MINES OF THE FUTURE

Version 1.0 (Major Findings)

Society of Mining Professors
Societät der Bergbaukunde

2019

Published by

Society of Mining Professors / Societät der Bergbaukunde (SOMP)

https://miningprofs.org

ISBN: 978-0-7334-3865-3

FOREWORD

The Society of Mining Professors/Societät der Bergbaukunde (SOMP) (https://miningprofs.org) is a vibrant society representing the global academic community and committed to making a significant contribution to the future of the minerals disciplines. The main goal is to guarantee the scientific, technical, academic and professional knowledge required to ensure a sustainable supply of minerals for society. SOMP facilitates information exchange, research and teaching partnerships and other collaborative activities among members.

SOMP created the "Mines of the Future" project to produce a high quality, internationally focused reference report and established an editorial committee which invited academic and industry thinkers, and technologists to contribute to the report. The editorial committee and contributors are listed on Pages IX & X.

This report provides a vision of the mines of the future, for 2030 and beyond, and the impacts on required skills and future educational curricula and research needs.

The Mines of the Future report has five main chapters, with the topics in each chapter focusing on the Current Status, the Future, and Transitioning to the Future:

- *Operational efficiency*
- *Novel mining systems*
- *Sustainable mining practices*
- *Education*
- *Research.*

This report is expected to be a leading international reference for the next 10–15 years – primarily for mining educators and researchers, but also for other mining industry stakeholders such as mining companies, equipment suppliers, governments and other interested parties. This report is the summary of the comprehensive report which is available separately.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

THE MINING INDUSTRY IS VITAL

Mining production is vital for socio-economic development and is connected to almost every business value chain. The global minerals industry has expanded over two centuries and now produces a wide range of minerals.

THE INDUSTRY IS FACING CHALLENGES

The minerals industry worldwide is suffering from rising costs and increasingly difficult conditions such as deeper and steeper or unconventional deposits; lower ore grade or quality; geotechnical challenges; isolated mine sites and infrastructure challenges; lack of human resources and skill shortages; extreme mining conditions; a range of social and environmental challenges; and adverse community reaction to mining projects.

The ‘normal’ economic environment for mining has been either a boom or a bust. Despite the industry’s unpredictable cycles, the nature of mining and the techniques used have only experienced incremental change for almost a century.

Mining technologies have changed incrementally – linked to new technologies, different and changing orebody or deposit characteristics, market forces and issues of social license incorporating public acceptance, government approvals and standards, and self-imposed improvements in safety performance and expectations. Incremental changes and improvements will continue.

MORE THAN INCREMENTAL CHANGE IS REQUIRED

As many internal and external factors continue to pressure mining companies and their operations, there is a growing need for more than just incremental change. The minerals industry of the future must embrace new approaches to mining systems and technologies that represent quantum step-changes in how minerals are extracted and processed.

Our world will be different in the future, so the way of efficiently extracting mineral resources will also be different. Change is essential and inevitable. The expected exponential growth in new technologies and systems will have significant implications for the future minerals industry. Work processes and infrastructure will be more dynamic and decentralised, with personalised technology enabling increased mobility and accessibility.

THE INDUSTRY OF THE FUTURE WILL BE DIFFERENT

The broad minerals community must collaborate to develop a new way of thinking and a new approach to how it secures, nurtures and revitalises its social license to operate and establish an enduring innovation and research culture. To look beyond the current challenges, it is essential to develop an understanding of what the minerals industry might look like in the future.

2030 AND BEYOND: FOCUS ON KNOWLEDGE

For 2030 and beyond, the common goal is to fundamentally enhance the extractive business model of the minerals industry. We must also aim to foster and grow an R&D culture within the minerals industry, creating new job opportunities including more higher-degree qualified jobs through implementing new technologies in the industry.

The minerals industry must aim to improve and/or learn to adopt scientific and technological knowledge, and emerging technologies from other disciplines; enhance business capability and growth; ensure the global minerals industry's sustainability in a rapidly transforming technology landscape; and build effective and engaging strategic global partnerships.

The role of mining engineering schools is to develop the mining engineers of the future through curriculum changes and educational experiences. This requires collaboration between the mining industry and technological experts to accelerate both innovation and commercialisation; and implement the RD^3 (Research, Development, Demonstration & Deployment) approach to create a “Value Add” for the minerals industry by developing world-leading research initiatives with the highest ethical standards and integrity.

EDITORIAL BOARD

CONTRIBUTORS (IN ALPHABETICAL ORDER – BY SURNAME)

Professor Frederick Cawood, University of Witwatersrand, South Africa

Dr Kobus de Jager, Sibanye-Stillwater, South Africa

Dr Diana Drinkwater, Mineralis, Australia

Lana Eagle, Canadian Institute of Mining, Metallurgy and Petroleum, Canada

Professor Bruce Hebblewhite, University of New South Wales, Australia

Professor Michael Hitch, Tallinn University of Technology, Estonia

Susan Joyce, Common Ground Consultants, Canada

Professor Michael Karmis, Virginia Tech, USA

Professor Bern Klein, University of British Columbia, Canada

Professor Peter Knights, University of Queensland, Australia

Associate Professor David Laurence, University of New South Wales, Australia

Professor Bernd G. Lottermoser, RWTH Aachen University, Germany

Nthati Monei, Tallinn University of Technology, Estonia

Professor Jan Palarski, The Technical University of Silesia, Poland

Professor Serkan Saydam, University of New South Wales, Australia

Dr Karlheinz Spitz, Greencap, Indonesia

Dr Ian Thompson, ShingleSpit Consultants Inc., Canada

John Trudinger, Trudinger Consultant, Australia

Professor Tomás Vargas, Universidad de Chile, Chile

Bruce Watzman, National Mining Association, USA

Hermann Wotruba, RWTH Aachen University, Germany

OPERATIONAL EFFICIENCY

Coordinator: Serkan Saydam

Contributors: Frederick Cawood, Kobus de Jager, Diana Drinkwater, Bruce Hebblewhite, Peter Knights, Serkan Saydam, Bruce Watzman

Introduction

The mining industry has made various technological changes from the early 20th century to the 21st century by implementing new mining systems and technologies.

THE MINING INDUSTRY HAS ADVANCED FROM 'MODERN MINE' TO 'REAL-TIME MINE' AND THE INDUSTRY HAS INITIATED A NEW TERM, THE 'INTELLIGENT MINE'.

This development reflects advances of autonomy, from simple user interface and monitoring development, through to more complex features of perception, positioning, navigation and planning technologies. Mining in the 21st century requires innovations for *operational efficiency* where all systems are optimised for effective interface between the elements describing mining systems – i.e. how excavations, workers and machines interact synergistically with the environment that mines operate in and the combined impact these have on communities. Innovative management approaches must ensure that the marginal costs of production equal marginal revenue for mining in an unpredictable market. However, it is not possible to separate operational efficiency from sustainability, and mine health and safety matters.

Advanced technologies integrated into mining operational systems aim to improve productivity and create demand for new products and services plus sustained innovation, resulting in best practice in safety, cost and environmental compliance. From a technology perspective, some surface mines, specifically hardrock (metalliferous) mines, are already incorporating technology systems in their operational environment. This is mostly because these technologies are available and only need minor adaption to work in harsher environments than they were originally designed for.

The challenge now is also to apply advanced technologies to the much harsher and more complex underground mining environments. Focus areas include low-impact mining, reducing hydraulic and energy footprints, creating '*invisible mines'*, and adapting communication technologies as part of operational efficiency.

This chapter explores operational efficiency for safer, more efficient mines that are smart and operated by highly skilled workers. The goal is to develop an intelligent (smart) mining concept, so the industry can do more with less cost by taking responsibility for what mines do have control over – *operational efficiency*. This chapter presents a series of topics in the main areas of operational efficiency, however many of these topics are inter-related and also overlap with other chapters:

- Autonomous mining
- Big and smart data management
- Mineral processing
- Risk management

- Mine management practices
- Technology Management And Incremental Innovations.

Autonomous Mining

The mining industry is undergoing a profound digital transformation encompassing mobile computing, cloud data storage, big data analytics, advanced process control and the implementation of autonomous mining equipment.

Current Status

The development of autonomous mining equipment lags the process control. Advances in positioning systems, CPU capabilities, ruggedised computers, low cost laser and radio ranging sensors (Lidar and Radar) and centralised bus architectures have contributed to the rise of autonomous mining equipment. Most major equipment original equipment manufacturers (OEMs) now offer autonomous truck haulage options. Autonomous fleets of Komatsu, Caterpillar and Hitachi mining trucks are routine in iron ore mines and at least one coal operation in Australia (the Pilbara) and in copper operations in Chile. BHP Iron Ore has operated fully autonomous blast-hole drilling operations in their Pilbara operations since 2017.

Automation in underground mines, particularly in coal mines, is complicated by the need to ensure that all electrical componentry is intrinsically safe (that is, it cannot ignite any explosion). There are now at least two fully automated longwall shearer systems in operation in Australian mines.

A number of mining companies now supervise and remotely operate equipment from remote operating centres located in major urban centres. Some even use off-site services in other countries for specialised machine health diagnostics. Mines of the future will require fewer operators, but more highly skilled personnel to maintain, analyse and improve operations.

REDUCING COSTS AND INCREASING PRODUCTIVITY ARE DRIVING AUTONOMOUS MINING.

The need to both reduce the total cost of operations and enhance mining productivity as existing mines become deeper and head grades (quality) decline is driving autonomous mining. Automated machines do not need to take breaks which increases the operating hours for autonomous equipment. By eliminating sources of operating variance introduced by operators, enhanced fuel efficiency, greater tyre lives and extended component lives can be achieved.

The Future

One of the principal technical barriers to the uptake and interoperability of autonomous mining equipment in the mining industry is the lack of an agreed set of standards across the industry. OEMs employ different bus structures, with the most common being CANBUS or PROFIBUS. There is little agreement on standard communication protocols.

Developments from the introduction of autonomous vehicles by the major car manufacturers in conjunction with internet giants Amazon, Alibaba, Google, Apple and Uber, may provide a guide. Future city dwellers may no longer own cars but instead hail and rent autonomous vehicles using an Uber-like application. As the value of the passenger market significantly exceeds the market for autonomous mining vehicles, it is highly likely that technologies and standards developed by the automotive industry will find their way into mining operations.

AUTOMATION IN MINING IS DEPENDENT ON THE TECHNOLOGY DEVELOPED IN COMMUNICATION AND INFORMATION TECHNOLOGIES.

Increased mine automation will also change skill requirements and how the workforce is organised and located.

Transitioning to the Future

The challenges facing the autonomous mines are not just technical in nature. There are important social issues to manage in the transition to the future mine, such as workforce and social license.

It is unlikely that the increase in skilled workers for autonomous mines will counterbalance the loss of traditional operating roles. *"The mine of the future will have fewer employees and lower spending on domestic procurement for items that are linked to employees and new technologies"* (Cosbey, et al. 2016). This, in turn, may result in lower taxation collections and, perhaps more importantly, in-country procurement spends of mining companies which can account for around 60% of all company spend. Reduced contributions to the host state have *"implications for a firm's social license to operate, and beyond that, for the willingness of host states to allow investments in mining"* (Cosbey, et al. 2016). Mining companies need to be sensitive to these requirements. For example, companies that invest in local talent for service roles, such as some analytics functions, may be better perceived than those that do not.

Big and Smart Data Management

Big data, also called big and smart data, global connectivity and pervasive real-time analytics are changing how companies manage their business. Mines are capable of collecting terabytes of data on operational processes, however they currently extract only a small percentage of the information content of this data.

Current Status

In 2015, McKinsey & Company identified opportunities valued at US$370 billion annually through greater adaptation of data analytics across the mining industry. These opportunities relate to:

- deeper understanding of the resource base
- optimisation of material and equipment flow
- improved anticipation of failures
- increased mechanisation and automation
- monitoring of real-time performance versus plan.

The true value of analytics lies not in producing routine information, but in generating new insight on process performance.

The Future

A mining enterprise can be modelled as a chain of sequential processes, such as discovery, development, mining, processing, transport and shipping, each supported by a number of support functions such as finance, human resources, procurement and maintenance.

Sources of value for mining companies involve value creation (projects that enhance production or product quality); value protection (projects that enhance safety or address environmental or community concern) or value definition (defining ore reserves). Data analytics must target one or more of these value levers.

Applications can be classified as either enterprise or process analytics depending on their scope of coverage.

- Enterprise analytics aims to better integrate the mining value chain, either by facilitating information flow between processes or by integrating support functions across the processes they are designed to support.
- Process analytics encompasses both performance and maintenance analytics.
  - Performance analytics identifies sources of delay, rate and quality losses, as well as focusing on efficiency measures such as energy and fuel efficiency.
  - Maintenance analytics encompasses machine health monitoring, prediction of remaining useful life and root cause analysis.

A major opportunity is integrating and correlating data from different databases, but this is often complicated by the different storage formats used for data in different databases.

BIG DATA RETAINED IN MINES WILL ALSO BE MORE MEANINGFUL IF COMBINED WITH ARTIFICIAL INTELLIGENCE TO BE USED FOR DECISION MAKING.

The Internet of Things (IoT) is becoming very popular, with a clear trend towards the merging of IoT and artificial intelligence. The IoT will continue its strong growth and development due to the emergence of the Industrial Internet of Things (IIoT). With the current number of IoT devices and forecast growth, artificial intelligence and automation are becoming the real focus of operations in almost in all industries and security challenges are increasing. The Mine Internet of Things (MIoT) is a term just coming into use, however the new term for the future will be AIoT which is the combination of AI and IoT.

Transitioning to the Future

PERVASIVE, REAL-TIME CONNECTIVITY AND DATA ANALYTICS HAVE THE POTENTIAL TO GREATLY ENHANCE THE EFFICIENCY AND EFFECTIVENESS OF MINING BUSINESSES TODAY AND INTO THE FUTURE.

The growth of big data requires new skills and creates new job opportunities. Dr Hal Varian, Google's chief economist, interviewed in 2011 on trends in the analysis of data generated by Google's search engine, said: *"the sexy occupation of the next decade will be that of a statistician"*. A statistician could become known as a Big & Smart Data Analyst.

Mineral Processing

In the last 200 years, mineral processing and extractive metallurgy have developed into substantial and significant professional disciplines. The level of technological sophistication has steadily increased in response to increasingly complex mineralogy and decreasing ore metal content, as well as the stricter product quality demands imposed by end users.

