THE FOURTH INDUSTRIAL REVOLUTION AND INDUSTRY 4.0 CONSIDERATIONS DURING THE PRODUCTION PHASE OF THE MINING VALUE CHAIN: AN UNDERGROUND CONVENTIONAL DEEP-LEVEL GOLD MINE CASE STUDY

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2021

Declaration

I declare that this dissertation is my own unaided work. I hereby submit this dissertation in fulfilment for the degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been previously submitted to any university for any degree or examination.

Signature: Date:

10/10/2021

Abstract

The mining industry plays a significant role in the economy by providing employment and contributing towards the fiscus. While South Africa prides itself in having some of the deepest mines in the world and the third largest gold reserves, mining in these operations has become an arduous challenge as there is constrained safety and production. This is as a result of mining at depth, low-grade reserves, illegal mining and labour issues. The Fourth Industrial Revolution (4IR) has brought forth digital mining technology that has potential to increase safety, profitability, and life of mine through the use of smart sensors and software. The purpose of this study is to determine how 4IR can be implemented in conventional deep-level mines to address the challenges encountered in the industry. A conventional deep-level gold mine was used as a case study to create a mine modernisation blueprint highlighting how production during the mining cycle can be modified to increase safety and efficiencies. The study revealed that the adoption of 4IR in the conventional mining industry has a significant potential impact on reducing occupational hazards while enabling the industry to mine reserves which were previously inaccessible. To ensure successful adoption of technology in conventional mines, the research proposes the creation of a digital level. This digital level will be a testing station for new technology at the mine. The successful adoption of various technology at the digital level can then be rolled over to the rest of the mine. This ensures sufficient time to gradually implement technology without causing too much of a shock to the system and to understand the technology before adopting it on a larger scale. However, the implementation of technology in the conventional mining industry is challenged by the lack of adequate infrastructure, competent skills as well as the potential of worker resistance.

Acknowledgements

I would like to show the outmost gratitude to Prof. Frederick Cawood who supervised my work and also awarded me an opportunity to pursue this Master's degree through the Wits Mining Institute. A special thank you to Alex Fenn, Robert Van Niekerk, Wayne Robinson and Sibanye-Stillwater for their good faith and investment towards my studies. I would also like to appreciate the many underground miners I have worked with over the years who work tirelessly to ensure safe production every day. I have learnt an incredible work ethic from you, and I hope the contents of this dissertation takes us closer towards achieving zero-harm in our deep-level mining operations. Lastly, my mother Eunice and father Justice Maswanganyi, you have been my pillar of support and source of comfort during this entire period, thank you.

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List of Abbreviations and Acronyms

4IR	The Fourth Industrial Revolution
5IR	The Fifth Industrial Revolution
ABET	Adult Basic Education and Training
AET	Adult Education Training
AHS	Autonomous hauling system
AI	Artificial intelligence
AR	Augmented reality
CMMS	Centre for Mechanised Mining Systems
CPS	Cyber-physical systems
CSIR	Centre for Scientific and Industrial Research
CSMI	Centre for Sustainability in Mining and Industry
DigiMine	Sibanye-Stillwater Digital Mining Laboratory
DMR	Department of Minerals and Resources
FET	Further Education and Training
GDI	Gas detecting instrument
GDP	Gross domestic product
ICT	Information and communications technology
IoT	Internet of Things
IT	Information technology
IPAP	Industrial Policy Action Plan
LiDAR	Light detection and ranging
MCF	Mine call factor
MCSA	Minerals Council of South Africa
MHSA	Mine Health and Safety Act
MHSC	Mine Health and Safety Council
MHSI	Mine Health and Safety Inspectorate
ML	Machine learning
MOSH	Mining Occupational Safety and Health

MPRDA	Minerals and Petroleum Resources Development Act
MQA	Mining Qualification Authority
MVC	Mining value chain
NERSA	National Energy Regulator of South Africa
NIHL	Noise induced hearing loss
NPV	Net present value
OEM	Original equipment manufacturer
PGM	Platinum group metals
PPE	Personnel protective equipment
RBE	Rail bound equipment
RDO	Rock drill operator
ROI	Return on investment
RTVis	Rio Tinto Visualisation
SLAM	Simultaneous localisation and mapping
TB	Tuberculosis
UAV	Unmanned aerial vehicle
VR	Virtual reality
Wits	University of the Witwatersrand
Wits Basin	Witwatersrand Basin
WMI	Wits Mining Institute
WUSN	Wireless underground sensor nodes

1 Introduction

1.1 Background and Context

Between the eighteenth century and the twenty-first century, the world has seen the rise of four industrial revolutions. The industrial revolutions have been inter-dependent; each industrial revolution enabling the rise of the next revolution. The first industrial revolution, dating back to the end of the eighteenth century, involved the use of water and steam power for production, Figure 1. A century later, the world had advanced to the use of assembly lines for mass production enabled by electricity to result in the second industrial revolution. The third industrial revolution gave rise to computers, information technology (IT) and electronics (Deloitte, 2017). As the computer age of the third industrial revolution progressed, it shaped the Fourth Industrial Revolution (4IR) some decades later. Although 4IR is a continuation of the third industrial revolution, it is more efficient but also more complex.

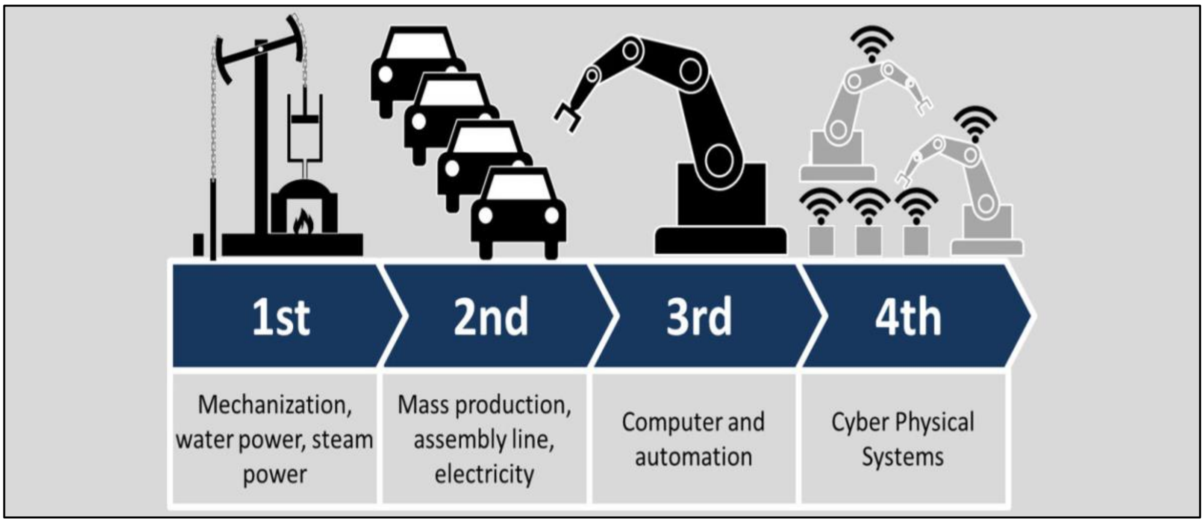


Figure 1: The Four Stages of the Industrial Revolutions (Roser, 2017)

Sishi and Telukdarie (2017) reported that the progression from one revolution to the next accelerated over time. This is because as the systems and technologies evolved, they became more reliable and accessible for use due to the great speed at which new ideas and technology are growing around the world (Benioff, 2017). The 4IR, as described by Rojko (2017), is the use of sensors and software through digital innovation for economic growth and productivity. The 4IR has given rise to the term Industry 4.0, which was first introduced by the German government in 2011 to restore competitiveness in the manufacturing industry through innovation. Over time other industries also begun to adopt the Industry 4.0 principles. Today, there is also Mining 4.0, which can be defined as the application of 4IR to the mining industry (Länger, 2018).

1.1.1 Gold Mining in South Africa

Gold mining begun in the late nineteenth century and currently, there are an estimated 35 large-scale gold mines in operation in South Africa (Acquisdata, 2018). Van Wyk (2010) refers to depths beyond 2 250m as deep-level mining and depths beyond 3 500m as ultra-deep mines. Ranjith, et al. (2017) revealed that deep-level mines face operational challenges such as high working temperatures and seismic events. Hence, maintaining safe production within the deep-level gold mining industry has become an arduous challenge. According to Neingo and Tholana (2016), steeply dipping and narrow underground orebodies characterised by geological discontinuties have prevented the application of mechanisation and automation in the conventional gold mining industry. Therefore, the mining industry has shifted from attempting to mechanise operating conventional mines to the digitalisation of existing mining operations. *The Minerals Council South Africa (2019a)* defined such modernisation of mines through 4IR as the use of new technology to transition the mine of yesterday and of today to a mine of the future to contribute towards skills development, employment, exports, and revenue.

1.1.2 Mine Modernisation

The *Minerals Council South Africa (2019a)* found that modernisation will allow the extension of life of mine by mining deeper resources and lower grade reserves at a profit while improving the health and safety of workers. The modernisation of mines, through digitalisation, also has the potential to reach the goal of zero harm by reducing the number of miners who are exposed to occupational risks and hazards. This will be achieved by removing miners from dangerous working places to operating equipment from a safe distance or remotely from designated control rooms (Lööw, et al., 2019).

Through 4IR technologies a rock driller, for example, can drill the working face without the potential of experiencing face bursts and falls of ground thus, preventing injuries and fatalities. The Internet of Things (IoT), Big Data, cyber-physical systems (CPS), virtual reality (VR), augmented reality (AR) and artificial intelligence (AI) are the digital technologies in the forefront of Industry 4.0 smart industries (Schwab, 2016). These technologies work together to result in a highly efficient system. Therefore, Industry 4.0 can be further described as a collaboration of new technologies to ensure maximum output is achieved by using fewer resources (Kamble, et al., 2018).

1.2 Problem Statement

Decline in Gold Production and Employment

South Africa has the world's third largest gold reserves (6 000t) after Australia (9 500t) and Russia (8 000t), accounting for over 10% of the world's gold reserves (Minerals Council South Africa, 2019b). According to *Statistics South Africa (2015)*, the remaining gold reserves as predicted in 2012, will last South Africa for another 39 years. However, gold production in the country has declined by over 82% in the past 25 years from 524t in 1995 to 90t in 2020, Figure 2. The decline in gold production is attributed not only due to operational challenges but also because there have not been any new significant gold discoveries since 1951 (Phillips, 2013). Viljoen (2009) revealed that the Witwatersrand Gold Field still contains about 35 000t of gold resources located between 2 500m to 5 000m, with the remaining shallow resources at a much lower grade. The gold resources located deeper below surface can only be converted into proven reserves once the safe mining thereof becomes possible.

