developed along the way and incorporate them in the project if they prove to add value.

CAPEX and Execution Period Estimation

Process validation can be expensive, especially the industrial validation phase. Special care must be taken in the economic evaluation that justified the project and in the execution time and budget estimation. CMS project was stopped and finally cancelled due to problems in its construction phase, not because of unsatisfactory results of the test itself: this did not even get to be executed (similarly, also the first Epiroc Mobile Miner – back then Atlas Copco – was initially not accepted for prototype testing by the foreseen mine site[61]).

Infrastructure Required and Coordination with the Operation

New designs for extraction and material handling methods must be proved under real conditions for their industrial validation. For this, first the company needs to have access to ongoing mining operations, of its own property or coordinate with another company, in other cases. Then, a proper coordination with the current operation must be conducted, to minimise interferences and ensure the availability of resources (e.g., energy, water).

It is important to highlight the relevance of the CMS project, regarding its potential to improve extraction rates and safety in caving operations. Material handling systems through batch operations, such as the use of trucks and LHDs, are highly inefficient, from a macro point of view. Equipment show low levels of utilisation and the productivity of the overall operation remains restricted. The design proposed by the CMS initiative offered the possibility of achieving higher production levels with lower requirements of active area, reducing CAPEX and OPEX, and gaining future dividends of the project earlier in time. All these factors have a positive effect on the economic indicators of a mining project: net present value increases and payback period is reduced, for example.

Finally, continuous mining and automated operations are trends that will likely shape the mining of the future. Initiatives like the CMS design should not be immediately dismissed, especially considering that this particular project failed in the construction stage of its industrial validation phase, having no chance to prove its applicability (or inapplicability) in a real operation.

CONCLUSIONS

Innovation plays an important role in the mining industry as a tool to improve the efficiency of its processes, reduce costs, but also to meet the increasing social and environmental concerns among communities and authorities. Technological progress has also been crucial to allow the exploitation of new deposits in more complex scenarios: lower ore grades, extreme weather conditions, deeper deposits, harder rock mass, and high-stress environments.

That is, the importance of innovation for the mining industry, as a critical factor in the improvement of labor productivity through past decades, was analysed. Though its relevance, mining companies usually show low levels of R&D intensity, similar to mature industries and far from high-tech sectors. The tendency to vertical disintegration has led firms to focus on their core business, relying mainly on equipment manufacturers and suppliers for the development of innovative solutions. Also, collaborative alliances between mining companies, suppliers, and research centers share a significant participation in the development of new technologies.

Nowadays, several technological trends can be identified as main factors that will shape the mining of the future. The first and most relevant one is the digital transformation (DT), as the process of adoption and incorporation of a set of tools, the so-called technologies 4.0, into the mining business. Automation, robotics, remotisation of operations, internet of things, analytics, and digital twinning, among others, have the potential to enhance processes along the whole value chain of mining. However, though DT is frequently mentioned as one of the main concerns among most large-scale mining companies, the level of digitisation of the industry remains low, indicating that most of the potential of DT for the sector is still to be unlocked. The main challenges that firms must face to achieve a successful digitisation are the commitment and joint-task coordination between the different business units, implementing proper organisational structure changes, and promoting a new cultural mindset regarding cybersecurity strategies and their continuous improvement.

Other important trends are electromobility, invisible zero-waste mining, and continuous mining. These concepts answer the necessity of building a more sustainable and efficient industry, reducing the environmental footprint, and enhancing safety of mining operations. The replacement of fossil fuel-powered vehicles is a "must" in a world moving away from such energy sources to cleaner ones, and stricter safety and environmental regulations being implemented all around the world are a reflection of that. Every day more companies are evaluating the incorporation of electric-powered fleets into their operations, as existing technologies can already offer economic alternatives, while R&D keeps advancing in this matter.

Invisible mining strategies, such as in situ leaching methods, have minimal impact on the surface and surroundings, and generate practically no waste. Yet, for a widespread application of this mining method, progress must be made in rock mass permeability enhancement (e.g. preconditioning techniques) and hydrogeological management, to ensure an optimal leaching process, in the first case, and minimise risks associated with groundwater pollution, in the second one.

Finally, though the concept of continuous mining has been applied for many years in the coal mining industry, its application in other mineral sectors has the potential to increase productivity, reduce costs, and improve safety, along with technological tools brought by DT, such as automation, robotics, and remotisation of operations.