Minerals engineers also need to be able to work effectively in multidisciplinary teams, with mechanical, electrical and specialist instrument engineers, as processing plants rely heavily on mechanical equipment and instruments. All team members need to understand the mine-to-value chain, also called 'mine-to-mill' from end-to-end.

Process plants of the future will continue to crush, grind, classify, float, leach and smelt, though the equipment mix will change and there will be mechanical design improvements. Plants will start to look different, have smaller footprints, and appear in surprising new locations. Some may be mobile. There will be fewer people, because processes will be monitored with cameras, microphones and other kinds of sensors.

Process selection and design will increasingly be driven by energy and water demand, social and community issues, and environmental factors related to disposal of waste and release of effluent, as well as capital and operating costs.

Current Status

COMMINUTION MEANS NOT WASTING ENERGY BY CRUSHING OR GRINDING MORE THAN IS NECESSARY.

Operational efficiency requires best practice in comminution by not wasting energy by crushing or grinding more than is necessary. Most ores cannot be reduced to the required liberation size by crushing alone, as crushers are not effective at producing product smaller than a few millimetres. Particles can only be reduced to the often required 50 to 100 micrometre size range by grinding in a mill, most commonly Semi-Autogenous or Autogenous Grinding (SAG or AG) mills or ball mills (Wills and Finch, 2015). New and more efficient types of grinding mills are emerging, for example stirred mills such as the IsaMill and the Stirred Media Detritors. Another size reduction technology for coarse particle breakage is the high-pressure grinding roll (HPGR) (Morley, 2010), which breaks particles by compressing them in a tightly packed mass between large rotating rollers.

Comminution energy can also be reduced by discarding ore that does not contain any valuable minerals early in the process, before energy is wasted grinding it to final liberation size. This is called coarse gangue rejection, and has been done for decades in magnetite circuits where magnetic properties allow rocks to be identified as gangue at sizes above 20 mm.

Dense medium separation has also been used for this purpose in Bougainville (Papua New Guinea) and Mount Isa (Australia) in the 1980s, and more recently at the McArthur River Mine in Australia (Wallace, Strohmayr and Cameron, 2015).

Physical separation exploits a physical difference like density, magnetic properties or electrical conductivity. An emerging physical separation field is sensor-based sorting (SBS), which separates on the basis of radiometric, colour, reflectivity, response to irradiation and other characteristics (Wills and Finch, 2015).

Real-time process monitoring is rapidly improving as the quality and reliability of sensors improves. However, fully automated mineral processing is still a long way off, at least for metalliferous ores, because of their variability and complex process requirements. Daily production still relies on the knowledge and creativity of humans. However, best practice requires constant evaluation of process performance against targets, such as monitoring and comparing daily or weekly results in the plant with results achieved on the same feed material in a laboratory setting.

Leading design engineers seamlessly integrate their disposal strategy into their overall process design. Management of waste and transport of concentrates are not issues to be addressed only when the primary design issues of liberation and separation have been dealt with.

The Future

To improve process sustainability, regular ore characterisation, process modelling and control, real-time in-stream analysis of process plant feed and intermediate streams, integrated mine and process optimisation (mine-to-mill) and a strong emphasis on good up-front design and planning are recommended.

FULLY AUTOMATED MINERAL PROCESSING PLANTS WILL BECOME A REALITY.

Geological data for resource definition gathered during the project resource definition phase from remote imaging and drilling logs will drive the mine plan. Individual ore blocks and waste will be tracked in real time to the concentrator or tailings storage. Mineral process engineers will be part of a multidisciplinary management team managing several operations simultaneously from a control centre in the head office. These operations will have more in common with oil rigs than current mining operations.

Dry processing of minerals such as iron ore, coal and some base metals will be common. Drier processing of base and precious metals will be achieved using flotation or leaching systems that can treat thicker slurries. Combined with improved dewatering processes and better internal water management, this will have an order of magnitude reduction in water consumption.

One visionary scenario for the mine of the future is that it will be deep underground and completely invisible. Ore will be fractured in-situ and leached where it sits. Environmental concerns about leakage of contaminated process effluent are alleviated by ensuring that processing takes place well beneath the level of the water table, or by creating physical barriers to contain mine effluent.

CIRCULAR ECONOMY WILL DRIVE MINERAL PROCESSORS TO COMBINE RECYCLING WITH CONVENTIONAL METALS PRODUCTION.

There will also be increasing levels of metal recycling, either in combination with raw material processing, or in stand-alone recycling centres. Standard mineral processing technology works just as well extracting metals from industrial or urban waste, though the feed presents very differently and there are challenges ensuring security of supply. Studies of the circular economy will drive mineral processors to look for more opportunities to combine recycling with conventional metals production.

Leaving waste underground is one of the main goals of the invisible mine of the future. Studies have demonstrated the potential of underground processing in combination with backfill for increased resource efficiency. The use of sensor-based sorting techniques for waste rejection underground has high potential. In most underground mining operations, the entire extracted ore is transported to the surface. For low-grade commodities, a major part of the transported mass contains only barren rocks. Sensor-based sorting can be used to separate valuable minerals from barren rocks at an early stage underground, reducing the mass which needs to be transported to the surface. Particles with no or low valuable content can be separated which reduces downstream operational costs. For mining techniques where backfill is required, near-to-face processing by sensor-based sorting can decrease mining costs. Operational costs for the beneficiation plant, especially milling costs, can be reduced, while higher contents of pre-concentrates increase efficiencies of processing operations. Sensor-based sorting can greatly increase the sustainability of raw materials exploitation.

Breaking rocks consumes an enormous amount of energy. Energy productivity in general is now regularly monitored by governments around the globe and energy efficiency is the primary sustainability driver related to comminution. Other drivers include dust, noise, heat and vibration, but energy is the primary focus, and will increase in importance as energy costs increase. The energy used in mineral processing is directly related to the amount of size reduction by crushing and grinding. Coarsening the grind in a concentration process will reduce energy use but will also have a negative impact on mineral liberation. Controlling grind size to provide just the right level of liberation is complicated.

The emerging science of geo-metallurgy provides tools and methodologies for this process (Bye, 2011). The use of alternative and renewable energy resources will also have great potential for future mineral processing.

Transitioning to the Future

Technology development in plant automation, modularisation and *operational efficiency* will continue. This will be coupled with innovative developments such as dry processing, use of salt-water for processing plants, and the large field of sensor-based sorting technologies where both technology developments and then scale-up to full production operations is required.

A number of commonly used mineral processing technologies are surprisingly inefficient. SAG, AG and ball mills waste a lot of energy, and hydrocyclones, used almost universally as sizing devices in grinding circuits, often misclassify 30%–50% of their feed. While this has been well understood by minerals engineers for decades, cyclones and tumbling mills are still installed in new operations because they are cheap, familiar, robust and easy to run. *Operational efficiency* will improve when these machines are removed from process plant circuit designs. Performance can be optimised by monitoring and controlling equipment.

Use of process instrumentation and control is key to improving modern mineral process plant operations. For the best outcomes, control systems need to be well designed by a multidisciplinary team with a deep understanding of the process requirements and instrument capabilities. Managing and maintaining the system also requires a high level of knowledge and experience, and good process control should encompass the entire comminution circuit, including materials handling, feed distribution and discharge systems.

Real-time monitoring of mineralogical properties of an ore, either by direct measurement or use of proxies, is available now using XRD, IR or electron scanning techniques. The use of this technology will steadily increase. Operations can combine this data with information in their ore resource model, backed by a solid understanding of the metallurgical characteristics of their various ore domains.

In parallel with technical developments, a holistic approach to the whole of mine operation is needed – an extension of the conventional concept of mine-to-mill, involving exploration geologists, mine planners, operators, processing specialists and environmental scientists to collaborate and optimise the entire process of resource recovery, to move towards the invisible mine of the future.

HUMANS STILL MAKE MOST OPERATIONAL DECISIONS AND ADJUSTMENTS, BUT INCREASINGLY GOOD OPERATIONAL MODELS WILL PROVIDE THE BASIS FOR FULL AUTOMATION.

If the right work practices and information flow protocols are in place, information can be used to make decisions about many aspects of process circuit operation such as blending schedules and stockpile management strategies, optimum tonnage targets based on known circuit bottlenecks, grinding mill loads and recycles, target grind size for optimum liberation, and reagent dosing levels for processes such as flotation, leaching or thickening. This produces real productivity benefits. This is the first step to full automation. Currently humans are still responsible for making most operational decisions and adjustments, but increasingly good operational models will support the process of full automation.

Risk Management

Health and safety in mining is regularly monitored through statistical records. However, many statistics are simply performance measures, and often just lagging indicators of how the industry has performed in the past. To continue to improve its health and safety record in the future, the industry must adopt performance practices and management systems that are proactive in addressing the root causes of health and safety problems and eliminate them from the workplace altogether. Risk management methodologies provide one such approach to achieving tangible and often very significant improvements in the health and wellbeing of mine workers and mine workplaces.

Risk assessment has been used in the mining industry in many countries since the 1980s, sourced originally from other high-risk industries such as the petrochemical, aviation and nuclear sectors. Risk assessment practices can be applied under any form of mine management or operational system, and there are many different forms of risk assessment tools available (from qualitative to semi-quantitative) such as Workplace Risk Assessment and Control (WRAC) analysis, fault tree analysis, Bow-Tie Analysis and others.

Every workplace will always involve hazards that can pose risks to workers or to mining systems and these must be recognised and managed in some way. There is no such thing as a risk-free environment in a mining scenario, or in any other aspect of daily life. Failure to recognise hazards and the risks they pose in the workplace allows accidents to happen, and management systems to fail.

THE HIERARCHY OF RISK CONTROL IS: ELIMINATE, MITIGATE AND TOLERATE.

A key component of risk assessment is the implementation of controls to either eliminate or mitigate the risk, if it is present at an unacceptable level; or controls to mitigate the consequence posed by the hazard.

- Eliminate: If an unacceptably high level of risk posed can be eliminated by changes to the design, or to procedures or through additional controls, this is the first-choice control approach.
- Mitigate: If elimination is not possible, then the second option is risk mitigation, to reduce the risk to a lower, more acceptable level.
- Tolerate: Finally, if the risk level is deemed sufficiently low to be acceptable under prevailing, existing controls, then that is deemed to be sufficient and no further control measures are needed. The concept of ALARP – As Low As Reasonably Practicable – is often used to describe tolerable, or acceptable residual risk levels.

Current Status

HSEC (Health, Safety, Environment & Community) encourages companies to move beyond simply complying with regulations to recognise the social and economic benefits of such an approach. As an example, the sector is pursuing now a goal of zero fatalities.

HSEC activities tend to be reactive in nature and linear in approach. The reality of the modern workplace suggests that the environment is more systems based – a set of activities and situations working together as an interconnected network. HSEC incidents are rarely simply cause and effect.

The CORESafety-USA approach focuses on preventing accidents before they happen and aims to achieve zero fatalities and a 50% reduction in mining-related injuries.

A Bow-Tie Analysis risk assessment approach is also a powerful means of identifying a full range of causes and their preventive controls, as well as consequences and their mitigating controls. The bow-tie approach has been adopted in a comprehensive coal industry-funded project in Australia, known as RISKGATE (Kirsch et al., 2014) which assembled a suite of risk assessments based on industry best practice, and built an online interactive knowledge database (http://www.riskgate.org), covering at least 18 main safety-related topic areas. The Australian RISKGATE team, together with Virginia Tech (USA), was funded by Alpha Foundation to build a prototype of the US version of RISKGATE (Jong et al., 2015, Restrepo et al., 2015).

Risk assessment methodologies and management practices are widely used in a number of mining industries around the world, primarily for safety-related issues, but also applied to mining system and equipment design, compatibility issues and similar applications. In countries that have actively pursued risk management as a way of doing business, such as in Australia or South Africa, the use of risk assessments and development of risk-based controls and procedures have led to risk-based management plans that cover all major hazard areas, such as ground control, spontaneous combustion, fire, inrush etc.

A development that has now become accepted, at least in Australia following the 1999 Northparkes Mines' airblast accident, is the concept of identifying (and hence managing) what are referred to as “core risks” for any mining system, at the feasibility stage of a project (Hebblewhite, 2003).

A core risk is used to describe any risk associated with a major hazard or potential hazard that is an inherent feature of a generic mining method. Almost by definition, core risks cannot be totally eliminated, and must therefore be controlled and managed during the life of the mining method or system of work.”

It is critical that once these core risks are identified, specific risk management plans are developed for each core risk, and they must be continually implemented throughout the life of the mine, as part of the overall mine management system.

An important external consideration that provides the background to effective and comprehensive risk management is the prevailing legislative environment in any mining country – both for HSEC generally, and mining legislation in particular. While mining-specific legislation will cover a number of specific mining industry technical requirements, the HSEC framework is generally more about provisions for ensuring a safe place of work, safe systems of work, and various forms of management and operator duty of care obligations.

In Australia, where risk management in the mining industry is well advanced and widely accepted by all stakeholders, these legislative regimes have developed over the last two to three decades into what can be described as a largely enabling legislative framework, where the mine management has a controlling responsibility for developing mine plans and systems of work – provided they are also capable of demonstrating to authorities that there has been a rigorous hazard identification process and an implementation of appropriate risk management strategies and controls that deal with all the hazards involved. This does not mean that mine operators can do what they like. They have a very clear responsibility to develop and demonstrate a well-constructed set of mine plans and designs and associated procedures that recognise and take account of all the possible risks that might manifest themselves in the mining operation. The system allows for innovation and progressive ongoing development of practices, but under a very tightly controlled set of processes.

The alternative to an enabling legislative environment is the "prescriptive" approach where the regulator develops a set of rules and standards, and requires all mines to comply with such rules, at the risk of citations, fines and other forms of penalty and embargo on future development, if non-compliance is detected. This form of legislation tends to stifle development and innovation and can lead to operations not taking full responsibility for their own safety management, but rather simply complying with the regulations – whether they are appropriate to the specific site conditions or not.

The Future

Risk management and mine safety in the future depends very much on external factors such as national legislative environments.

Mining companies should operate under enabling form of legislation, with risk-based management plans that address all major hazard and risk areas of their operations.

RISK-BASED MANAGEMENT PLANS MUST BE FULLY INTEGRATED INTO THE OVERALL MINE MANAGEMENT SYSTEMS,

and the various areas of responsibility and accountability clearly linked to individual position descriptions of all key personnel in the mine management structure. Even the best mines do not have such a transparent and fully integrated system today, but it is certainly achievable. The ultimate test, and expectation for the industry, is to focus on the safety outcomes and deliver a safe workplace for all personnel and equipment fleet on or about the mine site, and a healthy and safe workforce.