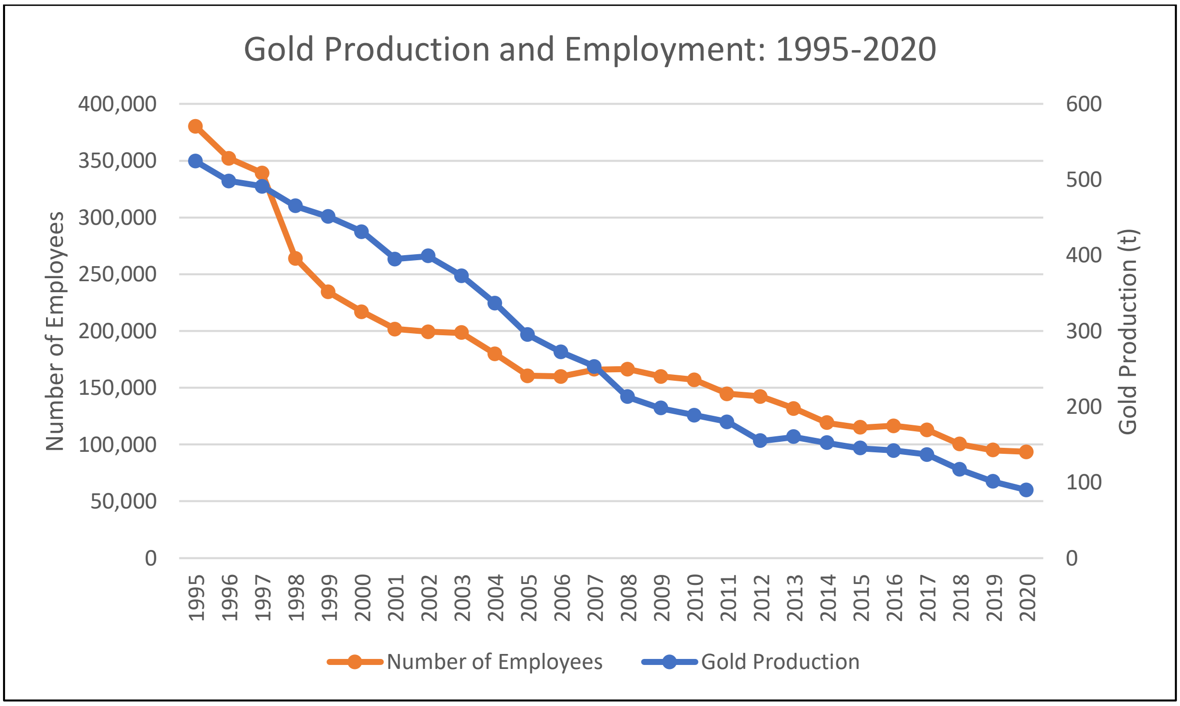


Figure 2: Production vs Employment in the Gold Sector: 1995-2020 (Minerals Council South Africa, 2019g; Minerals Council South Africa, 2021; National Accounts, 2015)

Figure 2 also shows that the decrease in production has also resulted in a decrease in the number of individuals employed by the industry. This is because the sector is now unable to sustain the hundreds of thousands of workers it once employed. In 1995, the gold mining industry employed 380 086 people and this number decreased to 93 682 in 2020; that is a 75% decrease (Minerals Council South Africa, 2021; Statistics South Africa, 2019a). One of the reasons for the decrease in gold production in deep-level gold mines is mining at great depths. According to Neingo and Tholana (2016), deep-level mining is associated with accessing complex reserves, high operational costs as well as high occupational hazards.

High Fatality Rates

The Mine Health and Safety Council (MHSC) introduced the occupational health and safety milestones in 2014 envisioning zero harm in the mining industry by eliminating all occupational fatalities and injuries by December 2020 (Mine Health and Safety Council, 2014). The Zero-Harm campaign is one of the many mining industry campaigns promoting health and safety in the industry. However, the *Minerals Council South Africa (2018a)* reported that there are still high fatalities rates recorded in the industry despite the many initiatives in place. Table 1 shows that the goal of zero harm has not been achieved across the different mining commodities. The question that needs to be asked is why the South African mining industry is still failing to implement zero harm. Typical reasons include the harsh physical working conditions, unsafe mining practices and behaviour of workers.

Table 1: Mining Industry Fatalities: 2009-2019 (Minerals Council South Africa, 2011; Minerals Council South Africa, 2019c)

Year	Gold	Platinum	Coal	Other	All Industries
2009	81	41	18	28	168
2010	63	32	13	20	128
2011	51	37	12	23	123
2012	51	28	11	22	112
2013	37	27	7	22	93
2014	44	15	9	16	84
2015	33	21	5	18	77
2016	30	28	4	11	73
2017	40	29	10	11	90
2018	40	12	9	20	81
2019	18	20	7	6	51

The fatality rates from 2001 until 2019 in the South African mining industry is also illustrated in Figure 3. It can be observed from Figure 3 that the minerals industry has been achieving better occupational health and safety performance. According to *The Department of Mineral Resources (2016),* the average annual fatality rate was 800 miners with 12 000 injuries prior to 1994. Democracy in the country and The Mine Health and Safety Act (MHSA) played a fundamental role in the reduction of occupational fatalities and injuries. The introduction of new regulations, which hold the industry accountable for the health and safety of mining employees, was a significant improvement. The MHSA and Mining Charter are some of the legislations introduced after 1994 to address the injustices of the past due to the apartheid era (Mogotsi, 2005). The MHSA is responsible for the regulation and safeguarding of all mining employees and those affected by mining activities (Minerals Council South Africa, 2019d).

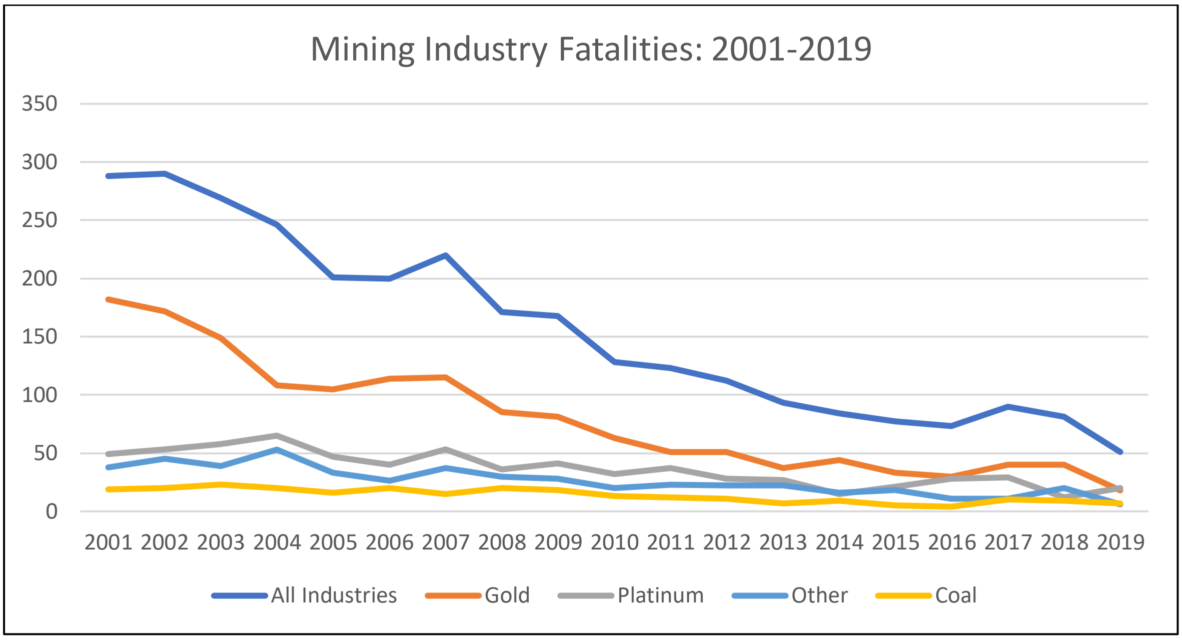


Figure 3: Mining Industry Fatalities per Commodity: 2001-2019 (Minerals Council South Africa, 2011; Minerals Council South Africa, 2018b; Minerals Council South Africa, 2019)

Lack of Technology Adoption

The *Minerals Council South Africa (2019b)* reported that South Africa has the deepest mines in the world, but the conventional gold mining industry is yet to experience twenty-first century mining. In a changing world, gold mining in the country has remained constant as majority of gold mines still use conventional means of drilling, blasting, and cleaning of the stope face. Without a shift in the conventional gold mining industry, the industry will ultimately fail to mine the remaining complex deep-level orebodies profitably. This can result in the sterilization of resources, hence, accelerate mine closures and job losses in the industry (Minerals Council South Africa, 2019a). In addition, the gold industry faces market challenges such as fluctuating exchange rates and volatile gold prices, which further contribute to weakening the strength of the industry.

Condition of Conventional Gold Mines

This is Gold (2018) reported that most gold mines in South Africa are struggling to break-even while *Minerals Council South Africa (2019f)* estimated that over 70% of gold mines were operating either marginally or at a loss in 2018. The presence of old infrastructure, declining grades and increasing depth of mining are some of the operational challenges encountered in deep-level gold mining. Most gold mines are referred to as mature as they have been in operation for many years; Schrader and Winde (2015) revealed mining in the West Rand begun as early as 1934. Hence, these mines consist of old infrastructure, remote underground working areas and poor grades as the high-grade reserves have been already mined out. Mature gold mines are associated with long travelling distances to working places because they are several kilometres from the shaft station and away from other working areas (Neingo & Tholana, 2016). This means more time is spent travelling to and from the working place rather than at the actual working place thus reducing the shift time miners have underground at the stope. Moreover, underground stoping areas are remote from each other meaning that there is little to no communication between them.

Illegal Mining

Illegal mining in the South African gold mining industry has become a serious concern. Illegal miners in South Africa are well known as ‘zama-zamas’. A report issued by *Minerals Council South Africa (2019h)* alleges that 70% of illegal miners are foregin nationals. The report further revealed that a majority of illegal miners were once employees in the mining sector but were later retrenched as the industry experienced low commidity prices and operational challenges. According to the *Minerals Council South Africa (2019g)* the theft of gold result in the country losing in revenue, taxes and employement opportunities. In some instances, stope panels have been closed off due to the severerity of illegal miners who tend to threaten the health and safety of current employees with acts of bribery and violence. Illegal miners often use the mine’s infrastructure to extract gold, and their illegal activities can at times interfere with gold production in working places. Hence, mining companies are inclined to have security personnel to detect the presence of illegal miners, adding to the operational costs of the company.

1.3 Purpose of the Study

The purpose of the study is to bring clarity about Mining 4.0 and the state of digitalisation within the deep-level gold mining industry of South Africa. The study investigates the required resources and factors which need to be considered as deep-level gold mines make digital transformation. This research is particularly looking at the digitalisation of the production phase of the mining value chain (MVC) to create a mine of the future. The study also discusses the future of work, skills and competence that will be required for a typical twenty-first century mine.

1.4 Benefits of Research

Research into Mining 4.0 is expected to bring light about digitalisation in the conventional deep-level gold mines of South Africa. This study will give insight on what can be anticipated as the industry makes the digital transformation. Having a better understanding of deep-level gold mining and Industry 4.0 ensures suitable technologies are selected for mining operations to achieve better production and efficiency. The implementation of 4IR to the conventional deep-level mining industry should not be because 4IR is the current trending topic; however, there should be a clear understanding for the need of digital transformation in the industry. The significance of the research is that it offers the deep-level gold mining industry challenges and benefits which need to be considered as the industry embraces transformation with the use of 4IR and Mining 4.0 technologies.

Currently, there has not been sufficient research conducted on the topic of Mining 4.0 within the South African context, especially its application to the deep-level mining environment. This research considers the distinct geological, socio-economic, political, and environmental factors of South Africa. The study of 4IR and deep-level gold mining is expected to bring light on the application of Industry 4.0 in the mining industry. The study of the current state of digitalisation in the South African mines will provide the industry a roadmap towards transforming conventional mines to digital smart mines. This research will also provide ideas regarding 4IR, which will deepen understanding on the topic of Mining 4.0 and its application within South African deep-level mining context.

Due to the physically strenuous work, the mining industry is male dominated (Botha & Cronjè, 2015). Therefore, a career in mining has not been an obvious choice for many women. Botha and Cronjè (2015) explained that until 1994, women were prohibited from working in underground operations. Two decades later, the *Minerals Council South Africa (2018a)* reported that the representation of women in the gold mining industry had increased to 15% by 2018. This research study will also determine whether the introduction of Mining 4.0 has the potential to fill the gender gap in the South African mining industry. This is because the industry can be transformed to be one where softer skills are required more than physical ability (Lööw, et al., 2019). Therefore, it can be expected that the digital transformation of the gold mining industry is likely to attract more females as the industry will tend to work smarter rather than harder (SAP, 2017). Through Industry 4.0 technologies such as IoT, VR, AR and AI, machinery and equipment can be operated safely with ease.