REFERENCES

1. Bartos PJ (2007) Is mining a high-tech industry? *Resources Policy* 32(4):**149-158**
2. Cambridge Dictionary. INNOVATION | meaning in the Cambridge English Dictionary. https://dictionary.cambridge.org/dictionary/english/innovation. Accessed 7 Jan 2020
3. Jara JJ, Pérez P, Villalobos P (2010) Good deposits are not enough: mining labor productivity analysis in the copper industry in Chile and Peru 1992-2009. *Resources Policy* 35(4):**247-256**
4. Fernandez V (2018) Copper mining in Chile and its regional employment linkages. *Resources Policy*
5. Tilton JE, Landsberg HH (1999) Innovation, productivity growth, and the survival of the US copper industry. *Productivity in Natural Resource Industries*: **109-139**
6. Aydin H, Tilton JE (2000) Mineral endowment, labor productivity, and comparative advantage in mining. *Resource and Energy Economics* 22(4):**281-293**
7. Garcia P, Knights PF, Tilton JE (2001) Labor productivity and comparative advantage in mining: the copper industry in Chile. *Resources Policy* 27(2):**97-105**
8. Upstill G, Hall P (2006) Innovation in the minerals industry: Australia in a global context. *Resources Policy* 31(3):**137-145**
9. Filippou D, King MG (2011) R&D prospects in the mining and metals industry. *Resources Policy* 36(3):**276-284**
10. OECD (2017) OECD Science, Technology and Industry Scoreboard 2017: OECD
11. Pietrobelli C,Marin A, Olivari J (2018) Innovation in mining value chains: new evidence from Latin America. *Resources Policy* 58:**1-10**
12. Stubrin L (2017) Innovation, learning and competence building in the mining industry. The case of knowledge intensive mining suppliers (KIMS) in Chile. *Resources Policy* 54:**167-175**
13. Alta Ley. El Programa de Proveedores de Clase Mundial (PPCM). https://corporacionaltaley.cl/noticias/el-programa-de-proveedoresde-clase-mundial-ppcm/. Accessed 10 May 2019.
14. AUSTMINE (2015) New realities, bigger horizons. Australian Mining Equipment, Technology and Services (METS) National Survey
15. COCHILCO (2019) Encuesta de Innovación en Empresas Proveedoras de la Gran Minería. Santiago, Chile