Implementation of an effective HSEC management system is a proactive way to prevent injuries and illness. While it will not and cannot guarantee that incidents will never occur, an effective HSEC management system will minimise the number and severity of workplace incidents and demonstrate due diligence and duty of care. The future of HSEC is to become a system, considering all contributing factors and conditions and their interrelationships, and moving beyond linear cause-and-effect thinking. Such a system, as exemplified by CORESafety-USA, is dependent on management leadership, commitment, and competency development and training. The system is proactive and takes a risk-first approach considering the range of eventualities, the probability or likelihood of an accident occurring, and assessing the level of severity.

Transitioning to the Future

At present, the mining industry has the full range of legislative environments – from a totally prescriptive approach in some mining countries, to a largely enabling approach in others. This diverse legislative background will take many years to change, but gradual change will occur across most mining countries. Even without such change, there is scope and value for mining industries to adopt and benefit from risk-based approaches to safety under largely prescriptive legislative regimes.

A broader acceptance of the concept of core risks associated with mining methods will occur, with corresponding responses in mining method decision-making and management systems.

The other major change already underway and likely to have a major impact over the next ten years or more is the development and adoption of the concept of Critical Control Management, as first identified by the London-based International Council of Mining and Metals in 2015 in a guide published on Health and Safety Critical Control Management.

HSEC management systems, such as CORESafety-USA, require the development of critical competencies including strong leadership, which can positively and knowingly affect an organisation's safety culture. The core competency is being able to manage the system through identifying and eliminating at-risk behaviours. Finally, HSEC systems must be continually measured against performance metrics to determine if the system is operating optimally or if modifications are required to meet the overall goals.

Mine Management Practices

The context of mine management practices is dynamic and ever changing.

TO REMAIN COMPETITIVE, MANAGEMENT PRACTICES HAVE TO EVOLVE REFLECTING THE GEOPOLITICAL, SOCIAL AND ENVIRONMENTAL BACKGROUND, PEOPLE SKILLS, EQUIPMENT AND MATERIALS USED.

Current Status

The availability of minerals and the demand for commodities determines the broad business model for mining. Mining is about logistics where the supply (resource availability) is determined by exploration activities. The viability of mining subsequently depends on the mining methodology applied and commodity prices (market demand). Resources will become increasingly scarce in future which will result in mining in more remote areas, deeper underground, in the sea or other planets. The consequence is that all aspects of the mining supply chain need to be dynamic and future ready.

Health and safety has become increasingly more important in recent years and has transitioned from being a modifier for mining companies to do business to now being a qualifier.

The Future

CHANGE MANAGEMENT IS KEY TO ENSURE STAKEHOLDER EXPECTATIONS ARE MET.

To be future ready the industry must consider increased requirements and challenges in safety, technology, management systems, environmental requirements, social expectation, legal requirements, political requirements, skills requirements, and production costs; and reduced availability of accessible resources, and variable commodity price and demand.

HEALTH AND SAFETY WILL CONTINUE TO BE A NON-NEGOTIABLE VALUE IN FUTURE.

The risk profile of mining in the future will be very dynamic as labour-intensive mining will increasingly be augmented by autonomous mechanised mining.

Leadership will have to ensure that management systems cater for a dynamic transition from labour intense mining practices to the increased use of technology. The expectations of society as well as those of the workforce will increase, resulting in new risks to be managed.

The recognition and subsequent assessment of risks and opportunities presented is crucial to ensure that management systems are put in place to address associated risks. More emphasis will have to be placed on all aspects of system design to support the introduction of new technology. The skills requirement and training for staff to manage and operate the mining systems of the future will have to be assessed, to ensure that the interfaces between people, technology (equipment), materials and the environment are synchronised.

Behaviour science will become more essential from a management systems viewpoint as the people and technology interface becomes more sophisticated. It is expected that fewer people will be required to increase production at a cheaper cost of production. In turn, the overall responsibility of individuals will increase and the consequences of non-performance or non-adherence to procedures will be more serious than previously. Management procedures and practices must cater for the new interface.

Transitioning to the Future

The increased sophistication in technology in a generally unsophisticated environment in some mining operations will pose challenges. More advanced equipment incorporating cutting-edge technology operating semi-autonomously will be deployed. Support services will be needed to ensure availability of the equipment, which, in turn, will have knock on effects on environmentally friendly management systems issues such as leadership, hiring and placement of staff, and equipment selection and training.

Input and output efficiency and productivity parameters of the applied technology must be relevant to enable proactive management. The energy associated with individual ‘autonomous’ machinery will increase as it is expected that fewer will do cheaper, but the consequences of something going wrong will increase compared to current practices. It is critical to put management systems in place to minimise the consequences.

Technology Management and Incremental Innovations

The mining industry operates in an ever changing environment including commodity prices, markets, labour and cost structures, and geological and geographical environment. Technology is used to deal with this world of change, to stay in business or to create new businesses. Technologies include not only physical hardware, but also operational procedures, organisational structures and management practices. Mining technology includes both the machinery and equipment commonly associated with mining and technologies that support mining such as monitoring, control and communications systems, and planning and design tools and services.

High technology projects are generally capital intensive and their benefits are uncertain and may not occur till far in the future. The reasons for adopting new technology can be grouped into the following categories, with many technologies involving a combination of these application areas:

- Improved productivity
- Improved safety
- Improved social license to operate
- Reduced cost and risk
- Improved sales value and revenue
- Adding more high-value assets
- Supporting service efficiencies.

Current Status

Innovation processes in mining are related to technological advances in the industry and the wider economy. Innovative technologies in mining not only advance productivity within the industry but generate demand for new supplies and services to the mining sector, which in turn spurs new innovations. Low market prices for products and resulting weak operating margins reduce the ability of the industry to raise the capital needed to invest in new technology.

Some examples of how new technologies can be implemented in a challenging underground environment with significant risks in depth, size, production rate and mining method are El Teniente block cave mine in Chile, Kiruna sublevel cave mine in Sweden and Ulan West longwall mine in Australia.

El Teniente mine, operated by Codelco, has implemented the following technologies successfully: remote process automation and control, real-time monitoring of rockmass behaviour, innovation in mine design and application of new techniques, and application of the concept of energy efficiency. The mine has also implemented technologies in mine management to improve productivity such as human resources management and maintenance management to achieve sustainable mining practices.

Kiruna mine, operated by LKAB, is considered the most modern mine in Europe and aims to be a carbon-dioxide-free, digitalised and autonomous mine.

Ulan West longwall mine, operated by Glencore in Australia, is considered one of the most technologically advanced underground coal mines in the world. It produces around 8 MTPA. The mine has implemented a series of new technologies and innovations in their mine planning and design, geotechnical monitoring, ventilation and processing and water management, health and safety.

Northparkes Mines, operated by CMOC in Australia, uses the block cave mining method and have successfully implemented autonomous mining systems, and applied innovations to their mine design, geotechnical monitoring and tunnel development technologies such as trials of tunnel boring machines, microseismic and remote monitoring for cave management, hydrofracturing for cave propagation, and electric loaders and jaw-gyratory crushers.

Cadia East Mines, operated by Newcrest in Australia, operates using the panel cave mining method to improve productivity and safety by implementing hydrofracturing to precondition the rockmass and new mine design techniques.

Mt Arthur coal surface mine, operated by BHP in Australia, operates using state-of-the-art technologies to improve productivity and environmental management. The mine has an excellent reputation in community interactions and implemented a series of technologies for noise management, visual impacts and blasting.

Iron ore operations in Western Australia operated by Fortescue, BHP and Rio Tinto provide more than 400 MTPA and the mines have used new technologies and innovations to improve productivity by applying innovative mine planning and water management systems, autonomous mining, environmental monitoring technologies, and remotely managed control centres.

The Future

In many cases, technology will have to be managed to achieve different tasks or performance levels than originally specified;

and it will often be replaced well before its useful life is over. Innovation must take place continually and systematically, and there must be a management environment that encourages innovation, and can accommodate, capitalise on, and reward it. A harsh financial environment can motivate managers to make major change in their operations to achieve significant productivity improvements.

It is imperative to have a clear reason for changing technology through identifying, selecting and justifying new or alternative technologies.

THE CHANGE PROCESS MUST EVALUATE HOW A TECHNOLOGY WILL AFFECT THE MINING PROCESS INCLUDING CAPABILITY, COMPATIBILITY, FLEXIBILITY, SENSITIVITY, SAFETY AND COST.

New needs of technology in the mining operation and process have to be carefully assessed. The downsides and negative impacts of technology implementation also need to be addressed. To achieve all, or any, of the perceived benefits of a new technology, an appropriate management system is needed. The management system must be able to manage the selection, introduction and ongoing operation of the new technology within the broader context of mining processes. Appropriate risk assessment, ergonomic considerations and ongoing risk management of the technology must be organised. Ongoing technical and process performance management must be introduced. The collateral effects of the overall system have to be carefully managed.

Transitioning to the Future

The majority of long-term commodity prices remain uncertain in the near future, which is forcing miners to be alert. Mining companies must focus even further on cost cutting and capital management to improve their place on the cost curve and still operate profitably. One of the most sustaining and long-term cost cutting techniques is implementing new technologies to improve efficiency in operations. Technological innovation for major international companies in any industry, including mining, is critical for success. An old mining proverb says *“miners like to be first to be second”*.

IT IS NOW TIME TO BE THE INNOVATOR AND MINING COMPANIES HAVE TO SUPPORT INNOVATION THROUGH RESEARCH & DEVELOPMENT.

The challenge is how to adopt and encourage a culture of innovation in mining companies.

SUSTAINABLE MINING PRACTICES

Coordinators: Michael Karmis, Michael Hitch

Contributors: Lana Eagle, Michael Hitch, Michael Karmis, Susan Joyce, Bern Klein, David Laurence, Bernd Lottermoser, Nthati Monei, Karlheinz Spitz, Ian Thompson, John Trudinger.

Introduction

The terms sustainability, sustainable development and sustainable mining practices are commonly used by most if not all mineral development companies today. The ideas have foundations in the 1980s and emerged from Brundtland's *Our Common Future* in 1987. They have evolved into the complex dynamic involving the interaction of social, biophysical and economic attributes of the world in which we develop our natural resources. Each of these attributes is deeply influenced by the network of stakeholders and actors that bear the responsibility to safeguard and preserve their attachment to the land, while at the same time recognising the need to develop mineral resources to the mutual benefit of society as a whole. Sustainable mining practices are those actions by companies that meet this responsibility to operate with recognition and respect for affected communities, to minimise the physical impact on the land, water and air, and to be an equitable partner and share the economic benefits of development.

This chapter examines the aspects of mineral development that characterise sustainable mining practices. A common element is *Communication* and the need for timely, plain or clear and respectful dialogue amongst all stakeholders.

The topics are:

- Community engagement
- Environmental management
- Acid mine drainage
- Water management
- Mine waste management
- Mine closure
- Energy efficiency
- Workforce diversity
- Indigenous perspective.

Community Engagement Has Grown into Social Performance

Community engagement is a process where companies work collaboratively with communities to address issues that will impact their wellbeing as a result of mineral resource development. This process ensures the community has an opportunity to voice their concerns and to contribute in a meaningful way as well as develop functional capabilities to participate to protect their interests and values.

Current Status

Social science phenomena are driving the need for change by the mining industry in community engagement and its logical measurement in terms of social performance. Most of these drivers from the social side are facilitated by and made much easier to manage through social media. Industry, on the other hand, faces technological change that it must embrace to ensure corporate sustainability, and this is reflected almost directly on balance sheets. Companies have come to understand the social dynamics around their industry and recognised that investing in social projects does not guarantee, far less compensate for, a poor relationship with host communities and other stakeholders.

COMMUNITY ENGAGEMENT IS ONE, ESSENTIAL ASPECT OF OVERALL SOCIAL PERFORMANCE.

The Future

A series of trends is driven by both internal corporate risk management and external societal changes. These are generally focused on the nature of the conversation with communities and how industry demonstrates its commitment to them as legitimate and equal partners. This will include the tenor and nature of consent, whether less formalised or through effective binding legal agreements, a shared vision and a clear explanation of risks associated with the development of the project, in terms that every involved party can understand. These aspects are not static, but always changing, and only through fair, open and timely dialogue can they be improved.

Transitioning to the Future

THE FUTURE OF COMMUNITY ENGAGEMENT AND SOCIAL PERFORMANCE LIES WITH INDUSTRY TO A LARGE EXTENT.

Industry must realise that the nurturing and development of effective relationships, and the costs associated with them, are an investment for the future and not just a line item of expenditure. Corporate Social Responsibility (CSR) is frequently used to define the social and environmental contributions and significance of corporate activities and action, which requires a behaviour shift rather than a philosophical shift. The measurement of social performance remains somewhat enigmatic, and a structure is required to reflect the financial advantages of doing it right. A new factor is the calculation of a Net Present Value (NPV) that puts economic numbers on social and environmental assets and risks. This will include developing a financial factor to incorporate social considerations such as the quality of social relationships. By reflecting the bottom-line impact of social performance, shareholders will then have a transparent lens into the operating behaviour of their company.

Environmental Management: Managing Effects During the Mine Life Cycle

In most mining scenarios, the environmental impact changes or evolves at each phase of the mine life. A careful predictive analysis of these impacts, and strategies to minimise or mitigate them altogether, is a key aspect of maintaining biophysical integrity and reducing negative effects on social wellbeing. Through effective planning, broader understanding and effective communication of the risks and outcomes of development are essential to a comprehensive environmental management approach.

Current Status

Proper concern and regard for the environment is fundamental for the success of an operation. As the levels of attention increase, so does the risk of being seen as an underperformer. A company's environmental management plan encourages going beyond simply meeting current regulatory standards to exemplify best contemporary practice at a minimum and, where possible, to eliminate any negative environmental effects. Most current environmental management plans incorporate environmental matters as a basic part of the planning cycle as well as obvious compliance with laws, regulations and prescribed standards.

Proactive companies actively participate in the development of evolving environmental regulation, and where possible, are advocates of environmental protection, compliance and emergency response. Any environmental management plan must ensure that the needs of the affected communities remain at the forefront and that full, timely and appropriate communication is a priority.

The Future

Conceptions of what is economically and technologically practical, ecologically essential, and politically viable are fast shifting. Implicit in altering approaches are differing philosophies of human nature relations.

ENVIRONMENTAL MANAGEMENT PLANNING IN THE FUTURE WILL INCREASE INTEGRATION OF ECONOMIC, ECOLOGICAL, AND SOCIAL SYSTEMS IN MINING.