The World Economic Forum (2016) indicated that some occupations, which are in demand today, did not exist a decade ago and this pace of transformation will accelerate even more. It is further estimated by *The World Economic Forum (2016)* that 65% of children entering primary school today will end up in jobs that do not yet exist. As industries change and become more digital, the future of work is also changing. Seemingly, the required expertise for a mine of the future is different from the knowledge required in the mines today. Industry 4.0 focuses on working smarter rather than harder while Schwab (2016) revealed the digitalisation of industries will result in a decrease in employment for middle-income and repetitive jobs. This sparks fear that embracing new technology may accelerate job losses in the industry. This research will discuss the type of workforce, skills and competence required for a twenty-first century digital mine.

1.5 Organisation of Chapters

Figure 4 outlines the layout of the research chapters and has been structured as follows:

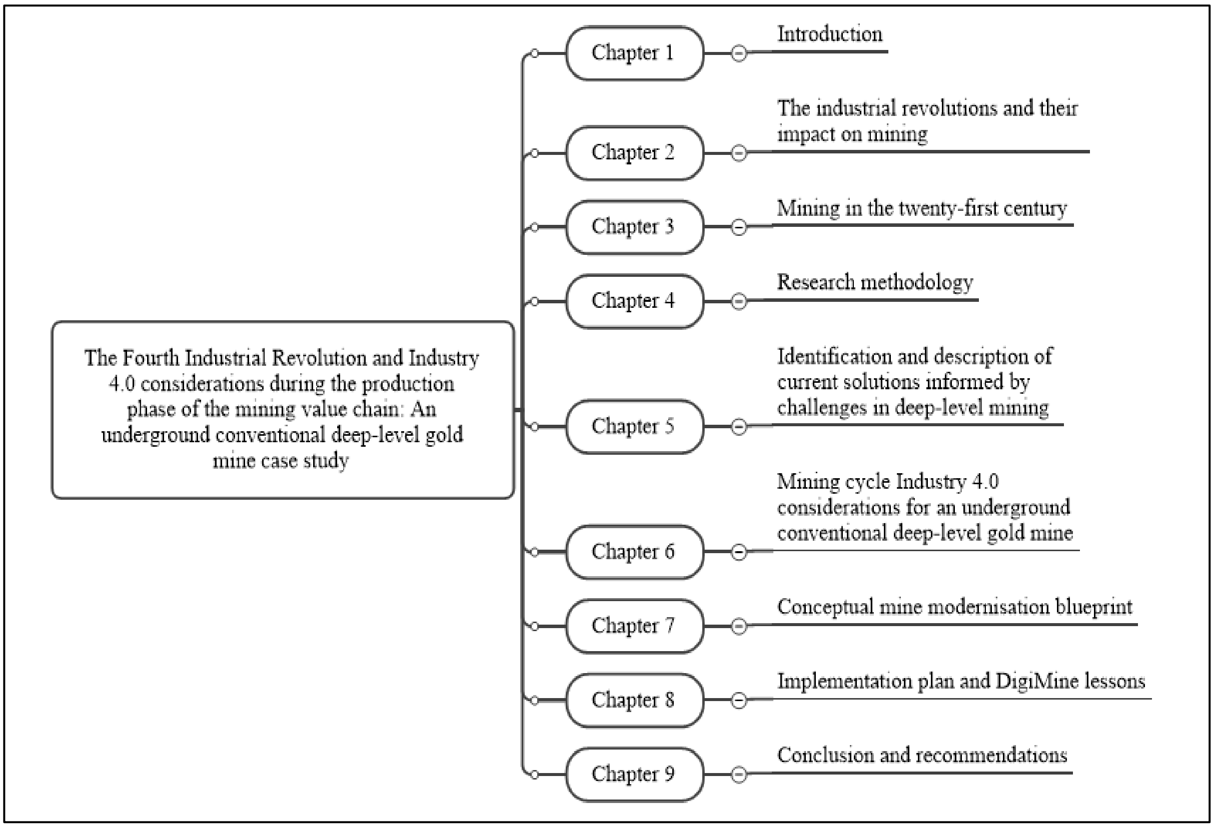


Figure 4: Organisation of Research Chapters

Chapter 1: Introduction

The first chapter gives a background of the research topic, it defines the problem statement as well as the purpose of the study. The benefits of the research study are also highlighted in the introduction.

Chapter 2: The Industrial Revolutions and Their Impact on Mining

Chapter 2 is the first section of the literature review and discusses the various industrial revolutions. The application of the 4IR is discussed in detail to understand its impact on employment, businesses, innovation, society, individuals, and the government. Chapter 2 further discusses the application of 4IR to smart factories and smart mines.

Chapter 3: Mining in the Twenty-First Century

The second part of the literature review is Chapter 3, and investigates the transition of narrow-reef mines to adopting mechanisation during the late twentieth century. Chapter 3 also discusses mining in the twenty-first century highlighting the characteristics of the mine of the future and future of work in such an environment. This chapter later discusses the opportunities of modernising the conventional gold mines of South Africa.

Chapter 4: Research Methodology

The research methodology details the methods used by the author to conduct the research. A case study of a conventional deep-level gold mine and DigiMine were used to conduct this study. Chapter 4 also revealed the research limitations encountered by the author. In addition, the research methodology highlights the hypothesis to be proven in the study, namely:

- The adoption of Industry 4.0 increases zero harm;
- The adoption of Industry 4.0 ensures conventional deep-level mining operations regain profitability; and
- The adoption of Industry 4.0 increases the life of mine.

Chapter 5: Identification and Description of Current Solutions Informed by Challenges in Deep-Level Mining

Chapter 5 identifies the challenges encountered in the conventional deep-level gold mining industry. Suitable digital technologies are identified to mitigate the mentioned challenges in the mining industry. The chapter further discusses the characteristics of the digital mine and how safety and efficiencies are obtained in such an operation.

Chapter 6: Mining Cycle Industry 4.0 Considerations for An Underground Conventional Deep-Level Gold Mine

Chapter 6 is the case study of a conventional deep-level gold mine highlighting the activities that occur in the mining cycle during the production phase of the MVC. The chapter discusses the considerations that need to be made prior implementing digital systems. Chapter 6 also details the challenges that can be expected when digitalising the conventional deep-level mining industry.

Chapter 7: Conceptual Mine Modernisation Blueprint

In this chapter, a conceptual mine modernisation production blueprint for the mining cycle was created for the conventional mine. This blueprint caters for all the activities in the mining cycle detailing how these activities can be automated and digital system introduced. This was done in order to establish a roadmap towards the modernisation of production in a conventional mine setup.

Chapter 8: Implementation Plan and DigiMine Lessons

Chapter 8 is the implementation plan discussing how the conventional mine can transition to become a modernised mining operation. The chapter also details the required roles, responsibilities, skills, and competence in a twenty-first century mine. This is because as the nature of work changes, the competence required in such a work environment will also change. Chapter 8 also discusses the lessons gained from the installation of digital systems at DigiMine.

Chapter 9: Conclusion and Recommendations

Based on the outcomes of the research study, conclusions and recommendations are made in Chapter 9.

Chapter 10: References

Credit is given to the material cited throughout the dissertation.

Chapter 11: Appendices

Supporting material used in the study has been attached as appendices.

2 The Industrial Revolutions and Their Impact on Mining

Schwab (2016) defined the term revolution as an 'abrupt and radical change', while Rundle (2017) described the term industrial revolution as the use of complex machinery to make work processes easier and faster. The industrial revolutions have had a significant impact on the world by raising the standard of living. As the industrial revolutions progressed, humans have found themselves more connected with each other and more lately, with machines. The need to improve production has been the driving force to progress from one industrial revolution to the next. Over time, the disruption caused by the revolutions has intensified and changed the nature of work. Hard physical labour is becoming outdated, as machines become digital. Industries are now forced to reconsider their traditional ways of conducting business because the world is experiencing a 4IR tsunami and it may not be long until the rise of The Fifth Industrial Revolution. This is because the time taken to progress from one industrial revolution to the next has reduced.

2.1 The First, Second and Third Industrial Revolution

Prior the first industrial revolution, Rundle (2017) reported that 80% of the world was using agriculture to survive. According to *Deloitte (2017)*, the first industrial revolution dates back towards the end of the eighteenth century in 1784. This revolution was brought forth using water and steam power for production. The first industrial revolution involved the construction of railroads, which together with mechanical production ushered by steam engines simplified production during that age. The world transitioned to the second industrial revolution towards the end of the nineteenth century into the beginning of the twentieth century. Industries begun mass production through the development of assembly lines. Four years after the discovery of gold in South Africa in 1886, industries begun to use electricity to increase production output. It was during this age that there was structural change in economies and the world moved from agriculture to manufacturing and mining.

The third industrial revolution was because of the application of electronics and IT to automate production. This was during the twentieth century in the 1960's. Some refer to this revolution as the computer or digital revolution because it was influenced by the use of computers and internet (Schwab, 2016). During this time, industries begun using technology to simplify work processes and it was in the 1990's that the internet was developed. Some argue that the South African mining industry is still in the third industrial revolution because there is very little adoption of digital technology of the 4IR. This is because of the lack of necessary infrastructure such as IT and electricity. Although the mining industry makes use of some level of technology, the industry is still labour-intensive and highly reliant on human experience than innovation to solve problems.

Morrar, et al. (2017) revealed that the three previous industrial revolutions resulted in the following:

- Massive economic growth;
- Increased productivity; and
- Better welfare.

The industrial revolutions are interdependent; each one enabling the rise of the next one. The second industrial revolution came about because of the need to improve production as the use of water and steam power could not achieve mass production. Without the discovery of electricity during the second industrial revolution, the world would have never advanced to the use of electronics and internet to enhance production. In addition, 4IR is because of the progression made from the use of the internet, IT, and electronics during the third industrial revolution. Therefore, 4IR is a build-up of the third industrial revolution yet it is more efficient and complex. The complexities of the industrial revolutions have intensified over time such that 4IR requires enhanced skills and competence in digital technology.

2.2 The Fourth Industrial Revolution

The difference between the industrial revolutions of the past and that of today is the speed at which the transformation is occurring. The world is connected, and the cost of access to technology is much cheaper. The speed of transition from the third industrial revolution to 4IR has been much faster yet this revolution is able to close the gap between the virtual world and real world. The 4IR is built on digital revolution and Rojko (2017) described this revolution as the use of sensors and software through digital innovation for economic growth and productivity. Schwab (2016) concluded that 4IR is a revolution characterised by smaller yet more powerful sensors, AI and machine learning (ML). As the world becomes more dependent on technology to enhance work processes and machine is becoming man, Cawood (2019a) argued that man must become smarter to fully benefit from 4IR.

Unlike the previous industrial revolutions, the ability to meet and satisfy customer demands has become the primary function of industries today. During the second industrial revolution, Henry Ford in reference to the Ford T-Model car once said, ‘You can have it in any colour as long as it is black.' Rojko (2017) described this quote as often used to describe the ability of mass production during the second industrial revolution without the possibility of product customisation. However today, industries have changed the nature of work to meet customer satisfaction and increase efficiency. Benioff (2017) revealed that in order to keep up with a rapidly changing world and to meet customer expectations, companies across different industries are now compelled to change their traditional ways of conducting business.

The term Industry 4.0 was first coined in 2011 by the German government and refers to the use of digital technologies to create smart factories which consists of smart products and services (Deloitte, 2017). Stankovic, et al. (2017) described Industry 4.0 as the digitalisation or complete automation of systems with the assistance of merging technologies such as IoT, Big Data, CPS, AI, VR and AR. Industry 4.0 was first introduced in order to exploit the potential of the use of the internet to integrate technical processes with business processes while merging the real world with the virtual world. In an Industry 4.0 environment, there is a connection of different physical devices, which have sensors and software to a wired or wireless network where they all interact together. This interaction and exchange of information is not only between machines but also between machine and man (Kamble, et al., 2018). Therefore, unlike the automation created in the first industrial revolution, 4IR offers an unprecedented relationship between man and machine as real and virtual worlds converge.