16. Lasi H, Fettke P, Kemper H-G, Feld T, Hoffmann M (2014) Industry 4.0. Business & Information Systems Engineering 6(4): **239-242**
17. Rüßmann M, Lorenz M, Gerbert P, Waldner M, Justus J, Engel P *et al* (2015) Industry 4.0: The future of productivity and growth in manufacturing industries. Boston Consulting Group 9(1):54-89 1398 Mining, *Metallurgy & Exploration* (2020) 37:**1385-1399**
18. Vial G (2019) Understanding digital transformation: a review and a research agenda. *The Journal of Strategic Information Systems* 28: **118-144**
19. Coombs D, O'Donnell C, Sparks J, Veiga P, Jones B (2019) Perspectives and opportunities in the mining equipment and services sector. Santiago, Chile
20. Deloitte (2017) The digital mine. What does it mean for you? Kalgoorlie, Australia
21. Bonomelli A (2018) Estrategia Digital Codelco. Santiago, Chile
22. Canart G (2018) Mining in the Digital Era. Aachen, Germany
23. Espinoza J (2018) Transformación Digital en Minería: la Clave de la Productividad Sustentable. Santiago, Chile
24. Romano V (2018) Mining 4.0: maximizing the potential as a premium, predictable company. Aachen, Germany
25. Sganzerla C, Seixas C, Conti A (2016) Disruptive innovation in digital mining. *Procedia Engineering* 138:64-71
26. World Economic Forum, Accenture. Digital Transformation Initiative: mining and Metals Industry; 2017.
27. Pino O (2018) Programa de Habilitación Tecnológica / Transformación Digital. Santiago, Chile
28. Mosqueira R (2019) Autonomía Open Pit. Santiago, Chile
29. Canelo A (2018) 10 Años de Operación Autónoma en División Gabriela Mistral. Codelco. Presente y Futuro, Santiago, Chile
30. GlobalData (2020) Development of autonomous trucks in the global mining sector
31. Jeschke S, Brecher C, Meisen T, Özdemir D, Eschert T (2017) Industrial internet of things and cyber manufacturing systems. In: Industrial Internet of Things: Springer; **3-19**
32. Carranza EJM, Laborte AG (2015) Random forest predictive modeling of mineral prospectivity with small number of prospects and data with missing values in Abra (Philippines). *Computers & Geosciences* 74:**60-70**
33. Chen Y, Wu W (2017) Mapping mineral prospectivity using an extreme learning machine regression. *Ore Geology Reviews* 80: **200-213**
34. Rodriguez-Galiano V, Sanchez-CastilloM, Chica-Olmo M, Chica-Rivas M (2015) Machine learning predictive models for mineral prospectivity: an evaluation of neural networks, random forest, regression trees and support vector machines. *Ore Geology Reviews* 71:**804-818**
35. Manyika J (2017) What's now and next in analytics, AI, and automation
36. Autonomous vehicles, electrification and automation with a focus on people. https://www.lkab.com/en/news-room/news/sjalvkorande-fordon-elektrifiering-och-automation-medmanniskan-i-centrum/. Accessed 8 Jun 2020.
37. International Mining. Resolute Mining starting to deliver automation benefits at Syama Underground - International Mining. https://im-mining.com/2019/07/30/resolute-mining-starting-deliverautomation-benefits-syama-underground/. Accessed 8 Jun 2020.
38. ResoluteMining. Syama - Project overview. https://www.rml.com. au/syama/. Accessed 8 Jun 2020.
39. Gustafson A (2011) Automation of load haul dump machines: Luleå tekniska universitet
40. Parada S (2018) Innovación en Minería - EXPOMIN 2018. Santiago, Chile
41. EY (2018) Los 10 principales riesgos de la industria minera 2019-2020
42. Consejo de Competencias Mineras (2018) Impacto de las nuevas tecnologías en las competencias requeridas por la industria minera. Santiago, Chile
43. Erdtmann B (2018) Productivity and safety enhancement with Siemens solutions for non-hazardous underground mines. Aachen, Germany
44. Varaschin J, de Souza E (2015) Economics of diesel fleet replacement by electric mining equipment. In: 15th North American Mine Ventilation Symposium
45. Paraszczak J, Svedlund E, Fytas K, Laflamme M (2014) Electrification of loaders and trucks – a step towards more sustainable underground mining. In: Proceedings of the International Conference on Renewable Energies and Power Quality (ICREPQ'14). Cordoba, Spain; **7-10**
46. Valicek P, Fourie F (2014) Fuel cell technology in underground mining. In: The 6th International Platinum Conference,'Platinum-Metal for the Future', *The Southern African Institute of Mining and Metallurgy*; **325-332**
47. Epiroc. Zero emission Epiroc. https://www.epiroc.com/en-za/innovation-and-technology/zero-emission. Accessed 8 Jun 2020.
48. Mining Technology. In charge: the battery technologies leading the way in mining. https://www.mining-technology.com/features/incharge-the-battery-technologies-leading-the-way-in-mining/. Accessed 8 Jun 2020.
49. International Mining. Sandvik's electric LHDs stepping up including new battery-assisted LH514BE model - International Mining. https://im-mining.com/2020/02/10/sandviks-electric-lhdsstepping-including-new-battery-assisted-lh514be-model/. Accessed 8 Jun 2020.
50. Seredkin M, Zabolotsky A, Jeffress G (2016) In situ recovery, an alternative to conventional methods of mining: exploration, resource estimation, environmental issues, project evaluation and economics. *Ore Geology Reviews* 79:**500-514**
51. Sinclair L, Thompson J (2015) In situ leaching of copper: challenges and future prospects. *Hydrometallurgy* 157:**306-324**
52. Schlueter R, Mischo H (2018) In-situ bioleaching in crystalline rockformations: comparison of conditioning methods for enhanced permeability. In: SME Annual Meeting
53. Batterham RJ (2017) Themine of the future – evenmore sustainable. *Minerals Engineering* 107:**2-7**
54. Scheepers E (2018) Vale's S11D Project. Aachen, Germany
55. Orellana LF, Castro R, Hekmat A, Arancibia E (2017) Productivity of a continuous mining system for block caving mines. *Rock Mechanics and Rock Engineering* 50(3):**657-663**
56. Codelco (2018) Memoria Anual 2018
57. Baraqui J (2014) Minería Continua: El Futuro de la Minería Subterránea. Santiago, Chile.
58. Codelco (2018) Investor Update October 2018. Santiago, Chile 59. Carrasco F, Encina V, Le-Féaux R (2004) Continuous mining for caving method. In: Proceedings ofMassMin 2004 Conference; **79-82**
60. Orellana LF (2012) Evaluación de variables de diseño del sistema de minería continua a partir de experimentación en laboratorio. Master in Mining, Santiago
61. RamströmM.Mining Industry Game Changer: Atlas Copco News. http://www.atlascopco.com.au/auus/news/companynews/amining-industry-game-change.aspx. Accessed 25 Dec 2016.

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