Transitioning to the Future

The pathway to more integrated environmental management planning lies in a company's relationship with affected stakeholders and community members, such as a social license. Through effective and meaningful dialogue, acceptance as stakeholders as partners and governance structures that ensure and regulate performance through negotiated agreements, meaningful environmental management plans will become more relevant and encompass all three of the guiding principles of sustainable resource development: social well-being, economic sufficiency and biophysical integrity.

Acid Mine Drainage: Characterisation and Mitigation

Acid mine drainage (AMD) is a high priority in any mining operation where reactive sulphide minerals are present and the potential for oxidation exists. Through early characterisation, and spatial planning, the risk of acidic water generation can be managed effectively and the risk for discharge into the receiving environment controlled.

Current Status

Understanding the chemical behaviour and mitigation approaches to managing AMD has improved, with irreparable environmental damage seen increasingly less often. Significant national and international bodies have been established which has resulted in major scientific and technological advances effectively reducing the liability and risk of acid mine waters. The industry should be proud of success in this area.

THE EFFORT TO UNDERSTAND MANAGE AND CONTROL AMD IS A REMARKABLE SUCCESS STORY AND OUR SECTOR SHOULD BE PROUD.

The Future

As our global population is expected to grow from eight billion people to almost nine billion in the next decade, the pressure on safe and clean water increases at an even greater rate. It is critical that AMD is not part of the problem and that future mines must be established risk-free with AMD management and relevant discharge planning through the entire mine life cycle including post closure into perpetuity.

Transitioning to the Future

MORE RESEARCH IS REQUIRED TO ACHIEVE SAFE AND CLEAN WATER FOR SOCIETY.

More research is required on more energy efficient ways to clean discharge waters of dissolved solids, pH, nutrients, dissolved metals, and other ions. Early prediction of the occurrence and kinetics of potential acid generating (PAG) and neutralising (NAG) materials will allow more effective management measures.

Water Management

Water is the most precious input in any mining operation and its value must be preserved. In many mining regions, extensive infrastructure is required to supply the necessary water to operate processing plants, dewater mines, and provide cooling and dust suppression. Competition for this precious resource with other industrial applications or communities requires careful planning and consultation with all stakeholders to achieve a sustainable outcome.

Current Status

WATER CONNECTS MINING OPERATIONS WITH THE SURROUNDING LANDSCAPE AND COMMUNITY.

For most mining operators, water is seen as an asset, not a liability, and there is a global recognition that water is a precious resource. As commodity demand continues to increase, so does the demand on water and estimates suggest that half of mining infrastructure investment over the next decade will be in water-scarce areas consuming 10%–15% of capital expenditure.

The Future

The future of mine water is through risk-based management that considers both the strategic risks, reputation, limits to growth, social license, and operation risks associated with supply, excess water from extreme climate events, and water quality.

Transitioning to the Future

Companies have now recognised that the operating conditions of the recent past are no longer valid or acceptable to stakeholders and host communities. Comprehensive water management planning involves promoting responsible stewardship of water resources by providing education, incentives and collaboration with stakeholders.

Mine Waste Management

There is growing awareness that the amount of mine waste is unacceptable and that a sustainable management approach is required. One aspect is finding and developing new opportunities and uses for this material. In many cases the co- or byproduct value of this transformed waste material can have a significant impact on the financial viability of the operation itself.

Current Status

Mining activity has increased due to a significant increase in population, emergence of an affluent middle class, and an overall increase in demand for mineral resources. This is occurring alongside a heightened sense of environmental awareness and growing sense of society’s stewardship of the environment. The popularity of the ideal of a circular economy has prompted society to pursue a more sustainable form of development and careful monitoring of all activities related to mining, in particular the management of waste products (or byproducts of mineral production) during each phase of the mining life cycle.

CURRENT MINE WASTE MANAGEMENT IS THE PRODUCT OF THE CONSEQUENCE OF FAILURE.

The industry continues to learn from our mistakes, and even with the best planning and management of these systems, failures and accidents continue to occur. Often these failures are the product of operational failures, not structural failure. There is a need to consider each type of failure to better understand how they are interconnected.

Waste materials are often not recognised by operating companies as potentially economic products. The production of mine wastes is a cost element and a new paradigm must emerge where production byproducts have value in other ways not traditionally considered such as for building products and industrial feed applications.

The Future

New technologies and declining resources have created new found value from traditional mine wastes. Many rare earth elements, such as neodymium and europium, that are used in lasers, solar panels and televisions can be recovered from traditional mine wastes.

Transitioning to the Future

To transition to the future, it is imperative to revalue the byproduct materials traditionally discarded from metals and mineral production. A more holistic view is required to consider what current or future values are available in these materials and work towards complete resource utilisation.

Mining, Energy Efficiency and Innovation

Comminution, or the reduction in particle size, consumes over 3% of the world's generated electric power usage (Mining

Technology, 2019) and represents almost 50% of the total onsite mine operating cost (Jeswiet and Szekeres, 2016).

Current Status

It is generally accepted that the mining sector has little control over energy consumption, however this is only partially true. It may have limited options on how it obtains power for operations, due to location and lack of available infrastructure, but there is opportunity in when power is required and where it is applied. Like many aspects of mining system optimisation, energy efficiency is approached through incremental change to the design of unit operations and systems. The increasing attention and awareness of greenhouse gas emissions from industrial operations have caused mining operators and the sector as a whole to consider where emissions can be reduced or eliminated as part of an overall energy reduction strategy.

The Future

THE FUTURE OF ENERGY EFFICIENCY AND EMISSIONS REDUCTION IN MINING IS COMPLETE INTEGRATION OF THE MINING SYSTEM.

Opportunities for energy advantage start at the point where rockmass qualities are being observed, measured, recorded, and transformed into considerations on optimal blasting and particle size reduction, making the highly energy consumptive crushing unit operation more effective. Loading is also more energy efficient with highly blasted materials. Heat recovery and mechanical energy streams (i.e., fugitive energy) will become recycled secondary sources of energy, ultimately reducing the need and stress on existing sources.

Transitioning to the Future

More research is required to develop and make energy efficiency technologies more cost effective. Cost is not limited in economic terms (dollars and cents), but rather there are other 'currencies', such as the value-loss to the biophysical environment, associated with energy efficiency that have to be included in the overall profile.

Workforce Diversity - Gender

Even with increasing automation and autonomous mining systems, people will continue to be a critical asset in any mining operation. Gender equity requires the removal of systemic barriers to gender inclusion so that both men and women have the opportunity to enjoy meaningful and long-term careers in the minerals sector.

Current Status

For decades, the mining industry has been a male dominated industry and the effects of that gender imbalance remain. The perception that women participate best in jobs that require less strength and more administration continued until the reform of job equality acts in many countries. There has been a reasonable transformation in the work structure, and the employment of women in positions that were initially deemed "male jobs".

This has reduced the most noted gender barriers. However, in-depth progress is affected by both conscious and unconscious mental rejection, cultural beliefs, and general expectations of society towards men and women. Gender discrimination cases are still reported, and there is restricted transfer of knowledge between male supervisors and female trainees, pay gaps between genders, and few women in executive positions.

The Future

Gender practices will evolve to provide equal employee freedom to all. The future includes overcoming barriers created by cultural beliefs and transforming into an environment of employee awareness of gender equality, with consistent orientation and training focusing on inclusive and respectful working environments. Support and networking from women in mining groups and publicity on successful role models will help achieve balance.

SOLVING THE SYSTEMIC FACTORS CONTRIBUTING TO GENDER INEQUITY WILL ALLOW THE INDUSTRY TO DEVELOP SUSTAINABLY.

Reducing gender inequity means no gender pay gaps, equality in executive positions (relevant to qualifications and expertise), improved social security, and protection to create non-hostile working environments with infrastructure that accommodates all employees.

Transitioning to the Future

The transition to the future of mining with balanced gender roles is mostly dependent on the companies with a progressive social emphasis proving that diverse teams are more productive and innovative and that organisations with diverse leadership perform better. Legislation applied in the mining industry globally and the sustainability and development teams different organisations have are also important. Diversity and inclusivity leadership has a direct impact on corporate culture and helps to define goals, targets and areas for improvement. Appropriate legislation is evolving, providing the legal environment for change. There should be laws, mechanisms and macroeconomic policies that foster employee development.

Organisations can provide unconscious bias training projects that encourage personal commitment to adapting to modern-day gender roles and the legal implications. The transfer of training and skills plays a crucial role in the inclusion and development of employees. Thus, communication strategies should promote non-gender-based training and development. This could improve communication between male supervisors and female employees and vice versa. In addition, it will build confidence in all employees, knowing they are qualified to do the job.

Technology plays a major role in sustainable development in general, and the use of modern technology can overcome the misperception that women are physically unfit for labour intensive duties. Countries with a successful transformation in gender equality issues can be used as exemplary models for those that are still lagging behind.

Indigenous Perspectives and the Future of Mining

It is rare that mineral development does not intersect with indigenous people. The underlying principles that affect indigenous participation and acceptance of mineral development are mineral ownership and broader human rights. The minerals sector continues to develop its understanding of the innate relationship indigenous people have with the land and the need to afford a higher level of consideration and cooperation through specific negotiated production sharing and benefit agreements.

Current Status

Enhancing the level of contribution of indigenous people in mining should be based on cooperation and partnerships. Dialogue and negotiations in many jurisdictions are on a First Nations government to industry basis, particularly where treaty rights already exist. This relationship is founded in respect and acknowledgement of rights and interests. Negotiated agreements, such as Impact and Benefit Agreements, have, in recent history, been an enforced mechanism of land claim settlements and establish a mutually accepted schedule of responsibilities and obligations in the spirit of transparency, fairness and mutual respect. These agreements provide for a supportive relationship that fosters capacity building as part of the development process.

The Future

THE FUTURE OF INDIGENOUS PARTICIPATION AND COLLABORATION IN MINING IS FOUNDED IN THE SPIRIT OF AN EQUAL PARTNERSHIP.

The principles of social license apply to indigenous participation; however, the difference remains in the nature of the ownership of the underlying resource and the long-held tradition attachment and rights to that land. Negotiated production sharing agreements and Impact and Benefit Agreements codify not only a commercial partnership but also a substantive connection to grow skills and capacity in indigenous communities in a fair and transparent way.

Transitioning to the Future

The transition to the future of indigenous participation requires provision to build capacity to review and evaluate resource development proposals, contribute to decision-making, and equally represent their interests. The notion of community readiness relies on individuals having the skills and training to be able to take benefits that arise.

Mine Closure and Post-Mining Realities

Closure of a mining operation is inevitable and brings changes in the social fabric and functioning of affected communities, changes in the biophysical landscape and changes in economic prosperity. Closure in the light of sustainable mining practices considers post-mining land uses and how this new landscape can provide other opportunities for stakeholders. Through effective consultation and inclusion in the pre-mining stage, post-mining land use can be built into the operating plan to ease the transition once a mine closes.

Current Status

Life of mine planning is now common practice in the mining industry. Environmental and socio-economic assessment requires companies to evaluate all aspects of the post-mining reality, not only to absolve the host government of any unrealised liability, but also to ensure and demonstrate commitment to the long term protection of resilient communities.

CAREFUL PLANNING OF MINE CLOSURE IS INEVITABLE.

Once reserves and resources of a mineral have been exhausted, the process of an orderly closure of operations includes mine site rehabilitation and preparing the community and local stakeholders for the new reality. As the minerals sector is a price taker, not knowing or being confidently able to predict unforeseen changes in commodity prices, premature suspension or closure of operations does occur and contingency and management plans for both the operation and the community must be developed and in place.

The Future

The future of mine closure practices follows many of the same attributes and tenets of healthy corporate social responsibility behaviour to uphold the principles and spirit of social license. Free, prior and informed consent, and their equivalents, are as important as they are in the development stage of the operation and are key characteristics of effective communication.

Mining operations must have built-in resilience, flexibility and durability to weather periods of economic hardship and have production lives long enough to even out cashflows and ensure corporate economic sufficiency and the social wellbeing of the affected community, and not risk longer-term biophysical integrity.

Transitioning to the Future

The transition to this vision of the future requires maintaining the principles and spirit of the social license relationship and developing a resilience mindset, one that accepts change and can smooth out the bumps in a rational empathetic way. A balanced approach to production scheduling builds in grade and tonnage flexibility, minimising land disturbance, progressive rehabilitation to reduce unfunded or limited resources for site rehabilitation and prepares for fluctuation and change.

NOVEL MINING SYSTEMS

Coordinator: Bruce Hebblewhite

Contributors: Bruce Hebblewhite, Peter Knights, Jan Palarski, Serkan Saydam, Tomás Vargas, Hermann Wotruba

Introduction

This chapter focuses on a representative selection of areas where step-change might occur, based on evidence already available of what some of these novel technologies, systems and mining methods might offer. The concept of the *'invisible mine'* is attracting growing interest – where the surface footprint of the mine is significantly reduced by systems and technologies such as:

- greater focus on underground rather than open cut operations
- direct placement of tailings and waste from surface processing back underground with elimination of surface tailings dams
- underground mineral-waste sorting, with waste material being separated and placed underground, without ever coming to the surface for processing
- in-situ mining using systems such as leaching, solution mining or gasification.

Topics are grouped by type of mining:

- In-situ mining
- Large scale mining
- Deep-sea mining
- Off-earth mining.

In-Situ Mining

Two techniques are discussed: in-situ leaching and underground coal gasification.

In-situ leaching (ISL) offers the possibility of treating orebodies with an approach radically different from conventional mining. In ISL, metal values can be recovered from the rock by direct dissolution into leaching solutions which are supplied to the orebody and are then pumped out for further processing of the dissolved metals. ISL could enable recovery of the metal values without need for ore removal, crushing or grinding. In addition, production of tailings is avoided, and landscape disturbance is minimised.

Underground coal gasification (UCG) is a process in which the carbon in the underground coal seam is converted into gas by a controlled partial combustion (in-situ process). The final product of the process is the so-called syngas, a mixture of CO, H_2 and hydrocarbons and other gases which may be used either as fuel or as a feedstock in a number of chemical processes. To run the controlled gasification process safely and effectively, the specific amount of oxygen or air or a mixture of air and steam or other gases should be supplied through the borehole to the burning coal seam. Under such conditions coal in an oxygen-deficient atmosphere is subject to the gasification process in the so-called UCG reactor (generator) and syngas is obtained, which is then carried to the surface gas cleaning plant. As a result of converting coal into syngas, a cavity in the coal seam is created, which is partially filled with ash, slag, residues of coal and rocks falling from the roof.