The adoption of Industry 4.0 has been seen as a success such that it has been applied across diverse fields such as education, logistics and automotive. Industry 4.0 principles remain the same across the different industries, mainly consisting of merging the real world with the virtual world via technologies such as connected sensors and software. Rojko (2017) has found that data collected via IoT aims to identify, locate, track, monitor and optimize the production process. Hence, Industry 4.0 entails efficient data collection to ensure better production with minimal human intervention (Rylnikova, et al., 2017). Minimising human intervention in some fields such as the mining industry not only increases productivity but safety as well. This is because miners are removed from significant exposure to risks and hazards by using VR and AR to monitor underground conditions from safe control rooms.

South Africa would not be the first country to adopt Industry 4.0 technologies. Rojko (2017) revealed that China has introduced the 'Made in China 2025' initiative in 2015 to upgrade and meet future industry needs for the country. This concept has also introduced transformation and competition in the manufacturing industry such that by 2035 China is predicted to be amongst the leaders in the manufacturing field against Japan and Germany. France introduced 'Industrie du future" to support French companies to adopt new technologies, promote employee training as well as to raise international industrial standards. Therefore, as one of the leading mining countries in the world, South Africa must be in the forefront of mine digital transformation to restore competition in the mining industry once again.

The advantages of adopting Industry 4.0 as reported by Rojko (2017) include:

- Enabling mass production without significantly increasing production costs;
- A flexible and environmentally friendly working environment; and
- More efficient use of energy and natural resources.

2.3 Impact of the Fourth Industrial Revolution

2.3.1 Employment

According to Schwab (2016), the adoption of 4IR will have a significant impact on the global economy in terms of the gross domestic product (GDP), inflation, employment, investment, consumption, etc. The biggest fear associated with the adoption of technology is unemployment. Repetitive jobs such as cashiers, bookkeepers and telephone operators are being replaced by computers. Schwab also revealed that disruptive technologies and innovations increase productivity by replacing existing workers rather than creating new products which will require more labour to produce them. Therefore, it can be expected that there will be a decrease in demand for repetitive and routine jobs but there will be an increase demand for creative and digital jobs.

A gender study report compiled by *World Economic Forum (2015)* revealed that at the current rate of progress it will take 118 years before gender equality is achieved. Schwab (2016) highlights that men still dominate in the fields of engineering, mathematics and sciences therefore, 4IR could increase gender inequalities rather than help bridge the gender gap. This means most women in low-skilled jobs are likely to lose their income, as these jobs will eventually become obsolete. However, women who are in occupations, which require empathy and compassion such as therapy, nurses, psychology, etc, will not be affected. This is because machines cannot fulfil these roles as they require human traits and touch. It is therefore important for people, especially women, to gear themselves by continuously learning and developing their skills to thrive in this new revolution.

As the nature of work is changing, so are the workers and workforce required. In the digital age, there are fewer people required for duty and those available can work remotely without having to report to the office. However, work that is remote is likely to promote isolation and trigger social anxiety amongst workers. Employers can also opt to hire contractors or independent workers to do work for them and therefore, do not have to deal with the hassles of paying workers company benefits or adhere to employer-employee regulations. It then follows that one would never acquire the financial security that employment offers today. One can also find themselves having several jobs to generate income. Manjoo (2015) quotes Arun Sundararajan who revealed: “We may end up with a future in which a fraction of the workforce will do a portfolio of things to generate an income- you could be an Uber driver, an Instacart shopper, an Airbnb host and a TaskRabbit.”

Figure 5 is derived from a study conducted by *World Economic Forum (2016)* and indicates the top skills employers in 15 economies seek when looking for employees. The result of the study revealed that complex problem solving skills and social skills are the leading qualities an ideal candidate should have while physical abilities are the least attracting attributes employers look for. This confirms that the nature of work in most industries have shifted from working hard to simply working smart therefore, today soft skills are in demand than physical skills.

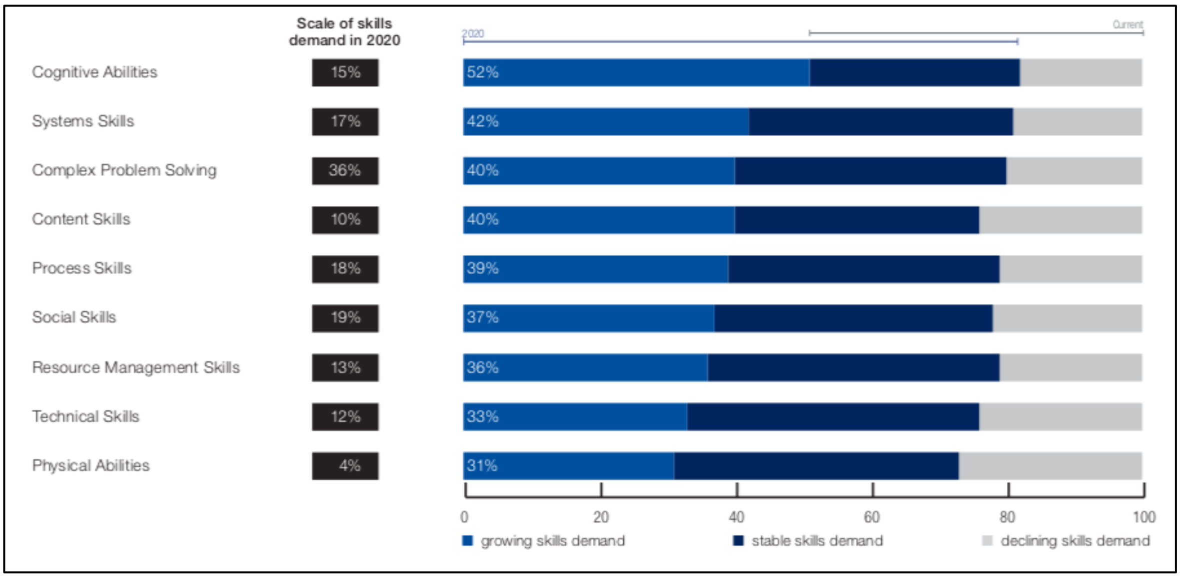


Figure 5: Work-Related Skills in Demand: 2015-2020 (World Economic Forum, 2016)

2.3.2 Businesses

Businesses in modern societies face the challenge of being disrupted failing to adapt in this new revolution. The way business is conducted has exponentially changed and those who have moved up the curve have benefited from the transition. This is highlighed by Schwab (2016) quoting Tom Goodwin: “Uber, the world’s largest taxi company, owns no vehicles. Facebook, the world’s most popular media, creates no content. Alibaba, the most valuable retailer, has no inventory. And Airbnb, the world’s largest accomodation provider, owns no real estate.” Yet, these companies are the some of the biggest companies in the world because they meet customer demands and expectations.

Businesses are able to now predict the performance of their assets through sensors. This is important because poor perfomance of the asset can be tracked in real-time to ensure repairs are done on the asset as soon as inconsistancies are experienced. Predictive maintenance thus reduces the repair costs as the asset is constantly monitored (Sganzerla, et al., 2015). Although operating costs may be reduced by keeping track of the perfomance of assets, huge amount of investment must be towards combating cyber threats and attacks. Businesses are then obliged to have high-data security systems as disruptions caused by criminals can halt the functionality of the business.

2.3.3 Innovation

Lane, et al. (2016) defined innovation as the creation of a new, viable and business offering. Gruenhagen and Parker (2019) quotes Baregheh et al’s definition of innovation as “a process of creating, adapting, implementing and realising the value from new ideas.” According to Jacobs and Webber-Youngman (2017), the need to adopt innovation in the mining industry is because mining operations across the world are 28% less productive today compared to a decade ago. This is partly due to mining low-grade reserves and the presence of hazards associated with mining at depth. These hazards include water inflow, gas discharge, seismicity, and ventilation restrictions. Jacobs and Webber-Youngman further report that the cost to operate mines is increasing three times faster than consumer-inflation rates. However, the mining industry spends 80% less on innovation and technology compared to the petroleum industry.

Therefore, modernisation to improve the current state of the mining industry is important for mining operations to remain viable in the future. Gruenhagen and Parker (2019) revealed that modernisation through adopting innovation can increase productivity, efficiency and to improve health and safety in the mining industry. Modernisation as defined by Jacobs and Webber-Youngman (2017) is “the innovative implementation, adoption and advancement of technologies in order to create and allow the transition towards a more technologically advanced and modernised industry.” These innovative technologies include AI, ML, IoT, VR, drones, and automation.

Lane, et al. (2016) identifies the following as the drivers of innovation:

- Reducing operating costs;
- Improving productivity;
- Reducing workplace risk;
- Reducing costs to develop assets;
- Improving time to develop assets;
- Sustainability; and
- Improving license to operate- regulatory relations and compliance.

Ramdoo (2019) lists the following as barriers to technological adoption in the mining industry:

- *Disruption to existing value chains*- the industry can face barriers from the already established value chains as people are accustomed to a certain way of working and do not want to change;
- *New safety challenges*- the use of new technology is accompanied by new hazards moreover; the workforce will be unfamiliar with the use of new systems;
- *Managing labour transitions*- there may be resistance when operations transition towards using a smaller labour force. This may result in mining companies losing their license to operate in communities that depend on mining for work;
- *High upfront costs*- the adoption of technology is expensive; adequate investment must be made towards modernising. Hence, *Society of Mining Professors (2019)* warned that as the minerals industry begin to embrace digital transformation, the marginal costs of production should equal marginal revenue;
- *Standards, costs and regulations*- there has to be an integration of different systems to work together, taking into account the current health and safety regulations in place. An ecosystem of vendors must be in place; and
- *Disrupting existing value chains*- political influence can block the adoption of technology through the drafting new policies and regulations which do not promote the introduction of technology into the industry.

2.3.4 Society

There are countries which did not fully experience the third industrial revolution due to a lack of electricity and electronics, basic sanitation, and clean water. Schwab (2016) estimated that nearly 1.3 billion people still lack electricity and therefore, have not yet experienced the second industrial revolution. This is while 4 billion people from developing countries still do not have internet access and are yet to experience the third industrial revolution. Schwab further quotes the World Economic Forum's Global Information Technology Report, which states: "Half of the world's population do not have mobile phones and 40 million people still live out of reach of a mobile signal. Some 90% of the population in low-income countries and over 60% globally are not online yet. Finally, most mobile phones are of an older generation." For these third world countries, 4IR is a phenomenon they may not experience any time soon.

According to Morrar, et al. (2017), there are fears that technologies brought forth by the latest revolution will bring problems in terms of inequality. South Africa is said to be one of the most unequal countries in the world, with a consumption per capita Gini coefficient of 0.63 in 2015 (Statistics South Africa, 2018). The Gini coefficient is a measure of inequality in a population by measuring the difference in income or the distribution of wealth amongst a population (Corporate Finance Institute, 2019). A Gini coefficient of zero represents an equal distribution of wealth and a coefficient of one represent a perfectly unequal distribution. Therefore, South Africa is amongst the least equal countries in the world. Additionally, nearly half of the population in South Africa is considered chronically poor, at the national upper bound poverty line of R992 per person per month in 2015 (Statistics South Africa, 2018).

It was revealed by Schwab (2016) that societies, which are unequal, are characterised by the following:

- More violence;
- Higher number of people in prison;
- Increased segregation;
- Greater levels of mental illness and obesity;
- Reduced educational outcomes for children and young adults;
- Lower life expectancy; and
- Lower levels of trust amongst communities.

2.3.5 Individuals

Schwab (2016) quotes Herbert Simon who revealed, “A wealth of information creates a poverty of attention.” The world in which we live today consists of a variety of information readily available at our disposal. Selecting the appropriate data suitable for our individual needs then becomes overwhelming. There are frequent interruptions which Schwab reported weaken our memory, scatter our thoughts, and enhance our anxiety. In this digital age, it will be often difficult to find time to reflect hence, exhaustion will pierce many decision makers across the globe. While social media platforms such as Facebook and Twitter have been created for people to connect and share information, these platforms can be used to spread propaganda and malicious content. Digital users must stay cautious not to be immersed in the inappropriate use and spread of information.

Although AI and algorithms help humans make better decisions and navigate through life easier, Schwab (2016) warned that this might take away human’s ability to be independent thinkers. Today, humans constantly make use of algorithms to decide what, who and where they might most likely find interesting. This information is based on previously collected data of the user’s searches online. Digital technology has thus taken away people’s ability to independently make decisions themselves without any assistance from technology. In addition, the more people leave traces of themselves online they become more likely to be victims of identity theft and phishing.

2.3.6 Government

Through digital technology, the government can be able to govern better as the public will be able to voice out their concerns quicker to relevant departments. The response time to public complaints can be monitored to ensure government service providers handle complaints with the sense of urgency it deserves when attending to the concerns of the public. Essentially, 4IR empowers communities to engage with the government and to become vocal regarding the level of service they receive from local and national government. This in turn forces the government to operate with a higher level of transparency and accountability. Government administration will then be obliged to modernise to improve performance and increase reliability. It can be predicted that government may find it more difficult to govern in the digital age as power goes back to the citizens, however Schwab (2016) challenges policy makers to learn to adapt.

2.4 The Application of the Fourth Industrial Revolution to Smart Factories

Industries are said to be smart when they can independently make decisions using sensors and software and change responses according to the immediate situation and environment by using a wired or wireless network for communication. Hozdić (2015, p. 31) defined a smart factory as "a manufacturing solution that provides flexible and adaptive production processes that will solve problems arising on a production facility with dynamic and rapidly changing boundary conditions in a world of increasing complexity." In a smart factory, workers and machinery work together to execute a task. Machines can also take the role of humans in such an environment through AI, ML and robotics.

Stankovic, et al. (2017) reported that a smart factory networks people, machinery, and resources through Wi-Fi and 5G for communication to occur. The introduction of these networks underground has made uninterrupted communication possible. Smart factories monitor products during the entire value chain and always opt for solutions which are safe and efficient. This is made possible by using history data, current information, 3D models and documentation available on the database of the product (Rojko, 2017). In such an environment, there is constant machine-to-machine interaction and human to machine interaction enabling a continuous flow of information.

In a smart factory, data is acquired from the beginning of the value chain and reconciled at the end. The digital systems within a smart factory therefore become an ecosystem; they work together to result in a highly efficient factory. Daw (2019) revealed that automation plays a huge part in a smart factory as equipment and machinery can be programmed and monitored to work continuously without any major disruptions. Automation enables work to occur without human intervention thus increasing safety and removing the element of human error in the workplace. The following, according to Sishi and Telukdarie (2017), are the opportunities that can be explored with the adoption of a smart factory:

- Automation;
- Better planning methods;
- Mass customisation;
- Agility;
- Visibility and optimised decision-making;
- Improved data analysis;
- Remote monitoring;

- Proactive maintenance;
- Integrated supply chain; and
- Energy management.

2.5 The Application of the Fourth Industrial Revolution to Smart Mines

The minerals industry cannot escape the shift occurring due to 4IR, as change is inevitable and in fact essential. As the world is transitioning to the use of 4IR, the way minerals are extracted must therefore also change for the industry to remain sustainable. In 1980, the mining industry's contribution to the GDP was 21% and had decreased to 7.3% in 2018 (Minerals Council South Africa, 2019b). The mining industry's reduction towards the GDP has been because of a decline in gold production in the country. This decline in production can be estimated to continue as Viljoen (2009) reported that the remaining gold reserves are located at depths below 2 500m to 5 000m with the shallower resources consisting of low-grade mineralisation. Therefore, unless new ways are discovered to mine deeper as well as lower grade ore reserves at a profit, many gold mines will fail to remain viable. The challenges faced by the mining industry as highlighted by *Society of Mining Professors (2019)* include:

- Mining deeper and complex deposits;
- Lower ore grade;
- Geotechnical challenges;
- Extreme mining conditions;
- Lack of adequate infrastructure;
- Shortage of skills; and
- Negative stigma surrounding digitalisation by the community.

Modernisation of the mining industry through developing smart mines is what *Minerals Council South Africa (2019a)* predicts will enable the industry to remain sustainable. A smart mine is one which has been transformed through digitalisation to merge the real underground environment and the virtual underground environment. Lööw, et al. (2019) revealed that the merging of the two worlds allows employees to operate equipment from surface in safe control rooms. In a smart mine, IoT is used to collect data and interpret the information before communicating with other systems and humans. Big Data is the database where such information is stored. Through technology such as VR and IoT, it is possible to have live visuals of the underground environment as is. A mine is referred to as smart when it uses digital technology, sensors, and software to transmit data in real-time to assist in decision-making (Daw, 2019).

The creation of smart mines is a form of modernisation which *Minerals Council South Africa (2019a)* predict will assist the industry to achieve zero harm by facilitating and monitoring occupational health and safety better. For example, temperatures in abandoned working areas can be safely measured through drones without putting the lives of miners at risk. Seismicity, the highest cause of fatalities and injuries in the gold mining sector, can be monitored in real-time to give sufficient warning before it occurs. However, the *Society of Mining Professors (2019)* revealed that surface mines will be relatively easier to modernise because digital systems require minor adaptions to work in surface mining operations. The digitalisation of surface mines will also leave minimal footprint on the environment thus creating invisible mines. However, it will be a challenge to implement technology to the harsh and complex underground mining environment.

According to Lööw, et al. (2019), the use of digital technologies in smart mines has proven to result in reliable, consistent, and profitable systems within the mining industry. Industry 4.0 innovations use the available data in an operation to result in the transmission of highly accurate information thus eliminating the element of human error caused by emotion and physical constraints (Maasz & Darwish, 2018). The ability to have mine data updated in real-time means decisions taken will be based on the available accurate information rather than relying on human intuition. Having access to such accurate information in real-time will assist the industry to prevent similar accidents from occurring and improve the way accidents that do happen are handled.

2.6 Leading Smart Mines

The below case studies of smart mines reveal that as mines digitalise their operations there is an increase in production while there is a notable decrease in operating costs. This is as a result of having fewer employees, better monitoring of assets and improved managing of mining activities within the MVC. According to *Dundee Precious Metals (2019)*, the digitalisation of the production phase results in a higher production output therefore, adjustment must be made on the other phases of the MVC to accommodate the increased ore tonnages. These smart mines consist of fewer but multifunctional mining equipment resulting in less generation of waste. Each mine has digitalised their operations specific to their needs hence have designed their own communication devices with network capabilities that cover their entire mining operation.

The success of digitalisation within these operations has been the need to thrive and improve mining processes by investing in innovation and technology.

2.6.1 Aitik Mine

Aitik mine is owned by Boliden and is said to be the most efficient open pit copper mine in the world and the largest of its kind in Sweden (New Boliden, 2019a). Located in Northern Sweden, the mine is 450m deep. Aitik ultimately aims to have a continuous mining operation running twenty-four hours, seven days a week all year round uninterrupted (Lööv, 2019). The operation realised that production decreases significantly when there are shift changes and lunch breaks and is therefore considering to fully automate their operation to combat this challenge. According to Lööv (2019), Aitik is the first mine to have installed wireless network in 2012 which covers 35km of the mine with 100% coverage. The mine also installed 5G allowing for faster response time and better remote control of machinery. The mine has also designed phones and tablets custom-made for the operation for efficient communication.

The mine can track individuals and equipment throughout the mine and therefore, adjust the ventilation supplies according to the presence of people and machinery in real-time. This in turn has resulted in the conservation of resources and less emissions. In case of a life-threatening emergency, digital systems automatically trace all underground workers and direct them to the nearest refuge bays to assist search and rescue teams locate the miners quicker (Lööv, 2019). Currently, the mine is investigating the use of remote-controlled vehicles for underground firefighting during rescue operations. In March 2019, Aitik started testing the use of autonomous blast hole drilling machines instead of manually operated drill rigs. The study so far has found a 30% increase in production (New Boliden, 2019b). *New Boliden (2019a)* reported that the high level of automation at Aitik has made the mine one of the most gender-neutral mines in the world with an almost equal number of female and male employees.

2.6.2 Belfast Mine

Kotze (2018) mentioned that the Belfast coal mine is a first of its kind in South Africa. The Exxaro owned mine is a digital mine comprising of a digital twin which is an exact replication of the original mine. This allows management and contractors to be constantly connected to the operation remotely. The digital mine will be able to make real-time decisions, remote monitoring, track equipment and performance. As a result, the operation is expected to have increased safety, efficiency and, better flow and transfer of information. According to Vivier (2019), the operation has potential to predict challenges and opportunites ahead of time.

Maintanance crews will have remote access to equipment such that breakdowns can be addressed quicker thus reducing downtime. Once in production, the mine will be exporting A-grade, high yield coal. According to Vivier (2019), production at the mine is expected to commerce in 2020 with an expected life of mine of 17 years. Studies conducted on the mine estimate the mine will have a 98% reduction on the overall environmental footprint. In addition, the project will be revalitising and upskilling the workforce as well as the surrounding mining communities (Kotze, 2018).

2.6.3 Chelopech Mine

The Chelopech mine is an underground gold and copper mine located in Bulgaria. According to Fenn (2019), the Chelopech mine has achieved a 48% reduction in operating costs and a 142% increase in production between 2008 and 2016. Chelopech mine is owned by Dundee Precious Metals and the company has invested close to 90% of its profit to modernise the mine to compete internationally with other leading modern mines. Chelopech mine's significant investment towards modernisation has resulted in the mine being regarded as one of the most efficient mines in Bulgaria (Dundee Precious Metals, 2019). The core purpose of the digitalisation of the mine was to ensure the safety of workers, protect the environment and promote sustainable development.

According to *Dundee Precious Metals (2019)*, Chelopech mine has been successfully modernised due to the presence of good infrastructure; the mine is in close proximity to major roads, communication facilities and powerlines, water resources and towns. Schmidt (2017) revealed that as Chelopech mine continued to mine at deeper levels, the traditional extraction methods using sublevel caving were no longer optimal and begun using the long hole stoping fill method. The change of mining method improved ground stability and resulted in the safe extraction of crown pillars by constructing an artificial roof above the stopes by reinforcing and consolidating the caved rock (Schmidt, 2017).

The mine also developed a new decline, installed an underground crusher and conveyance system for the hauling of ore. The upgrading of ore transportation systems has allowed continuous production and transportation of ore. In addition, there were upgrades made on the ventilation systems and equipment used for production in order to keep up with the increased ore flow. The upgrades implemented at the mine have resulted in a decrease in electricity and water usage as well as a reduction on the tailings and waste produced. The underground mine is monitored in real-time similar to a surface mine through integrated management system technology. Tollinsky (2016) revealed that wireless communications have been installed underground to ensure continuous communication between the surface and underground environment.

Due to the presence of wireless communication, miners make use of tablets underground instead of traditional logbooks to input information of occurances as they happen. This results in a continuous flow of data which is updated in real-time. In addition, there are less equipment used in the operation than before due to better monitoring and control of activities. This has resulted in a lean operation that generates less waste. Autonomous drones are used to track and monitor activities, creating more transparency within the operation. Thus, the overall mining efficiency at the mine has increased by 10-30% (Schmidt, 2017). In addition, the number of employees in the operation has decreased from 1 052 in 2011 to a mere 914 in 2016 as the operation became digital and autonomous (Dundee Precious Metals, 2017).