Current Status

In-situ leaching

In-situ leaching varies for different minerals.

- Uranium: ISL is currently a well-established commercial technology in the uranium mining industry accounting for about 45% of global production. About 90% of uranium produced in the US is extracted by ISL while uranium produced in Kazakhstan, which accounts for about 28% of world supply, is almost entirely extracted by this method.
- Copper: After uranium, copper is the metal with the largest number of ISL applications in industrial tests or semi-commercial operations. In most cases, in-situ techniques have been used to recover copper from low-grade ore and waste rock in old open cut mines, block-caved zones, and backfilled stopes as an addition to traditional mining. The main challenge to ISL being economically viable is limited access of solutions to copper minerals, which has generally resulted in lower recoveries.
- Gold: The application of ISL to gold has been largely restricted by the use of cyanide, which in this context is considered unacceptable as it could pose a substantial environmental threat.
- Other minerals: Scandium, rhenium, rare earth elements, yttrium, selenium, molybdenum, and vanadium have been leached in-situ as byproducts in pilot tests at uranium deposits in the 1970s and 1980s with good recoveries (Seredkin, Zabolotsky and Jeffress, 2016). Successful pilot tests have also been conducted to recover nickel from some

silicate nickel deposits and manganese from ores including pyrolusite and other minerals.

Underground coal gasification

Thermal processing of coal in-situ requires access to the underground coal seam, which can be obtained through drilling or mine workings. In previous trials on industrial scale, UCG was based on the drilling of two vertical wells into an underground coal seam connected by a channel in which coal was gasified and partially oxidised to produce product gas. One well was used to inject the gasifying agent while the gasification products were extracted through the other well. Unfortunately, this solution does not guarantee control of the process, or even the continuous production of syngas with a stable gas composition. Current UCG trials using directional wells allowed better control of the process. This UCG method has a moveable injection point known as CRIP (controlled retraction injection point).

The experience of UCG trials conducted in many countries confirmed the advantages of this technology. However, due to some process difficulties with stable gas composition, temperature, pressure and flow rates and threats of groundwater contamination, there is a need to modify the existing methods of the UCG process. Further problems are the application of the UCG at considerable depths (around 1,500 m) and development of a solution that will use the heat generated in the underground generator during the coal gasification.

The Future

In-situ leaching

When assessing the application of ISL to a particular ore deposit the analysis should consider from the start all the alternative technologies, which can be grouped in two main approaches: (a) ISL on material with natural or artificially induced fractures, and (b) ISL on rubblised material combined with partial underground mining. In an integrated approach, ISL of an ore deposit could include the application of these two types of technologies to different zones of the ore deposit. If in case (a) the ore deposit is below the water table and contained in an aquifer confined by impermeable strata the metal can be recovered with a system of injection and recovery wells while lixiviant excursion can be controlled by working with an artificial cone of depression around the production well. This is the current procedure in uranium ISL.

If, on the other hand, in case (a) the ore deposit is above the water table, leaching will be applied to waterless rocks by the infiltration method and the ISL design should include a system to collect the pregnant solutions before reaching the surface of the water table. Polymer injection has been proposed to construct an artificial barrier which could impede solution excursion below the collecting zone. The use of barriers with this or other materials should be further developed and tested in-situ.

Underground coal gasification

Internationally there have been many research experiments and demonstration projects, showing the many advantages of this technology, but also great risks to the environment. The main advantages of the underground coal gasification technology are:

- It has a relatively low cost of energy production, due to lower capital and operating costs than conventional coal mining.

- Human health and safety issues associated with underground coal mining activities can be avoided.

- There is high process efficiency as energy is recovered directly from underground coal deposits without the need for energy-intensive techniques of mining and processing, transport and stockpiling of the coal.

- There is multiple use of products. Syngas is the energy source, which after purification is transported in pipelines and can be used not only as a fuel in power plants, but also as a feedstock in the chemical industry for production of fertilisers and other materials or fuels.

- There is low environmental impact, with lower greenhouse gas emissions, minimal surface damages, groundwater contamination and waste production.

- It is possible to use gasification caverns for CO_2 storage.

- It creates the possibility of using unmineable coal resources, either very large and deep (above 1,500 m) or thin coal seams not suited to traditional mining.

Transition to the Future

In-situ leaching

SUCCESSFUL ISL REQUIRES A CLOSE COLLABORATION TEAM OF MINING ENGINEERS, HYDROMETALLURGISTS, GEOPHYSICISTS, GEOLOGISTS, HYDROLOGISTS, GEOCHEMISTS AND ENVIRONMENTALISTS.

The initial characterisation of the orebody will require geological models with higher definition and more accurate descriptions than those required for planning conventional mining operations. In addition, models should include detailed geological information related to the characterisation of fractures, their frequency and map of distribution, location of faults, discontinuities, stratification and impermeable layers in the orebody. It is also important to have a clear characterisation of the hydrological aspects of the orebody, clear definition of the water table level and the presence of inactive aquifers.

With the previous information, a detailed plan should be designed to define which zones could be leached without ore pre-treatment by drilling wells and which zones will require some type of pre-treatment, to define in each case the pre-treatment, and which zones are not amenable for ISL.

A global economic analysis of the operation considering the cost of blasting, underground mining works, hauling, transport, leaching, and the impact of ore pre-treatment on copper recovery, should be designed to optimise copper leaching economics of the whole operation. However, the type of ore pre-treatment and leaching configuration design finally applied to different orebody zones will always be conditioned to achieving the degree of solution containment required by the local environmental regulations.

ISL should be approached as a hybrid operation based on the integrated merging of underground mining and hydrometallurgical tasks to optimise the business outcome.

Underground coal gasification

Past UCG trials show that there are still barriers to overcome such as:

- real-time control of underground processes and gas production with stable parameters, in particular with high calorific value and in large quantities

- proper UCG site selection – a good knowledge of the site geology, hydrogeological conditions and strata behaviour during and after the coal gasification
- drilling technique with expected accuracy adapted to the specific conditions of the site
- environmental threats, in particular ground subsidence and groundwater pollution
- decommissioning of the UCG process, rehabilitation of an underground generator and a suitable final land use following rehabilitation activities.

The transition from today's UCG practice to potential new technologies may require:

- adapting techniques used in the recovery of shale gas and heavy oil deposits, methane drainage and extraction of geothermal energy to comprehensive energy extraction from processing of coal deposits
- developing new methods for monitoring and control of environmental hazards, UCG process data and movement of the gasification front and for measurement of rock mass deformation around the cavity
- improving backfilling of underground cavities, conducted simultaneously with the process of gasification
- determining the appropriate composition of backfill mixture containing backfill material, water and chemical catalysts e.g. mining wastes from certain ores, which allow the production of gas of desired composition
- developing CO_2 injection methods into an underground generator (in all stages – before UCG process, during

operation and in the decommissioning and rehabilitation phase)

- improving the underground coal fracturing techniques (underground crushing)
- developing chemicals injection, resistant to high temperature, to isolate the generator from contact with the deep underground water
- education of highly qualified personnel with knowledge of chemical processes, thermodynamic, geology, drilling techniques, monitoring, etc.

Large Scale Mining

The upscaling of current mining operations can, of itself, be regarded as novel, as it involves significantly different mining systems – equipment, materials handling approaches, and associated operational management and control technologies – all to deal with a major increase in production rates.

WHILE MOST CURRENT MINING METHODS AND SYSTEMS HAVE OPPORTUNITIES FOR INCREMENTAL EFFICIENCY AND PRODUCTION GAINS, THIS CHAPTER FOCUSES ON THE SECTORS WITH POSSIBILITIES FOR QUANTUM IMPROVEMENTS IN PRODUCTION AND/OR PERFORMANCE.

The resultant "large scale" mines pose a totally different set of demands on all aspects of mine planning and operations. While such mines can lead to far higher annual production tonnage outputs, through economies of scale they almost inevitably also have improved levels of efficiency, whether this is measured in terms of labour productivity, energy consumption per tonne of production, or other measures. On the other side of the threat/opportunity scale is the increased magnitude of environmental and community impacts from much larger mining footprints and larger mining operational scales.

Two types of mining are discussed: large open cuts and underground mining.

Current Status

Large open cuts

In many parts of the world surface mines face the choice of going deeper to chase ore reserves or transitioning to underground mines. Higher stripping ratios mean more waste removal, which in turn leads to increased truck and shovel fleet size to maintain mill feed capacity and greater environmental impact. Larger mining fleets also increase labour, fuel and tyre costs.

Underground mining

In underground coal mining, the mechanised retreat longwall mining method has been widely used around the world for at least the last 50 years. Some recent changes that have led to incremental improvements in longwall performance have included:

- the development of improved roadway development equipment with integrated cutting and bolting capabilities
- the level of automation of longwall equipment
- the reliability of the equipment involved
- improved planning systems and design
- more focused systems engineering approach to longwall performance management.

Modern longwalls are now performing at levels that were not thought possible even ten or twenty years ago, with annual production levels up to 10 MTPA or better being achieved.

Many of the newer faces in Australia are now using extensive automation packages for both shearer steering and shield operations.

Just as with underground coal mining, or large open cuts, the innovative future of underground hard rock mining rests with a combination of new technologies; a quantum increase in scale of operations to benefit from economies of scale; and then smart, fully integrated management systems, supported by smart people.

Apart from the opportunities offered by in-situ mining methods such as leaching, the direction for conventional underground hard rock mining methods lies very much in block or panel caving. This method is already the lowest unit-cost underground mining method in use worldwide and offers great potential if it can be scaled up to compete directly with large open cuts, in terms of both production capacity and mining cost. This introduces the future vision known as “super caves”.

The Future

Large open cuts

One solution being explored by a number of mining companies is the introduction of conveyor-based haulage into large surface mines. Conveyor systems require less labour to operate and maintain than comparable truck fleets. Because they are electrically driven, they can reduce a mine’s dependence on fossil fuel. If renewable power sources are available, they have the potential to significantly decrease greenhouse gas emissions. They also enhance mine safety by reducing mobile equipment in a mine, since vehicle collisions are still a leading source of accidents in surface mining. In addition, conveyor haulage systems reduce dust emissions and the associated need for watering truck haulage routes.

Material must be appropriately sized to feed onto a conveyor belt. Usually sub-300 mm particulate size is required, which needs the use of a crusher. Modern crusher alternatives include hybrid roll crushers and sizers, which can be fabricated as compact, transportable units. At the discharge end of the conveyor belt, stackers or spreaders are used depending on whether the transported material is ore or waste. These systems are commonly referred to as In-Pit Crushing and Conveying (IPCC) systems.

Underground mining

The future vision and target for underground coal longwall performance is to achieve consistent, industry-wide annual production levels of at least 10–15 MTPA per face, under a range of different mining conditions. This 50% step-up in production performance is considered achievable within the next 10–20 years, subject to a range of technology improvements, together with far more sophisticated and all-encompassing systems-based management systems than are currently practised across the industry.

The hard rock mining quantum step-up in block and panel cave mining capacity has been defined as super caves. Super caves are cave mines producing at least 25 MTPA, which equates to over 70,000 tonnes per day of production. Newcrest’s Cadia East Mines is the first Australian mine to approach this scale of operation, aiming for approximately 30 MTPA. Projects such as the expanded El Teniente mine in Chile, Grasberg in Indonesia, Resolution in the US and Oyu Tolgoi in Mongolia are all in planning or in construction stages and aim to be operating at the super-cave definition of scale.

Large open cuts

The transition to a high performance large open cut mining operation involving continuous mining and integrated materials handling systems requires a combination of improved mine planning and design, together with further development and adoption of new technologies, including:

- continuous surface mining systems
- fixed, mobile and semi-mobile IPCC systems for materials handling
- autonomous dozer systems for feeding mobile crushers.

A number of areas require further research, including the development of new mine planning solutions for the new mining systems. A mine should be designed around the capability of the new mining system, and not as an afterthought to a truck-shovel design.

Underground mining

Achieving consistent 15 MTPA underground longwall coal operations from a single face will require more of the same contributing factors that have provided the incremental improvements to reach the current status, as listed above. Automation will play a major part in such a step-up, as will comprehensive monitoring and reporting – relative to mining conditions, equipment health and operational performance.

Online, real-time monitoring must then be matched with a management system that includes smart, possibly artificial intelligence-based response systems to immediately respond to faults or changes in condition, as well as modifying operational performance based on well-informed data systems. This type of management system must incorporate a fully integrated database and decision-making system with different sub-disciplines that are currently often managed discretely or separately such as production, maintenance, ground conditions and ventilation.

To achieve such a scale-up of production performance, hard rock super caves need:

- improved orebody characterisation
- improved caving mechanics modelling and design
- more rigorous feasibility studies
- progressive automation of extraction level ore handling
- novel and effective secondary breakage systems
- extensive, online monitoring of performance of the cave
- greater efficiency and capacity improvements for ore hoisting or alternative bulk ore handling to surface (conveying etc)
- human capital – a mix of good operators, as well as very smart technical specialists, rather than "jack of all trades" operators.

Deep-Sea Mining

THE DECLINE OF ORE GRADES ON LAND, INCREASING DEMAND AND HIGH PRICES FOR VARIOUS MINERALS HAVE LED TO INCREASED INTEREST IN MINING THE DEEP OCEAN SEA FLOOR.

The interest in sea floor minerals goes back to the 1800s with the discovery of manganese nodules. Beyond manganese nodules, the other main undersea mining interest has been in alluvial diamonds off the coast of southern Africa, in regions such as Namibia.

More recently, there has been growing interest in exploring for deposits known as seafloor massive sulphides (SMS) which are formed by mineral rich gases venting through the earth's crust into the seafloor region, forming chimneys of solidified mineral deposits when the hot gases hit the cold seawater. SMS deposits of varying mineralogy and grades have been located in many parts of the world, mostly associated with plate boundaries and other tectonically active regions.

Current Status

One of the first SMS deposits to be explored to the extent of becoming a prospective mining lease has been the Solwara 1 deposit in the Bismarck Sea, north of Papua New Guinea. This lease area is owned and has been explored by Nautilus Minerals Inc. Nautilus has identified high concentrations of copper, zinc, silver and gold – all in sufficient quantities to represent a mineable prospect, albeit in water depths of in excess of 2,000 m in places.

The Future

Deep-sea mining clearly presents major challenges requiring absolutely novel mining solutions. Nautilus and its parent companies, and other partners, have been developing a number of concepts for remote undersea mining. The surface support vessel must house the supporting pumping infrastructure and facilities to pre-treat the mined slurry, before it is placed on barges for shipping direct to market. The vessel must have the associated Riser and Lifting System to bring the mined ore in slurry form to the surface.