2.6.4 Éléonore Mine

According to *World Economic Forum (2017)*, the Goldcorp mine located in Canada begun gold production in 2015. The mine uses smart sensors and software to ensure safety and efficiency is achieved in the operation. The sensors installed at the mine are able to turn lights on or off as well as electricity depending on the presence or absence of people in that particular place of the mine. Employees and assets are tracked throughout the mine at all times in real-time through tags. The sensor's tracking system in the tags enables supervisors to clear miners from planned blasting areas during the shift. *Cisco (2015)* reported that employees can be tracked and rescued much quicker in case of an emergency as the location of miners is updated in real-time. Moreover, the air filtration system at the mine supplies air according to the amount of people available in that area, directing fresh air to areas its required most. This has resulted in a 50% reduction in ventilation requirements. The reduction in electricity costs and ventilation costs as a result of the use of smart sensors has therefore reduced the mine's operationg costs significantly. A partnership between Goldcorp and Cisco has enabled employees to go underground with their iPads and iPhones for communication using the mine's network.

2.6.5 Kiruna Iron Ore Mine

Kiruna Iron Ore mine is situated Northern Sweden and mining at the site begun over a century ago. The orebody extends to a depth of 2km and is 4km long and 80m thick with sublevel caving mining method used for ore extraction (Mining Technology, 2020a). The mine is a fully autonomous operation with locomotives ran by operators in safe control rooms, making Kiruna the largest modern underground iron ore mine. The autonomous fleet can collect blasted ore from ore passes and transport it to crushing stations. The mine currently employs 1 800 people however, only 400 of these employees work at the mine (Mining Technology, 2020a). Kiruna iron ore mine is carbon free, digital, and autonomous. This is made possible by the transmission of data, which connects people and assets with the physical and virtual world through IoT. IoT is used to enable operators to predict problems before they occur and equip them to handle the challenges. Through predictive maintenance, equipment availability and reliability has improved significantly at the mine.

2.6.6 Kolomela Mine

The Anglo American's Kumba iron ore open pit mine based in the Northern Cape has implemented automous drilling, a first of its kind in South Africa. The automated drill offers operators a safe, clean and comfortable working condition situated away from the unsafe working site. The operators can drill remotely from a control room and *World Economic Forum (2017)* reported that this is made possible by the partnership between man and machine working alongside each other. *Anglo American (2015)* reported that the automated drill has improved safety to result in a 70% reduction in injuries and fatalities, a 19% reduction in drilling costs, a 18% improvement in the drilling rate while operating hours have also improved by 23%. The overall efficiency at the operation has therefore improved significantly.

In addition, Kolomela mine has purchased 10 drones which monitor the entire operation. These drones, operated by certified drone pilots working at the mine site, are fitted with advanced cameras and laser scanners to survey and map the mine site quicker. The use of the drones has also provided detailed information which otherwise could not be collected through conventional means. To further ensure the safety of employees and its fleet, Kolomela mine has installed an autonomous braking system on its haul trucks. This technology prevents collision of trucks by bringing them to a stop before colliding with each other (SAIMM, 2018).

2.6.7 Venetia Mine

The De Beers owned diamond mine begun to convert their surface operation to an underground mine in 2013. The completion of sinking two vertical shafts and a decline was completed in 2019 with underground production expected to commence early 2021 (Cornish, 2019). The underground mine will reach a depth of over 1 000m. Sublevel block caving methods will be the primary mining method used to extract the diamonds. The development of the underground operation is expected to increase life of mine up to 20 years (Cornish, 2019). James (2019b) revealed that the new underground operation will be a world class operation using the latest innovation and technology to continue supplying the world's diamond demands. *Mining Global (2014)* predicts that once Venetia starts underground production, the mine will make use of driverless trucks and automated drills operated from centralised control rooms. Currently, the mine has proximity detection systems to prevent machine-to-machine and man-to-machine collision. The system also provides the driver with a 360° view around the machinery. In addition to the above safety measures, Matthews-Green (2018) adds that fatigue detection systems have been installed on all haul trucks and shovels at the mine. The mine has recently installed the DebTech X-ray sorter at the plant to identify diamonds and estimate the carat, stone count and size as the diamonds pass through the conveyor in real-time. This enables production information to be updated constantly as the diamonds move through the plant.

2.6.8 West Angelas Iron Ore Mine

The open pit mine owned by Robe River Iron Associates started production in 2003 and is located in Pilbara, West Australia. The mine is currently expanding to increase production from 29Mt to 35Mt annually by mining the estimated 161Mt of proven iron ore reserves. According to *Mining Technology (2020b),* the $642 million expansion was set to begin in 2015 and is expected to increase life of mine by 13 years. The mine consists of autonomous haulage, automated rock breakers, automated drills and blasting hence, Job and Mcaree (2017) name West Angelas as the only mine in the world operating its production fleet autonomously. The automation of production at the mine has enabled the loading and hauling processes to be monitored and remote-controlled from the mine's Perth Operations Centre located more than 1 000km from the mine site. The extracted ore is crushed and screened at the mine site prior shipping.

Iron ore from the mine is transported via rails to Cape Lambert port for shipping. On arrival, there are two robots at the port's sample station to ensure the iron ore product meets the required specification. The robots carry 80kg samples at a rate of 40 per minute through different devices to determine sample quality and properties (Mining Technology, 2014a). This has resulted in increased efficiency and lowered operating costs. To accommodate the high capacity production as a result of digitalisation, *Mining Technology (2020b)* expects the mine to also upgrade their processing plant, ore stacker and access roads to the mine site.

2.7 The Fifth Industrial Revolution

Rundle (2017) predicts that the Fifth Industrial Revolution (5IR) may be closer than we think. Since 4IR enabled better communication and connectivity in the world, a question can be asked as to what to expect from 5IR. Since each revolution has ushered the next revolution, 5IR can be expected to be a build-up of 4IR. Joseph (2020) predicts that 5IR or Industry 5.0 will be an artificial intelligence revolution which allows humans and machines to work together. Joseph (2020) further states that Industry 5.0 will open "the way to curiosity, creativity, empathy, and judgement ensuring a balance between people and technology."

According to Gauri and Van Eerden (2019) this yet experienced revolution will result in humans and machines "dancing" together, working hand in hand, to increase labour productivity. Rundle (2017) predicts that although the previous industrial revolutions improved the quality life, 5IR will focus on intelligence. 5IR can therefore be predicted to be marked by an unprecedented relationship between man and machines through AI. Therefore, 5IR may be adopted by more people than 4IR and at a faster rate. Another prediction of the future is presented by Johansson, et al. (2010) revealing that that 5IR may be principled by lean production. Johansson, et al. (2010) describe lean production as the rationalisation of production leading to reduced waste therefore, energy efficient operations.

2.8 Summary and Conclusion

As industries transition from the third industrial revolution to 4IR, many disruptions can be expected on the economy, government, businesses, and society as a whole. Smart industries have fewer employees which has the added benefit of better supervision and communication. This is because employees have close encounters with each other. Digital operations with less employees also tend to have less reported cases of injuries and fatalities. In addition, some digital mines have bridged the gender gap through the introduction of digital systems. The previously male-dominated mining industry has now become attractive to women as the definition of the best miner has been redefined from being one of great physical strength. The best miner is now the one who can digitally solve complex problems and practice emotional intelligence. Therefore, the application of 4IR has the following implications on the industries where it is adopted:

- Safer operations;
- More efficiency in the workplace;
- Lower operating costs;

- Better employee supervision and ergonomics; and
- A gender-neutral environment.

This chapter highlighted the application of 4IR to the mining industry. Although the successful implementation of 4IR requires investment, the benefits are significant. Thus, the mining industry is moving towards modernisation in order to sustain the struggling industry. The most important finding from this chapter is that although the world is experiencing 4IR today, it will not be long until 5IR takes over. Industries must begin to adopt 4IR to transition to 5IR when the time comes so they are not left behind. The next chapter details mining in the twenty-first century by describing the timeline from the introduction of technology in the form of mechanisation during the late twentieth century to where the industry is today with the adoption of Mining 4.0. The mine of the future and nature of work in a Mining 4.0 environment are also discussed in the next chapter, Chapter 3.

3 Mining in the Twenty-First Century

While the previous chapter discussed the impact the industrial revolutions had on the mining industry, this chapter will detail the transition in the use of technology in the gold mining industry. Chapter 3 discusses the transition from conventional means of mining to mechanisation, to where the industry is today with the application of Mining 4.0. It details the impact, both positive and negative, of implementing 4IR in the mining industry. In a Mining 4.0 environment, machines can communicate with each other, with humans and their surrounding environments - hence these mines have redefined what a mine looks like. Through digital tools such as IoT, Big Data, AR, VR and AI the physical world has been merged with the virtual environment allowing real-time monitoring and feedback to occur. The nature of work in a digital mine is not the same as compared to a conventional mine, the role of a miner is changing, and physical strength is no longer mandatory. However, the South African gold mining industry is over a century old and struggles to adopt twenty-first century mining by embracing technology of this kind.

3.1 Conventional Gold Mining

In the early years after the discovery of gold in 1886 in South Africa, extracting gold was fairly easy. In some mines, Janish (1986) revealed that the gold would outcrop on the surface and labourers would extract it with ease by digging with picks and shovels. Over time, the mineral was located deeper and deeper from the surface; prospectors had to find means of accessing the mineral. It was then that shafts were created to locate such reefs underground. Today, South Africa has some of the deepest mines in the world with the average gold mine more than 3km below surface (Perold, 2013). Conventional mining methods are still used in many narrow reef mining operations today. These operations are labour-intensive, and Pickering (2007) reported that the technology used in these operations dates back to the early twentieth century.

Figure 6 illustrates the daily mining cycle used in a conventional mine. Using Figure 6 as a guide, Pickering (2007) demonstrated that the methods used in the mining cycle have rarely changed from a century ago. Pickering reported that the hydraulic props used as means of permanent support were first introduced in the 1960’s however, some mines have replaced them with yielding elongates. Pneumatic rockdrills were first introduced in early in the twentieth century and today, the hand-held rock drills are still commonly used. Moreover, the charging of shotholes with explosives is still done manually and so is the connecting of detonators. Blasting is initiated remotely on surface after the shift has been cleared. Pickering further identified that scraper winches which are used for cleaning the stope face and gullies were first introduced in the late 1920’s and are still widely used today. This shows the slow rate of change within the industry as well as the industry’s level of commitment towards implementing new technology.

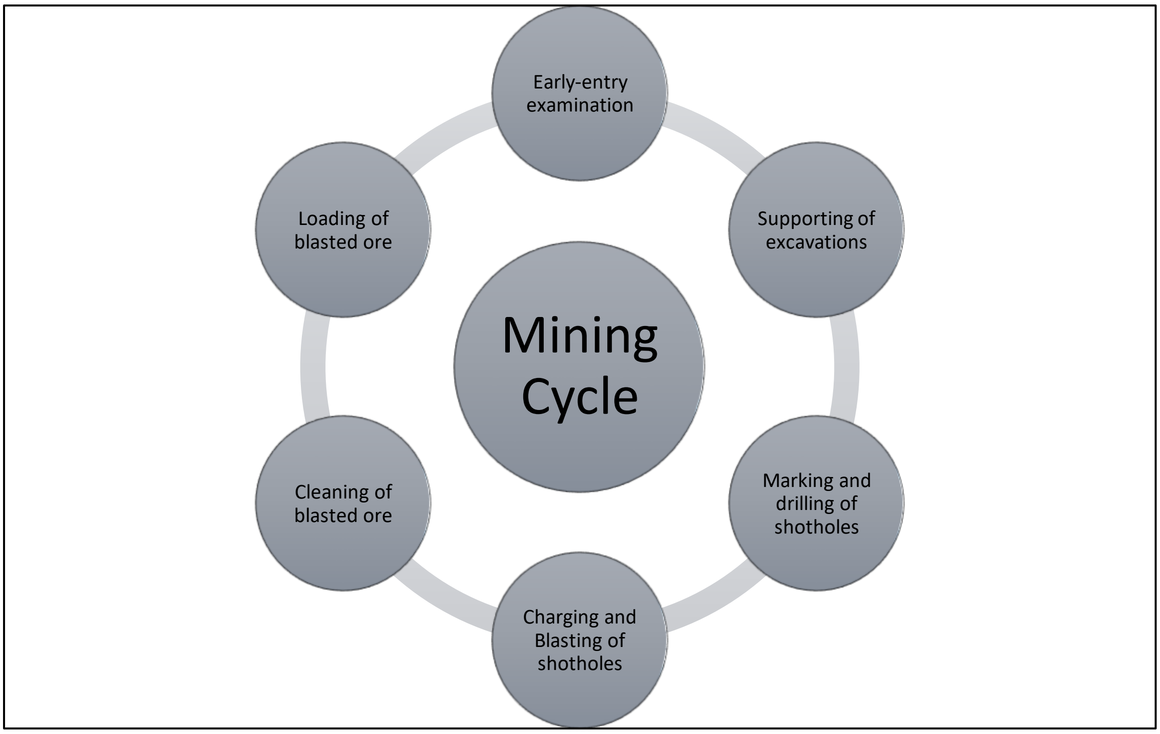


Figure 6: Mining Cycle

3.2 Mechanisation of the Gold Mining Industry and its Challenges

In the late 1980’s many gold mines begun mechanising their operations in order to improve production, cut costs and improve safety. Willis, et al. (2004) defined mechanisation as the use of any machine, process or activity which will result in less human effort to break or transport rock or material in a mine. Hattingh, et al. (2010) reported that mechanisation was introduced in different mining operations to address the concerns raised in that particular mine. Hattingh, et al. further revealed that mechanisation was not only implemented in narrow-reef mines to improve efficiency and safety, but to achieve gender neutrality and to accommodate workers suffering from HIV to use machines when performing strenuous work. Mechanisation could not be successfully implemented in many gold mines. Hence, Pickering (2007) argued that many conventional gold mines in South Africa are still operating within the second industrial revolution. This is because the methods used in the mining cycle of a conventional mine, as illustrated in Figure 6, have not improved since their introduction in the early twentieth century.

Steward (2013) revealed that although the stope is the most strenuous and labour-intensive part of the gold mines, the complexities of the reef have made it impossible to mechanise.

According to *National Accounts (2015),* South Africa's gold deposits are located in the Witwatersrand Basin (Wits Basin). The Wits Basin is 300km long, 150km wide and approximately 6km in thickness (Joughin, 1976). Gold from the Wits Basin is obtained from different conglomerate reefs, which differ in thickness, ranging from a few centimetres to a few metres. Joughin revealed that 50% of gold is mined in reefs that are thinner than 30cm, while 40% of the reefs mined is greater than 30cm to 1m and only 10% of the reefs are more than 1m. The dips of the gold reefs in the basin are estimated to range from 10º to 30º (Wagner, 1986). Narrow reef gold mines consist of varying channel widths, which in turn influences the stoping height. According to Steward (2013), the presence of low stoping heights, marginal grade and varying dip of reef in conventional mining have made it very challenging to implement machines in the face.

Pickering (2007) argued that it is far easier to mechanise an already partially mechanised mine than to convert a conventional mine into a mechanised operation. This was also confirmed by Steward (2013) who stated that mechanisation cannot be retrofitted into existing conventional mines. This is because the infrastructure cannot be easily upgraded to accommodate new technology. In addition, a mechanised operation already has a workforce that has a higher skillset than a conventional mine. Therefore, it becomes easier to train the existing workforce. The mechanisation of operations in South Africa has also been opposed by organised labour due to the fear of job losses, as mechanised operations tend to have fewer employees than conventional mines. However, Willis, et al., (2004) argued that mechanised operations have a workforce which is more educated and trained moreover, these employees have a better socio-economic status. Willis, et al. also report that although mechanisation reduces the number of employees underground, there is an increase in the number of employees required in the manufacturing industry.

Facing the difficulty of mechanisation, Vogt and Hattingh (2016) reported that some gold mines opted to implement hybrid-mining systems to enhance production. Hybrid mining is a combination of a conventional layout with the use of machines to maximum production output (Pickering, 2007). In hybrid mining, conventional methods of mining are used and access to the face and transportation of the reef is through trackless equipment. This layout, the combination of conventional mining and mechanised transportation, has been successful in some operations. However, the full mechanisation of mining operations has only been effective in mines with thick orebodies. Steward (2013) confirmed that there are only a few gold mines characterised by massive reefs that have been partially or fully mechanised successfully. Hence, mechanisation in the platinum sector has thrived because of the favourable characteristics of the orebody such as high stoping width and a lower dip of reef (Vogt & Hattingh, 2016).

South Deep gold mine stands out as one of the exceptional gold mines which have been successfully mechanised mainly due to its favourable orebody characteristics. *This is Gold (2018)* reported that South Deep also offers a safer working environment than tradititional conventional gold mines. This is because mechanised operations tend to distance workers from occupational hazards as miners are not subjected to close encounters with the stope face. Through bulk mining, South Deep has been able to mine lower grade reserves at a profit. Due to operational challenges, *Gold Fields (2018)* reported that in recent years the mine has not been able to deliver on production targets and is expected to undergo restructuring.

3.3 Mining 4.0 and the Digital Mine

According to Perold (2013), South Africa is home to some of the deepest mines in world; AngloGold Ashanti's Mponeng mine is currently the deepest mine and operates more than 4km below surface. As mineral resources become scarcer and more difficult to mine, the mining industry is challenged to re-imagine its mining practices and processes. Mining at great depths does not only pose a risk to the health and safety of employees, but mining companies are likely to operate at a loss while attempting to access deeper reserves. This is because the cost of transportation, communication, support, and ventilation increases with depth resulting in higher operational costs (Wagner, 1986). The increase in operational cost is accompanied by a decrease in production rate in deep-level mining. This is because the complexity to access the orebody increases with depth, making it difficult for operations to remain viable.

According to Vogt and Hattingh (2016), mechanisation in the gold and platinum industry has been slowed due to modest grades, low stoping heights and difficult dips. Hence, the gold mining industry has been challenged to find innovative solutions to address production and safety concerns. To address challenges encountered in the mining industry, Mining 4.0 has been adopted in many mining operations. Mining 4.0 is the application of 4IR to the mining industry (Länger, 2018). Mining 4.0 involves the digitalisation of mining operations to make them safer and efficient through the application of advance digital technology of the 4IR. The digitalisation of mines involves the use of sensors and software to monitor the underground environment, personnel, and assets.

3.3.1 The Digital Mine

SAP (2017) refer to digital mining as the use of digital technologies, comprising of a variety of sensors and software, working together to formulate a highly efficient system. Digital mining involves AI systems, which are capable of making independent decisions to ensure safe, efficient and sustainable mining. Thus, Ranjith, et al. (2017) referred to digital mining as ‘Intelligent mining’ as it can transform information, support automation and requires less human intervention. Hence, it can be concluded that the future of deep-level mining lies in modernisation through digitalisation. Figure 7 highlights the characteristics of a digital mine comprising of a digitally connected workforce which is in constant communication with the control room and surface environment.

Using sensors, equipment and the underground environment can be monitored in real-time. Deviations encountered in the environmental conditions underground such as the presence of toxic gases or high temperatures can be detected quicker and reported to the relevant department. The installation of sensors in mining equipment ensures that the equipment can be tracked at any given time thus increasing asset utilisation. In addition, through digital twinning it is possible to monitor the performance of equipment and detect any malfunction in the equipment and thus give it the necessary attention before the situation worsens.

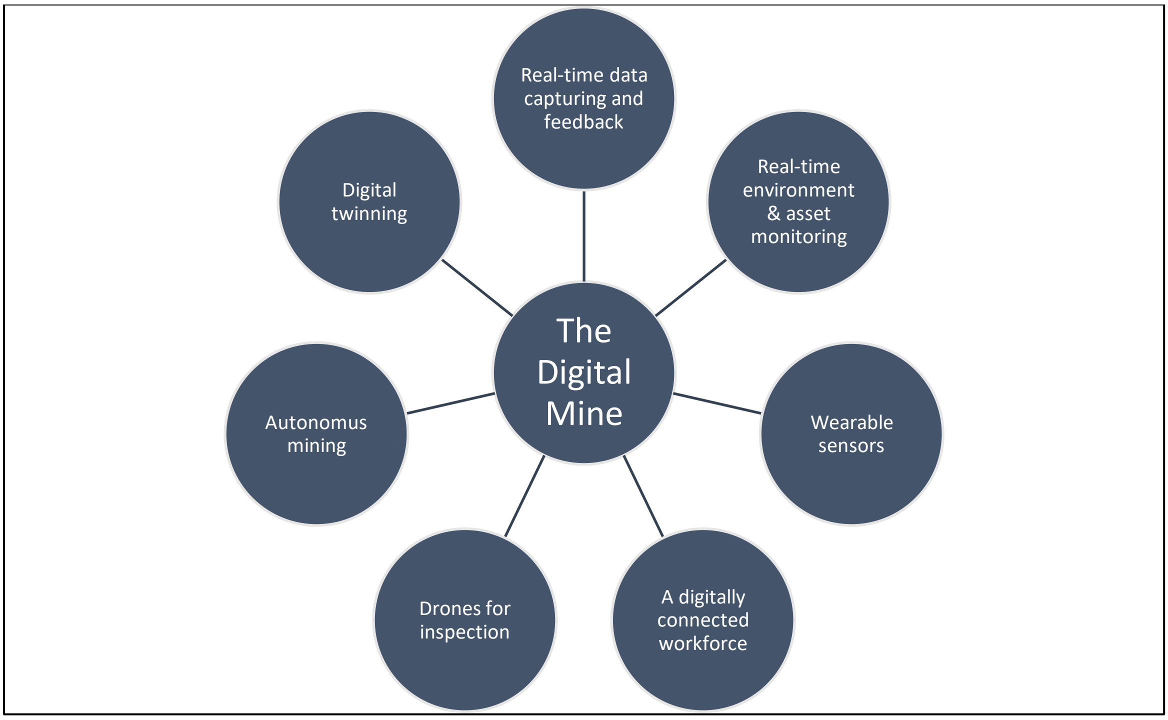


Figure 7: Characteristics of a Digital Mine

Personnel underground can wear sensors which can be in their helmets to detect any nearby hazards as well as to track their position in the vicinity of the mine. These wearable sensors also enable persons underground to communicate wirelessly to the control room in case of an emergency. Figure 7 also highlights that in underground areas where it could be deemed dangerous to send humans for inspection or where it would be humanly impossible to reach, drones can be used instead. In addition, the digital mine consists of autonomous vehicles for hauling and transportation purposes. DeWhurst (2018) reported that driverless vehicles increase mining output by 15-20%, cuts fuel costs by 10-15% as well as reduce maintenance costs by 8%. Ghodrati, et al. (2015) adds that automation has the additional benefit of having self-correcting functions that employ feedback thus reducing human error.

3.3.2 The Sibanye-Stillwater Digital Mining Laboratory

To promote safety and combat premature closing of mining operations, research institutions such as the Sibanye-Stillwater Digital Mining Laboratory (DigiMine) have been developed. DigiMine is an innovative laboratory, which researches new technology that can be implemented in the mining industry to ensure safe and profitable operations. DigiMine is also a state-of-the-art multidisciplinary research institution evaluating the benefits of using technology in the mining environment to restore safety, competition, and profit in operations. DigiMine is hosted within the basement of the University of the Witwatersrand’s (Wits University) Chamber of Mines building and was officially launched by the Wits Mining

Institute (WMI) and Sibanye-Stillwater in 2018. Potgieter (2019) revealed the WMI comprises of several research institutions namely, DigiMine, The Centre for Sustainability in Mining and Industry (CSMI) and The Centre for Mechanised Mining Systems (CMMS).