Transitioning to the Future

This mining system remains an unproven concept at this stage, although there are significant prototype equipment developments to bring the Nautilus operation in the Bismarck Sea to reality. The transition process is considerable as further technology requirements are addressed, proven and implemented. However, in conjunction with the technical challenges of deep-sea operations are the equally important issues of environmental impact and legislative governance. Work in these areas is still needed before deep-sea operations become a reality.

Off-Earth Mining

As history has repeatedly shown, where there are valuable minerals to be extracted, adventurous humans will arrive in droves – even if it means battling extreme conditions and risking life and limb.

WHAT WILL HAPPEN WHEN THE NEXT GREAT 'GOLD RUSH' IN OUR HISTORY IS LITERALLY OUT OF THIS WORLD?

Business analysts may reject the extraordinarily high costs of mining close to the off-earth bodies such as asteroids, or even the moon, nevertheless these quests are possibilities. Returning to the moon for off-earth mining will require innovative technologies and new ways of thinking, and this will eventually extend to the traditional business model.

Drivers promoting off-earth mining are an abundance of valuable resources that can support our technologically driven society, the passion and demand of discovering new areas to colonise, and the potential for development of new technologies and processes to enable these missions to create spin-off technologies for terrestrial operations.

Many scientists agree that, in the near future, opportunities will include the mining of off-earth bodies such as asteroids, comets, the moon, Mars and Mars' moons, which represent the most distant supplies of wealth that humankind has ever thought of recovering.

Current Status

Living and working in space for extended periods of time means that the crew have limited access to the life supporting materials which are available on earth. Humans travelling to deep space for colonisation will need to generate their own products with local materials, known as in-situ resource utilisation (ISRU). Off-earth mining will need to achieve ISRU, but it is entirely in the early R&D stage at present. There are numerous and very diverse research initiatives under investigation related to potential mining challenges for the moon, Mars, asteroids and even comets.

The Future

BUSINESS ANALYSTS AND SCIENTISTS AGREE THE MOST VALUABLE COMMODITY IN SPACE IS WATER.

As space lacks water, the first off-earth mining operation will most probably be the extraction of water from the moon surface to be used as a rocket fuel to sustain life in space.

In the last 2 years the focus has been on asteroids and then Mars, but focus recently moved to the moon. However, NASA considers that the moon is just a stepping stone, not an alternative to Mars. The moon is rich in resources; and it is estimated there are more than 6 billion tonnes of water on the moon.

The non-existence of a market in space is stopping potential research activities. However, recently, United Launch Alliances (ULA) announced that they will be purchasing fuel (H, O) for US$3,500/kg in Low Earth Orbit and for US$500/kg on the moon. This would certainly increase the interests of potential business investments and research opportunities.

OFF-EARTH MINING OPERATIONS WILL HAVE TO OPERATE AUTONOMOUSLY FROM A BASE SPACE STATION, MOTHER SPACECRAFT IN THE ORBIT OR DIRECTLY FROM THE EARTH.

Operations will have to be conducted by a robotic equipment fleet. Numerous off-earth activities have the potential to expand and stimulate the global economy, such as construction materials for off-earth structures, solar power stations to reduce greenhouse gas emissions while expanding energy access, space tourism, propellant depots, and resources for human habitation. Various risks to these commercial ventures include legal risks, business cases, and hazards to spacecraft such as space debris.

Transitioning to the Future

The uncertainties and challenges are significant, and must be overcome to develop the required knowledge. Mining knowledge will be essential to successfully achieve mining operations beyond earth and engineers will require different and/or new skills. Mining engineering programs will need to add to their curriculum relevant competencies such as automation, robotics, information technology, space orbital mechanics, and systems engineering. New programs that cover both space and resource engineering disciplines may also need to be established in engineering faculties and/or double or even triple degree programs will be essential. All these suggested skills will also be useful in terrestrial operations. Therefore, developing collaboration between academia, research institutions, governments and space and mining industries is a must to establish our future.

EDUCATION

Coordinator: Bruce Hebblewhite

Acknowledgements

The following people are acknowledged and thanked for their contributions which have informed the development of this chapter:

- All contributing authors to the earlier Chapters of this *Mines of the Future* Report.
- All SOMP members who have provided comment during presentations on this topic at recent annual and regional SOMP meetings.
- Colleagues at Mining Education Australia (MEA) particularly the members of the 2018/2019 MEA Curriculum Review Team.

Introduction

This chapter considers the needs of tertiary mining education for the future – in the context of where the mining industry is now, and where it might be in 10–20 years' time and beyond. It considers what skills the future mining industry might require, relative to today's professional skill set, in the discipline of mining engineering.

By necessity, this chapter represents some crystal ball gazing into the future, and includes subjective views on both the nature and state of the industry and the skills and personnel needs for the future. This cannot be a prescriptive chapter or outline of what is required. However, it is intended to prompt discussion, debate and at least some degree of consensus amongst international mining educators.

WHAT IS INDISPUTABLE IS THAT THERE IS A NEED FOR CHANGE. THE BIG QUESTION IS THE NATURE AND EXTENT OF SUCH CHANGE.

This chapter adds some ideas and topics for consideration in this important education discussion.

The chapter draws on the previous chapters in this report on the likely future of the mining industry. It has also drawn on an increasing amount of published discussion on the need for educational change, in many facets – by discipline, by content, by delivery mode and by menu of educational offerings.

What Is Mining Engineering?

This question is an essential starting point for consideration of mining education. Similarly, *"What is a mining engineer, and what do they do?"* There are many different answers on what mining engineering is, and there is no single correct answer. Some critical common elements include the following aspects of the discipline:

- Safe and economic extraction of minerals
- Planning and design of mines
- Management of mine sites – from evaluation, through planning, operation and closure

- Sustainable mining practices, with respect to all aspects of social acceptance, environmental compliance, safety performance, community engagement and more.

A recent discussion document by Smith (2017), prepared as an industry perspective to advise a Mining Engineering curriculum review by the University of the Witwatersrand in South Africa (Mitra et al., 2018), offered the following definitions:

Mining engineering is *"an engineering discipline that applies science and technology to the extraction of minerals from the earth"*. Smith (2017) then expanded this definition in an incremental manner, as follows:

- "*A mine is an excavation made to extract minerals and metals.*
- *Mining is the activity, occupation and industry concerned with the extraction of minerals and metals. Mining occurs in a socio-political context.*
- *Mining engineering is the practice of applying engineering principles to the discovery, evaluation, planning, closure and reclamation of mines in a safe, profitable, and socially acceptable way."*

A minor enhancement to this Smith definition is given below, capturing the operational role of mining engineering, but downplaying discovery which is more the role of exploration geologists and others.

MINING ENGINEERING IS THE PRACTICE OF APPLYING ENGINEERING PRINCIPLES TO THE EVALUATION, PLANNING, OPERATIONS, CLOSURE AND RECLAMATION OF MINES IN A SAFE, PROFITABLE AND SOCIALLY ACCEPTABLE WAY.

This definition is considered applicable to the mining discipline yesterday, today and tomorrow and, as such, is regarded as the basic building block for mining engineering education considerations.

How Do We Currently Educate Mining Engineers?

There are many different models around the world, but there is surprising similarity of mining engineering curricula across many different countries. There have been some significant changes over the past 20 or 30 years or more – particularly from some of the European mining programs, especially those from parts of former Eastern Europe, where there were often a number of different mining degree specialisations on different types of equipment, mechanisation, mine safety, surface mining and underground mining.

However, since that time, most programs around the world have adopted quite similar models which could be described as a comprehensive mining education curriculum – covering all aspects of mine planning and design, operations, technical support services and technologies. It is also common for a mining program to cover – at least in overview mode – all facets of surface and underground mining, as well as hard rock, soft rock/coal and the extractive or quarrying sector in some instances.

Degree structures differ significantly in different parts of the world, ranging from 4, 5 and even 6-year Bachelor programs, to 3 + 2 year or similar Bachelor plus Masters programs (i.e. the Bologna Process and the European Higher Education system). There is also some variation around the world as to whether students commence in year 1 of their Bachelor degree electing mining engineering, or whether they do a common or more generic year 1 and in some cases a year 2 engineering program before commencing their mining focus and content.

This chapter does not attempt to select or prescribe any one structural model for how a program is offered but rather focuses on content and delivery.

The Need for Change

Some important questions are posed to which we must have answers. As an industry, and as an education sector, we must give these questions serious consideration and have well justified responses. We cannot ignore the issue, hoping it will go away.

IS THERE ANY NEED TO CHANGE WHAT WE ARE DOING, OR WILL OUR CURRENT EDUCATION MODELS AND CURRICULUM CONTENT SERVE OUR INDUSTRY ADEQUATELY FOR THE NEXT 20 YEARS AND BEYOND?

ARE MINING ENGINEERS AN "ENDANGERED SPECIES" – NO LONGER NEEDED IN A WORLD OF AUTOMATED MINES?

WILL INDUSTRY RELY MORE ON THE MECHANICAL AND MECHATRONIC ENGINEERS, THE IT SPECIALISTS, THE SYSTEMS/PROCESS ENGINEERS?

CAN THESE OTHER DISCIPLINES RUN THE MINES OF THE FUTURE, WITH A SMALL AMOUNT OF MINING KNOWLEDGE, IN PLACE OF THE TRADITIONAL MINING ENGINEER?

Let us consider some possible or likely responses to these questions:

- Is there any need to change? YES, there certainly is. Doing nothing will simply be the start of a slippery, one-way road to oblivion.

- Are mining engineers an “endangered species”? Some people argue that mines will no longer need mining engineers in the future, in which case the current or traditional version of a mining engineer is truly an endangered species. However, this interpretation is considered to be quite narrow, and maybe misguided in the longer term. More often than not, this view comes from sectors of the industry that are predominantly engaged in large-scale surface mines, with varying levels of automation. In such mines, the role of the traditional mining engineer may be reducing and, to some extent, at least, is being replaced by “para-mining engineers” or other engineering graduates with a small knowledge or experience in mining engineering. However, for more complex mining operations on surface, and certainly for underground operations, the role of a mining engineer remains an important one and is expected to remain so into the future. But even these mining engineers must change, to adapt to, and adopt new technologies, new capabilities, more “soft skills”, and a broader capability to work and engage with other disciplines. The short answer to this question then, is NO, but mining engineers must change.
- Will industry rely more on the mechanical and mechatronic engineers, the IT specialists, the systems/process engineers? The answer to this question is YES, absolutely. All types of mining operations will involve more multidisciplinary teams of professionals – right from the start in planning and design, through operations to eventual closure. These teams will include all of the disciplines listed in the question, plus more.
- Can these other disciplines run the mines of the future, with a small amount of mining knowledge, in place of

the traditional mining engineer? The answer to this question comes back to the response to the second question. An overall answer, across the whole of industry, would be NO – especially for the more complex mines, and the underground mining environment where many of the specialist skills associated with ventilation and ground control are so critical to the safety and efficiency of the mining operation. Similarly, mine planning and mineral economics are skill sets that are not available within other engineering disciplines. However, there will be an increasing role for non-mining engineers in management roles at mine sites, and we need to recognise this, as well as seeing the immediate and growing educational opportunity that opens up for training such people in mining topics.

There is therefore a very strong case for the need to change the educational programs for future mining engineers, as well as a recognition that their future roles within industry may change and will involve working in much more multidisciplinary teams across all aspects of mining activity.

What Does the Future Mining Industry Look Like?

The earlier chapters of this report provide some useful insights into future developments and innovations across the mining industry. These should be a starting point for consideration of the future educational needs for the mining industry.

Industry 4.0 is the current fashion for automation and data exchange in industrial technologies which contains the internet of things (IoT), artificial intelligence (AI), cloud and cognitive computing. It is frequently stated as the fourth industrial revolution.

INDUSTRY 4.0 FOSTERS WHAT HAS BEEN CALLED A SMART FACTORY.

Within integrated smart factories, cyberphysical systems monitor physical processes, generate a virtual copy of the physical world and make decentralised choices. Over the IoT, cyberphysical systems interconnect and collaborate with each other and with people in real time, internally and across organisational services existing and used by all contributors within the value chain.

HOW WILL INDUSTRY 4.0 CHANGE THE GLOBAL MINING INDUSTRY?

Yeates (2017) made the following useful observations and predictions:

"... a world where mining equipment is fully autonomous, connected via through-the-rock wireless communications and sized to suit the extraction of just the orebody, with minimal waste.

In this world, we will see miners with core competency in software and data analytics working from virtual remote operating centres connecting the world's best skills through social networks and taking real-time data feeds from the equipment and process.

There will be a constantly updating interpretation of the orebody carried out on the fly as each new piece of information comes in. The mine plan will be updated as the orebody model changes and as operating parameters are refined and metallurgical requirements are fed back from the process plant, optimising value constantly and in real time.

Each operating decision will be simulated before it is made, with all options explored virtually before selecting the best *option to deploy. All operating parameters will be recorded, and machine learning will be utilised to ensure that the best combination of parameters is applied for every given situation.*

The operating model in this world will be characterised by flat organisations made up of agile, multidisciplinary teams tasked and measured on holistic goals. At the core of these teams will be data analytics and software engineering working with geoscientists, metallurgists and mechatronics engineers.

In this world, we will see new business models that are characterised by opening up the enterprise. We will see the live orebody model and mine plan published on an open platform and being accessed in real time by suppliers and partners. This close coordination and integration, with the full value chain taking constant feedback and optimising forward, will deliver huge value by reducing inventory, rework and friction between business processes, regardless of who is performing the activity. These worlds are possible and plausible in a disrupted mining industry that takes advantage of the convergence of digital technologies".

While not every mine will look like this in 20 years' time, many will be well advanced along this track and our education systems must be ready for this, while not abandoning the important conventional mining skills which will continue to be applied in many mining scenarios.

WHAT EXACTLY DOES THE DIGITAL MINE OF THE FUTURE MEAN?

In simple terms, the digital mine of the future will be mining that embraces digital technologies and the internet of things, not just for information, but to provide monitoring and real-time control systems. This will generate huge amounts of data. But data alone is of no value and can actually create confusion and misinformation. The real challenge in managing and using "big data" is being able to convert, sort and analyse data into useful information, and understand both the applications and the limitations of that information, to reliably use it for interactive, real-time control systems. Mining engineers must therefore have good skills in both big data and also digital technologies.

In support of the earlier discussion on the need for change to fit into this new world of the "digital mine", a number of different industry and professional insights further develop the argument for change, based on their views on what the future industry will look like and what it's professional needs will include.

Stegman (2015) made an interesting observation when speaking about the future needs of human capital in the mining sector, from a perspective within the Rio Tinto Copper Group. He sees a series of tensions and new needs within the skilled professional mining industry labour market:

- specialisation of engineers in traditional (e.g. geotechnical) and non-traditional (e.g. complex modelling) areas
- less technical roles for the "generalist" engineer, or "jack of all trades"
- a career split between "operators" and "subject matter experts (SMEs)"
- SMEs often will be well educated (PhD minimum), and more likely employed by specialist consultancies than mining companies
- mining companies will still need technically literate people who make sense of the detail but can also see the big picture
- skilled engineers need to be able to think globally but act locally

- need for high quality graduates with a solid technical education; an understanding of the concept of risk and risk management; ability to problem-solve; able to work collaboratively and in a culturally sensitive manner; and with a healthy sense of scepticism!

Jones (2018) stated *"It's becoming obvious that a science, technology, engineering and mathematics (STEM) education is going to be the first step for a career in the mining industry. Beyond that, pursuing digital mining-focused studies at a TAFE college or university will further develop collaborative, analytical and problem-solving skills". He further discusses the need for mining academics to have knowledge and experience of digital technologies and their application at digital mines; and further, to use such technologies in their teaching methodologies, including data visualisation, distance delivery, data analytics, advanced modelling and statistical tools. He also notes that …*

MINING COMPANIES AND CORPORATIONS WILL ALSO LOOK TO MINING SCHOOLS TO UPGRADE THE DIGITAL KNOWLEDGE AND SKILLS OF THEIR EMPLOYEES.

Johnson (2016) discussed what he referred to as *"the critical role of the mining technology professional"*. This is not necessarily a mining engineer, but it would undoubtedly include the mining engineers of the future. Some useful thoughts expressed by Johnson include:

- *"There is a technology tsunami sweeping across the mining industry. Every mining professional is impacted, such that we are all becoming mining technology professionals in some shape or form."*

- *"One thing is certain: technology is evolving so rapidly that it is hard to keep up. It pushes our ability to absorb change to the limit."*
- *"As the industry is transformed, … a 'mining technology champion' is vital. Such champions must have the following characteristics:*
    - *Deep technical knowledge of the mining value chain;*
    - *Expertise in change management practices;*
    - *Experience with integrating mining technology to solve problems to generate value;*
    - *Seniority and the necessary credibility to champion the technology initiative".*

While a university education program cannot and should not attempt to offer senior management skills, it can certainly train graduates to deal with technological challenges as outlined above.

The EY Report (2019) prepared for the Minerals Council of Australia made the following observation about future workforce skills, which reinforces a number of the above messages:

"Digital mining will see the need for traditional operators reduce, with a more technologically savvy workforce required. Mining professionals will combine technical mining skills with digital technological competency while newer capabilities such as data scientists, modellers etc. will provide core functional support".

A further consideration for the future mining industry, and hence mining educational needs, is the concept of "the invisible mine" – discussed in Chapter 5 in this report. This refers to a progressive, or incremental set of changes to mining operations in the future, where mining will have a greatly reduced surface footprint. The following trends will emerge, some of which are already well underway:

- underground placement of tailings and waste materials, to avoid large surface waste disposal facilities
- underground, on-line sorting and separation between mineral and waste to enable direct waste placement underground
- potential for underground mineral processing
- move away from large surface mines to higher capacity underground mines
- adoption of alternative mineral or commodity extraction in-situ, including in-situ leaching and in-situ gasification; deep-sea mining etc.

Future Curriculum Needs for Mining Engineers

Based on all of the above observations, the need for mining engineers will continue and the educational challenge for future mining engineers is to understand these different messages and embrace these rapidly changing industry needs and scenarios. To highlight just a few of the key messages, mining engineering education initiatives must include and develop engineers with the following key attributes:

- have high quality technical skills
- have an understanding and ability to use, optimise and adapt to rapidly changing and innovative technologies, particularly digital technologies
- be highly data-literate and capable of working with large datasets to achieve effective management and control systems

- be capable of planning and operating mines with more socially-acceptable surface footprints and environmental impacts
- understand the full value chain of the mining operation through a more holistic and systems-approach to planning and operations
- adopt a risk-based approach to planning, decision-making and management
- have a global or international perspective but be capable of working in a local environment and with a clear understanding of local constraints
- be capable of working in and leading multidisciplinary teams.

Conventional or current mining curricula around the world typically address some of these attributes but fall short of covering all aspects. It is therefore important to encourage universities to adopt major change to their current offerings, to ensure they are well placed for the future needs of the industry. The following sections provide some suggestions for content that will prepare the mining engineer of the future.

Enabling Content

As with most engineering disciplines, there is an essential need to gain knowledge and a reasonable level of competency in the major enabling sciences and generic engineering fundamentals.

Enabling sciences include mathematics and physics as essentials, and ideally chemistry. The mathematics must also include further statistical skills than might have been provided in the past, to deal with large but incomplete datasets. Students must also acquire some basic software coding skills and competence in a range of important generic data management and analysis software packages.

The generic engineering fundamentals are probably the same as have been traditionally provided, even though the mining applications for these will have changed. These include fluid mechanics and thermodynamics; structural mechanics and stress analysis; engineering design principles; together with an introduction to professional practice, ethics and the role of engineering in society. It is also critical that students are introduced at an early stage to the principles of systems engineering and process/systems analysis – to enable them to apply these principles to mining operations later in their studies.

On a more mining-focused level, the other area of essential enabling content is geology. If mining engineers need to take a more holistic approach to considering the entire value chain of the mining operation – the mine to mill concept – then they must have a good understanding of relevant geology – from an awareness of exploration technologies and their applications and different types of orebody relative to different commodities, through structural geology and geophysics, to some basic geochemistry to better inform their knowledge of metallurgical processes.

Core Content

The core content mining engineers need can be grouped into streams of similar application. One such model that may be useful is a six-stream model outlined below:

- Mine Planning and Design
- Socio-Environment Factors
- Mine Geotechnical Engineering
- Mine Services
- The Digital Mine
- Research Projects.

Within these overarching streams, individual subjects or courses may be configured to cover the essential core knowledge required by a mining engineer of the future. The major components of this core content are summarised for each stream noting these lists of content are not exhaustive:

- Mine Planning and Design
    - Resource estimation techniques; principles of mine planning and optimisation
    - Mineral economics context for mine planning, mine valuation – economic drivers and constraints (both local and international or commodity based)
    - Principles of different mining systems including methods, infrastructure, equipment and operational drivers and constraints
    - Application of systems engineering thinking and analysis techniques to mining operations
    - Evaluation and assessment of safety considerations and risk factors associated with different mining systems
    - Ability to conduct a project pre-feasibility study.
- Socio-Environment Factors
    - Awareness and management of social, environmental and cultural factors impacting on, or from a mining operation
    - Principles of license to operate, social responsibility and sustainability in a mining context
    - Project evaluation from a local through to an international socio-environment perspective
    - Mine closure implications and integration into mine planning and project economics.
- Mine Geotechnical Engineering

    - Fundamentals of soil and rock mechanics and engineering geology applicable to mining
    - Geomechanics applications in mining – from design to operations, including safety considerations, risk assessment and management.
- Mine Services
    - Fundamentals of mine ventilation and related safety considerations – applicable to design and operations
    - Management of the mine workplace and environment from an occupational health and safety perspective
    - Knowledge of current and emerging technologies in drilling, blasting and mechanised excavation and rock breakage.
- The Digital Mine
    - Mine robotics and automation – an understanding of emerging technologies and their application to mining, including planning and operational management of automated mining systems
    - Data analytics – understanding, interpretation and management of large mining data, information, sensing, monitoring and control systems
    - The role of the Internet of Things (IoT) in the above applications.
- Research Projects
    - Introduction to research methodology and practice; professional writing and publication about a mining-related topic, to serve as a capstone student project.

It is a deliberate and conscious decision to avoid recommending specific courses on topics such as mine safety or risk assessment and risk management. It is considered far more appropriate that these topics are embedded throughout the mining curriculum as simply “the way of doing business”, rather than placing them in a stand-alone course that is completed in isolation from other aspects of mining.

Elective Content

Mining engineering students should have the option to study a number of elective courses, beyond the above prescribed core. Suitable electives are likely to fall within the above streams, but there may be exceptions. It is also recommended that students have the option of making a specialisation decision and choosing all electives from one stream, as opposed to a broad spread across the streams.

Some relevant elective course topics could include:

- The mining value chain – including a holistic approach to all aspects of the operation, including mine planning optimisation; mining cost analysis and energy efficiencies; geometallurgical and related processing factors relative to geology and mining decisions
- GIS and remote sensing – understanding and application of advanced imaging, data collection and visualisation techniques in mining
- Technology management in mining – the evaluation, justification, introduction and assimilation of new technologies into mining operations
- Innovative technologies – exploring different technology scenarios from other industry sectors and managing their introduction to mining – including risk management, intellectual property and entrepreneurial

market development and commercialisation opportunities

- Tailings dams – material characterisation, dam design, monitoring and management
- Use of backfill underground – best practice design methodologies and management systems
- Shaft sinking methodologies, design and construction
- Emerging rock breakage technologies
- Mine waste water and environmental mine water management
- Innovative mining systems – the invisible mine
- Mine asset management – fundamentals of reliability engineering, maintenance management, preventive component replacement and capital equipment replacement decisions
- Management, leadership and effective communication.

A New Approach to Student Learning

The era of academic staff or faculty being the source of all knowledge and wisdom is over. It is unrealistic to expect a small group of academics at each mining university to possess all of the knowledge that students need to learn. The quantum of knowledge and the rate of growth of such new knowledge is far greater than can be contained within any cohort of academic staff.

What is required, and is far more effective, in terms of the learning experience for the students, is to teach students how to learn for themselves. We need to facilitate that learning experience; and through discussion, assessment and general communication and interaction, we need to ensure that students are seeking out the right information and knowing how to analyse, synthesise and assimilate it with their own growing body of knowledge, and then apply it in a practical manner to mining problems and challenges.

This approach of not expecting to “teach” everything also helps greatly in the context of limited time availability within structured curriculum teaching periods. It is far better that students use some of their own time, through different media outlets, internet and other information sources, to gain further and deeper knowledge.

WE WANT TO LAUNCH OUR STUDENTS ON A VOYAGE OF SELF-DISCOVERY – WITH A BIT OF HELP AND GUIDANCE ALONG THE WAY.

The quality of learning and the retention of new knowledge gained in this manner will be far greater, and deeper, than if students were just exposed to it passively sitting in a classroom listening to a lecturer.

Different techniques for these alternative learning approaches include:

- Using project and problem-based self-directed learning
- Integrating multiple topic and subject areas into one project
- Greater use of group work, including greater diversity within the group membership
- Distance education
- Using multidisciplinary project teams – e.g. mine feasibility studies including some civil engineers, environmental scientists, urban planners etc.
- Developing transformational project scenarios – novel mining approaches to new orebodies and complex community social contexts

- Using innovative data visualisation techniques such as virtual or augmented reality, with built-in data interrogation capabilities
- Providing multiple, flexible learning pathways through the curriculum (as mentioned in discussion of elective choices) – common core content, but flexible and potentially specialised elective streams.

Collaborative Education Initiatives

Following on from the above discussion, it is clear that the mining engineering curriculum of the future is going to include a wide range of topics that probably extends outside of the skillset or experience of the staff at each individual university. However, with the level and sophistication of online communication technologies, there is no reason why teaching and learning initiatives cannot cross over institutional boundaries, without the need for extensive physical presence across multiple campuses.

A world expert in tailings dam design, for example, should be able to provide lecture content and possibly also collaborative project assignments across different institutions – over the internet, extending not just nationally, but internationally.

Taking the collaboration concept further, common curricula, or parts thereof, across different institutions would allow for collaborative degree programs, more flexible student exchange, and more flexible staff exchange. There are existing examples of national and international collaboration in mining education. In the long-running European FEMP Program students moved between different universities across Europe over the course of a year or more.

Mining Education Australia is another well-documented Australian example of a collaborative 3rd and 4th year undergraduate mining curriculum across the four major Australian mining universities. There are others, but there is scope for even more collaboration.

As communication technologies continue improving and the tyrannies of distance and the cost of collaborative teaching diminish, the opportunities only increase for more, and more effective collaborative teaching – which can only benefit the student learning experience, as well as the desire of today's students for very flexible learning environments.

Other Mining Education Opportunities

This is a brief, final additional comment, but one that represents a huge and growing opportunity for mining educators. The future mining industry will be employing a wide range of disciplines beyond mining engineering – not just other engineers (civil, mechanical, electrical, environmental etc), but also other scientists, computer specialists, social science graduates and many more.

Very few, if any, of these people will have any knowledge of the mining industry before seeking employment within it. However, if they were able to take a small amount of mining content within their undergraduate or graduate programs, they would be far more employable, and be able to kick-start their working careers, which would also benefit the mining industry, in terms of job-readiness.

Mining educators should consider how they can package up a selection of key mining courses or modules and offer them as "minors" or specialist streams or electives, or even as part of double-degree programs offered to other disciplines. For example, it would be valuable for a mechanical or mechatronic engineer seeking mining industry employment to have some knowledge about mining systems, resource estimation, mine planning and mineral economics.

The challenge is to identify these additional opportunities (which may actually involve much larger student numbers than the mainstream mining engineering student cohort) and develop appropriate offerings – whether a minor in another degree, micro-credentialing of single courses, double degree programs, or non-award professional education programs.

RESEARCH

Coordinator: Serkan Saydam

Introduction

The mining industry has major key challenges and opportunities that require research, but research in mining faces several challenges due to the small industry size and specialised applications.

The most significant mining research areas are: energy and water, human capital and skills shortages, productivity, environmental sustainability, innovation and commercialisation, and community engagement and acceptance, including indigenous collaboration in some locations.

BARRIERS TO RESEARCH

Generally, in developed countries the contribution of mining to the economy is comparatively minor compared to other industries, and a nation’s ability to finance R&D explicit to mining is limited. Therefore, many technological innovations in mining are adopted from other disciplines such as construction, automobiles, IT etc.

Reducing environmental impacts, such as noise, diesel emissions and dust, are generally addressed by manufacturers instead of mining companies. Regulations are rarely cited as an inhibitor of innovations.

Mining equipment often has no application in other sectors. Thus, research, development, demonstration, and deployment (R&D[3]) costs per number of units sold are high.

In the last 20 years, mining companies have scaled down their R&D operations. This decrease is reflected in low rankings of mining related industry in a comparison of R&D expenditures across industry sectors. Almost all mining companies have limited their R&D activities to short-term and site-specific problem-solving (www.rand.org). However, the long-run availability of mineral commodities can be described as *"a race between the cost-increasing effects of depletion, and the cost-decreasing effects of new technology"* (Tilton, 2003).

COMPANIES DO NOT HAVE THE RESEARCH CAPACITY OR FINANCIAL MEANS TO CARRY OUT THE INNOVATIVE R&D AND PRIORITISE R&D TO SHORT-TERM OR SITE-SPECIFIC PROBLEM-SOLVING.

Current Status

Globally, research into integration of technology in numerous industries is demonstrated through outcomes of the fourth industrial wave (Industry 4.0) which is the term commonly used to define the ongoing global digital transformation; however, industrial revolutions are usually named after the origin or driver of the impact.

The digital revolution, increasing knowledge innovation exponentially and disrupting every industry, will continue to drive technological advancement. Gavin Yeates, the former Vice President of BHP, acknowledged the need for technology integration in mining when quoting Klaus Schwab, the Founder and Executive Chair of the World Economic Forum (ww.ausimmbulletin.com, April 2017; www.weforum.org, 2018):

"BILLIONS OF PEOPLE CONNECTED BY MOBILE DEVICES, UNPRECEDENTED PROCESSING POWER, STORAGE CAPACITY AND ACCESS TO KNOWLEDGE, ARTIFICIAL INTELLIGENCE, ROBOTICS, AUTONOMOUS VEHICLES, 3D PRINTING, NANOTECHNOLOGY, BIOTECHNOLOGY, MATERIALS SCIENCE, ENERGY STORAGE AND QUANTUM COMPUTING ARE ALL CONVERGING TO ALLOW THINGS TO BE DONE THAT WERE NEVER CONCEIVED OF BEFORE".

The Future

TECHNOLOGIES COULD BE ADAPTED TO MINING OPERATIONS

Mine Internet of Things (MIoT)

Considering the dominant power of the computer, technology now is very different compared to 50 years ago. The future improvement will focus on integrating all aspects of the mining process starting from geology to the end products and all stages of planning from strategic to tactical plans. These plans should integrate uncertainties to mitigate the risks in mining projects. Internet of Things (IoT) devices aim to provide more reliable data to avoid the level of stochastic optimisation required to make predictive sense of it (Kent and Eisner, 2015). The technological developments in mobile internet technology are getting increasingly cheaper and capable through using high capacity mobile computing devices and high-speed connectivity. The IoT concept is going to increase the connectedness of individuals' networks using low-cost sensors and actuators for data collection, monitoring, decision making, and process optimisation. When the produced data and processes accurately couple each other, in the communication of things-to-things and things with individuals, a powerful model is able to create digitisation and transformation of companies, industries and the whole world.

Productivity and safety are two key drivers of the mining industry. Removing personnel from the operations and into the remote-control centres will directly benefit companies. By leveraging IoT technologies, the interaction between people, process, data and “things” can be securely and reliably monitored, modified and maintained remotely through the use of computer hardware and software resources provided over a network or the internet, regularly as a service i.e. cloud technology.

Advanced Big and Smart Data Analytics and Data Visualisation

In the future, more wireless and mobile devices will be able to be instrumented, sensed and controlled more efficiently. This will create high volumes of data that need to be analysed to generate meaningful information. Data needs to be intelligently captured, correlated and analysed to optimise operating systems. At the same time this data is collected, it needs to be used in real time to improve short-term planning so a remote operating centre can modify the plans, if necessary, and use the assets.

One of the issues in using big data is the lack of similarity across situations, and therefore variability in definitions. In many cases, big data will be based on datasets from different sources, of multiple structures and size, leading to a variety of definitions. There is urgency for mining operations in using the information they have already invested in for optimisation, improving their efficiency and resilience to economic downturns. Virtual Reality (VR) technology can be used to visualise complex data in 3D which is particularly useful in spatial relations of point cloud and surface information. This type of visualisation uses a powerful tool for human visual pattern recognition and problem detection. These 3D presentations of complex data free the human brain from performing these tasks and allows brain power to be focused on investigation (Tibbett et al., 2015).

Machine Learning

The capabilities of artificial intelligence and machine learning are increasing at an extraordinary rate. These technologies have many widely beneficial applications ranging from machine translation to medical science. Machine learning algorithms can be considered the next step for digital mine transformation. Some mines have already moved beyond descriptive analytics and visualisation platforms and into machine learning prediction and artificial intelligence, such as using the assessment of ore fragmentation in open pit and underground operations. In the near future, these algorithms will also be used on geotechnical inspections through 3D mapping data and will be widespread in mining operation applications.

3D Printing

3D printing is the process of making physical objects from a digital model using a printer. Additive manufacturing techniques create objects by orienting layers of material based on digital models. For mining companies, often operating in the most remote and hostile environments and requiring a broad array of inputs, most notably spare parts at high frequency, 3D printing can provide an opportunity to streamline and optimise in-bound supply chains.

Autonomous Vehicles and Robotics

Autonomous vehicles can navigate and operate without human intervention, and progressively proficient robots with improved senses, dexterity and intelligence can be used to automate responsibilities or augment people. The application of robotic technology, although very limited in current mining operations around the world, has far reaching potential for the mining industry. Robotic devices powered by artificial intelligence can perform a range of tasks including drilling, blasting, loading, hauling, bolting mine roofs and ore sampling and rescuing trapped miners.

Autonomous Load Haul Dump (LHD) vehicles using robotics are advanced and are already in use. The robots, working in an enclosed environment, transport the samples quickly through the various devices used to determine the sample properties and quality. The use of robots in rescue operations also presents a lifesaving technology (Radenkovic and Kocovic, 2017).

Biotechnology (Next-Generation Genomics)

Fast, low-cost gene sequencing and synthetic biology is a technological development which can be adopted by the mining industry to reduce the environmental impact of mining. Applying genomics, geochemistry and modelling to mine waste and seepage water can help develop biological monitoring, management and treatment options. There are already examples of the use of bacteria for mineral processing.

Advanced Materials and Nanotechnology

Low density and high-strength materials can be designed to have superior characteristics such as, strength, weight, resistance to high/low temperature, conductivity and corrosion protection. Mining operations can benefit from those materials especially ground support technologies, explosives, infrastructure construction, and processing.

Energy Storage and Renewable Energy Usage

Devices or systems that store energy for later use, including batteries, and generation of electricity from renewable sources with reduced harmful climate impacts will be important in the future for the mining industry. Currently, some large mining companies have already invested in wind power and solar thermal energy.

Advanced Exploration Techniques and Advanced Imaging Technologies

Advanced exploration and recovery techniques can make extraction of unconventional deposits economical through the use of hyperspectral core-logging technologies, unmanned aerial vehicles (UAVs), and emerging geophysical portable geochemical exploration tools such as XRFs, Raman Spectroscopy, LIBS, and macro/micro XRDs.

3D imaging technologies have transformed the exploration of large mines and continue to hold promise with a number of emerging technologies. Seismic surveys for studying the geology of potential mining areas are not new, but applications of 3D imaging technologies have enhanced the effectiveness of the research significantly. An innovative technology that has arisen in 3D imaging is 3D laser scanning, which aids to capture spatial data using laser light and allows geologists to build 3D geological maps merging the surface mapping data. In mining, the technology has been used by rock engineers, ventilation engineers and safety officers as well as those surveying in hazardous or inaccessible mining environments.

Advanced Excavation Technologies

Increasing global demand for rough materials is forcing mining companies to investigate high performing mechanisation technologies. This will not only improve productivity but also safety. Mechanised vertical shaft sinking, raise boring, v mole system and shaft boring with air lift are technologies currently used for shaft sinking at mines. Micro gripper, box hole machines and reef mining machines, and trenchless technologies, are also used in mining operations. Road header technologies have been widely used for tunnel development in underground hard rock and coal mines. Tunnel boring machines have been trialled to improve the development speed in both hard rock and coal underground mines in South Africa and Australia.

Transitioning to the Future

The current climate of sustained global minerals demand, coupled with deeper orebodies and lower ore grades, extreme mining conditions, and a range of social and environmental challenges, presents a series of challenges for the future. To eliminate and overcome these challenges, the mining industry is presented with new opportunities to co-develop emerging technologies with leading research institutions, and create new ways of thinking, research culture and approaches to integrate multidisciplinary advanced technologies from a broad range of industry development sectors and leading practices into all level of operations.

The mining industry is generally considered to be a simple and not a complex business. If we integrate technology and develop robots for fully automated mines, can we still consider the industry to be simple?

FUTURE MINES MUST ACHIEVE A SYNERGISTIC COLLABORATION BETWEEN HUMANS AND MACHINES WITH INTEGRATED DESIGN, PLANNING AND OPERATIONS TECHNOLOGIES LEADING TO SAFER, ENVIRONMENTALLY-SUSTAINABLE AND MORE PRODUCTIVE MINING OPERATIONS.

There must be a focus on how to engage academia and industry better to develop a multidisciplinary research focus for the future of the mining industry. It is imperative to look at technology transfer opportunities from other disciplines into the mining industry. It is also key to establish consortiums to include multi-institutions, globally, to assemble the best resources, facilities and people. Proactive engagement with the industry will help achieve these goals. However, strategic government engagement and support are also essential.

REFERENCES

Bye A. R. (2011) "Case Studies Demonstrating Value of Geometallurgy Initiatives". Edited by D Dominy, GeoMet 2011, The First AusIMM International Geometallurgy Conference 2011. Brisbane, QLD, Australia, (9-30).

Cosbey A., Mann H., Maennling N., Toledano P., Geipel J., Brauch M. D. (2016) "Mining A Mirage?: Reassessing the Shared-Value Paradigm in Light of the Technological Advances in the Mining Sector". Published by International Institute for Sustainable Development (IISD), Canada.

Hebblewhite B. (2003) "Management of Core Geotechnical Risks for Underground Mining Projects". Mining Risk Management Conference. Australasian Institute of Mining and Metallurgy Publication Series, Sydney, NSW, Australia, (241 – 245).

Jeswiet J., Szekeres A. (2016) "Energy Consumption in Mining Comminution". Procedia CIRP Volume 48, (140-145).

Johnson K. (2016) "The Critical Role of The Mining Technology Professional". AusIMM Bulletin Magazine, Posted in June 2016. (www.ausimmbulletin.com/feature/the-critical-role-of-the-mining-technology-professional).

Jones O. (2018) "Digital Mines: The Need for Restructuring University Courses". AusIMM Bulletin, Posted in June 2018. (www.ausimmbulletin.com/feature/digital-mines-need-restructuring-university-courses).

Jong E. C., Luxbacher K. D., Kirsch P. A., Mitra R., Hebblewhite B. K., Schafrik S. J., Conley B. N. (2015) "Risk Management: Adapting RISKGATE for Underground Coal Mines in the United States". Mining Engineering. March 2016, Volume 68, Issue 3, (51-57).

Kent D., Eisner D. (2015) "What the Internet of Things Means to Mining". Edited by S Saydam & R Mitra, Proceedings of the Third International Future Mining Conference, Australasian Institute of Mining and Metallurgy Publication Series, Sydney, NSW, Australia, (65-69).

Kirsch P., Harris J., Sprott D., Cliff D. (2014) "RISKGATE and Australian Coal Operations". Proceedings of the 2014 Coal Operators' Conference, University of Wollongong, Australasian Institute of Mining and Metallurgy Publication Series, Wollongong, NSW, Australia, (389-398).

Kocovic P., Behringer R., Mihajlovic R. (2017) "Emerging Trends and Applications of The Internet of Things". IGI Global Book Series: Advances in Wireless Technologies and Telecommunications.

Mitra R., Musingwini C., Neingo P., Adam Z. (2018) "Curriculum review process at the School of Mining Engineering at the University of the Witwatersrand". International Journal of Georesources and Environment – IJGE, Volume 4, Issues 3, (54-58).

Morley C. (2010) "HPGR-FAQ, HPGR". The Journal of the Southern African Institute of Mining and Metallurgy. Volume 110, (107-115).

Radenkovic B., Kocovic P. (2017) “From Ubiquitous Computing to the Internet of Things”. IGI Global Book Series: Emerging Trends and Applications of the Internet of Things.

Restrepo J., Luxbacher K., Ripepi N., Schafrik S., Kirsch P., Shi M., Mitra R., Hebblewhite B. (2015) “Barriers and Incentives: The Application of Comprehensive Risk Management in the US Underground Coal Mining Industry”. SME Conference, Denver, CO, USA, 15-18 Feb 2015.

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, Volume 79, (500-514).

Smith G. (2017) “Mining Engineering – 2020 And Beyond. Discussion Document prepared for the School of Mining Engineering, University of the Witwatersrand” (unpublished).

Stegman C. (2015) “What Does the Future of the Mining Industry, and Hence its Human Capital Requirement, Look Like into the Future?”. Presentation to Society of Mining Professors Session, SME Annual Conference, Denver, USA, February 2015 (unpublished).

Tibbett J., Suorineni F. S., Hebblewhite B., Colebourn, A. (2015) “Virtual Reality Scientific Visualisation - A Solution for Big Data Analysis of the Block Cave Mining System” Edited by S Saydam & R Mitra, Proceedings of the Third International Future Mining Conference, Australasian Institute of Mining and Metallurgy Publication Series, Sydney, NSW, Australia, (109-116).

Tilton J. E. (2003) “On Borrowed Time? Assessing the Threat of Mineral Depletion”. Taylor & Francis Group. Washington, DC USA: Resources for the Future.

Wallace J., Strohmayr S., Cameron K. (2015) “McArthur River Mine heavy medium plant – the benefits of applying modern coal plant design principles to base metal heavy medium separation”. Proceedings MetPlant 2015, Australasian Institute of Mining and Metallurgy Publication Series, Sydney, NSW, Australia, (311–323).

Wills B., Finch J. (2015) “Wills’ Mineral Processing Technology, An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery”. Butterworth-Heinemann Print Book.

Yeates G. (2017) “The Mining Industry Disrupted. How ‘Industry 4.0’ Will Fundamentally Change the Global Mining Industry”. AusIMM Bulletin, April 2017. (www.ausimmbulletin.com/feature/mining-industry-disrupted)

Society of Mining Professors
Societät der Bergbaukunde