DigiMine has received R30 million funding from Sibanye-Stillwater with the aim of promoting research in the field of digital mining to reduce risk and increase efficiency in mining operations (James, 2018). Research conducted at the DigiMine aims to create a mine of the future and to determine the resources and skills required for such an operation. DigiMine consists of a diverse team of postgraduate students, local and international, who have graduated from different faculties such as electrical engineering, mining engineering, geology, etc. Currently there are close to 15 students committed full time in research studying towards either a Master of Science or Doctor of Philosophy. According to James (2018), students at the DigiMine conduct research that varies from underground communication systems, seismicity and mine design, underground mapping and navigation, real-time integration of technologies and skill-based research. The research topics given to students are aligned with their area of interest although the DigiMine sponsor, Sibanye-Stillwater, can request specific research topics to be investigated.

Digital systems are assigned to students based on their field of research and they are responsible for ensuring the systems are functional and always updated. DigiMine has partnered with different companies such that there is a collaboration of different vendors within DigiMine. These systems work together to result in the high transmission of data. Different vendors offer students essential training on running the system and can be contacted at any given time should students encounter difficulties with the functionalities of the systems. The digital systems at DigiMine communicate with each other and to the control room via a wireless network. The Wits ICT department assists DigiMine with high Wi-Fi coverage. The Wits Wi-Fi covers the entire DigiMine space including the mock mine. The network provider, Wits ICT, also provides protection against cyber threats.

DigiMine comprises of a mock mine and a control room at the basement of the Chamber of Mines. The mock mine has an underground development end, which has been drilled with production holes, charged, and connected with electronic detonators. The mock mine also consists of a simulation of an underground stope panel. The mock panel imitates the real underground mining scenario equipped with actual underground support such as packs and pre-stressed elongates. DigiMine also consists of a variety of digital and communication systems installed at the mock mine, which transfer information in real-time to the control room. Digital systems at DigiMine are developed and tested at the mock mine and results are interpreted at the control room where there is live feedback back and forth. The control room contains a videowall displaying the performance of the different systems in place. The performance of the systems at the DigiMine can be managed remotely from anywhere at any time. DigiMine has made use of Mining 4.0 to digitalise the nature of mining work at the institution.

According to James (2019a), the WMI is also collaborating with the Tshimologong Digital Innovation Precinct to fast-track technologies and prototypes in the digital space to bridge the gap between research outcomes and commercialisation of prototypes. Tshimologong also takes in students, who do not have any mining background or qualification yet have digital knowledge and skills. The students are given a platform to engage with mining technology companies to increase the potential of their ideas and innovation becoming commercialised. DigiMine also hosts several seminars annually; presenting industry experts a platform to give their input on the state of the South African mining industry and 4IR, with intentions of promoting the subject of technology and innovation in the country.

3.4 Opportunities of Digital Mining

A digital mine is one which there is an integration of systems to ensure a continuous flow of data across the operation. The control room in a mine, which can be considered the heart of the operation, links all the departments within the mining operation together; from human resource, maintenance to finance (Walsh, et al., 2017). This allows for integrated planning and consultation with the various departments to occur when making decisions. Data from different communication systems underground flows to the control room in real-time where it is interpreted and stored. Since the flow of information in a digital mine is continuous, previously obtained data can be used to interpret recent data to understand patterns and trends. Having insight of historical trends can help make predictions of the future which in turn reduces uncertainty.

Mining 4.0 has been regarded as a potential efficiency solution to South Africa's much struggling mining industry. *CGI (2017)* reported that Mining 4.0 not only has the potential to turn resources into reserves but can obtain new ways of mining resources safely and productively using twenty-first century technology and innovation. According to *Minerals Council South Africa (2019a)*, there is an estimated 160Mt high-grade gold ore, which has been left as support pillars in the Wits Basin. This is because deep-level mining operations tend to leave bigger support pillars behind. Therefore, adopting twenty-first century mining is essential in order to achieve higher a pillar extraction rate. In addition, a study conducted by *Minerals Council South Africa (2019a)* revealed that there are 400Mt of low-grade ore left underground, which cannot be mined at a profit using the current methods of mining. The study also revealed mine life can be extended 15 to 25 years through modernisation made possible by adopting new technology.

Accessing deeper resources has proven to be difficult for the gold mining industry. Lööw, et al. (2019) argued that Mining 4.0 can convert the remaining resources in an operation into reserves by accessing reserves which could not be safely extracted through conventional means as well as the mining of lower grade reserves at a profit. If new ways of mining the remaining gold reserves are not implemented, *Minerals Council South Africa (2019a)* predicted that it will lead to sterilisation of resources, which will accelerate mine closure and employment losses. When a mine worker loses their job, the loss of employment does not only affect them but also the many dependents relying on them for provision. It was estimated by *This is Gold (2018)* that each mine employee supports between five to 10 depedents.

Due to the nature of work underground, women are subjected to physical strain. Because of this, Botha and Cronjè (2015) mentioned a study by Badenhorst, which revealed that 43% of female recruits are not physically fit for the nature of work in mining. Moreover, Botha and Cronjè report on a study conducted by Ashworth revealing that the lifting capability of a woman is 60 to 70% that of a man. This is because of the following:

- The genetic predisposition of women - women have less physical strength than men;
- Workplace design- the mining environment has been designed to cater for men; and
- Lifestyle- women are usually less active than men.

Botha and Cronjè (2015) also revealed a study conducted by Schutte and Campbell, which reported that the design of equipment in the mining industry was designed for men as the height of these equipment caters for the average South African man who is taller than a woman. The lack of consideration for women when designing mining workplaces, equipment, and protective clothing, have disadvantaged women tremendously. Women, therefore, tend to opt for other careers away from the mining industry because they have not been considered in this nature of work. Contrary to the strong trend of conventional mines, physical strength is no longer mandatory for operations which have embraced Mining 4.0. Equipment and machinery can be run remotely from safe control rooms with the use of digital tools such as IoT, AR and

VR. Therefore, Mining 4.0 has the potential to bridge the gender gap in the mining industry as mining has been previously known as a musculine industry.

Therefore, Mining 4.0 is adopted in the mining industry for the following reasons:

- To improve productivity and efficiencies and therefore, reduce operating costs;
- To increase life of mine by mining complex and lower grade orebodies;
- To reduce occupational risks and hazards thereby improving safety and;
- To promote gender equality.

3.5 Tools for Digital Mining

Parviainen, et al. (2017, p. 64) defined digitalisation as "the adoption or an increase in the use of digital or computer technology by an organisation, industry, country, etc" and refers to the process of converting analogue data into digital form. Digital transformation, as described by Sganzerla, et al. (2015), refers to the speed at which new information is readily available to people and companies thus resulting in new ways of doing things. When a company digitalises their operation, data collected from different sources can be captured and updated in real-time. Given access, collected data can then be readily made available to employees at any given time and anywhere, allowing people to work remotely. The convention from analogue to digital format has the benefit of safely storing information for long periods without the need for large office spaces and leaving paper trails. The digital tools used in 4IR enable information to be transmitted back and forth through a wired or wireless network. These tools are highlighted in Figure 8 and further explained below.

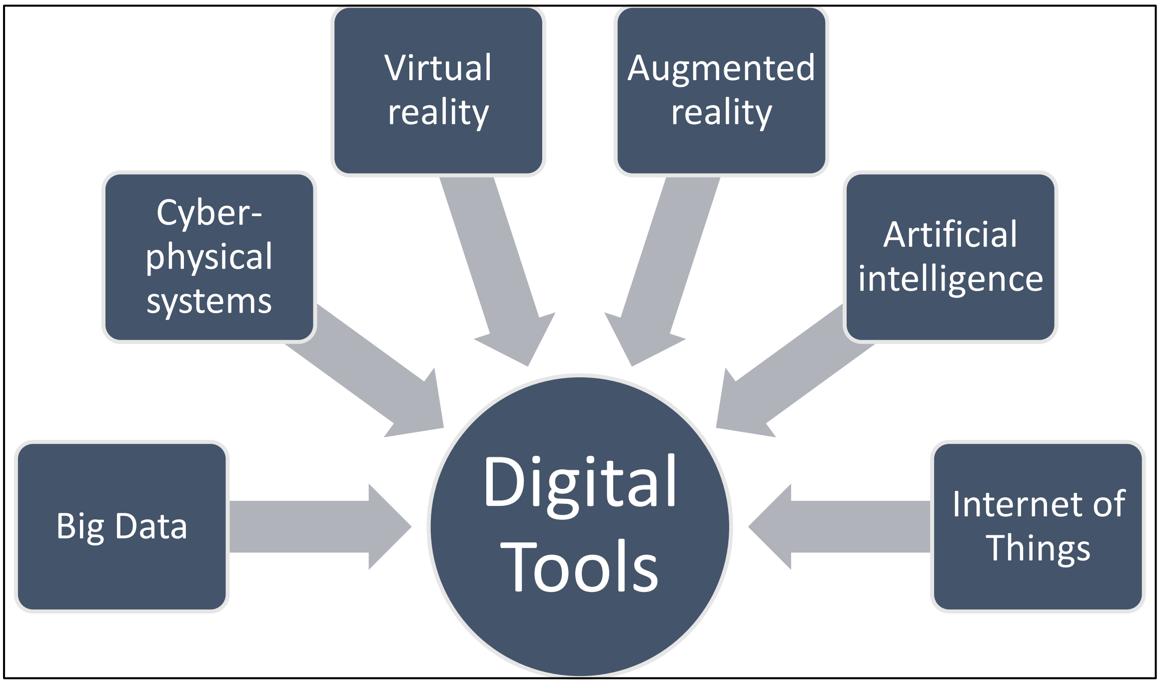


Figure 8: Digital Tools in Mining

3.5.1 Big Data

Big Data is the use of the internet to store and access information, which was not available before the connection. Access to such information reduces uncertainty and performing based on speculation rather than facts as history information of the operation can be stored and readily accessed (Maasz & Darwish, 2018). Real-time data collection leads to real-time decision-making resulting in higher product quality, energy efficiency and improved maintenance. This can be achieved because the product and its consistency are connected and tracked throughout the system. Stankovic, et al. (2017) refers to Big Data as the storing and processing of large amounts of data to select the appropriate information quicker therefore, enhancing the speed at which information is obtained and decisions are made. This in turn increases productivity. However, Stankovic, et al. (2017) reported security and privacy concerns to be the leading challenges associated with the use of Big Data as it involves the storage of large amount of data online.

3.5.2 Cyber-Physical Systems

Sishi and Telukdarie (2017) defined cyber-physical systems (CPS) as different kinds of devices, which independently make decisions, exchange information, trigger action and control each other. CPS consists of human-machine interfaces, which communicate altogether and can independently make decisions (Maasz & Darwish, 2018). Another definition of CPS, as presented by Rojko (2017), are autonomous systems, which can make their own decisions based on data captured in real-time, machine learning algorithms, analytic results, and recorded behaviours of the past, which have been successfully logged into the system.

3.5.3 Virtual Reality

With virtual reality (VR), special glasses or similar devices are used to digitally immerse the user into a virtual environment. This technology can be used for training purposes where the user has first-hand experience of the environment without physically being there (Maasz & Darwish, 2018). In addition, VR can be used for training of risky mining environments as the user gains the necessary knowledge of the environment without physically being there yet see the environment in real-time. This offers individuals who have never been underground exact description of the mining environment as it is.

3.5.4 Augmented Reality

Augmented reality (AR) technology immerses an object into the user's immediate environment to determine the changes that occur due to the presence of the object using smart digital devices such as glasses and smart phones. Maasz and Darwish (2018) report that this technology creates an opportunity to view the object in 3D and its effect on the environment before physically placing it there. An AR user can input different objects into the environment to see the changes that occur in the system due to the presence of that object; while VR puts the user into the virtual environment without having the ability to alter anything in that environment. AR and VR are thus bridging the gap between the physical world and the virtual world.

3.5.5 Artificial Intelligence

Marvin Minsky's definition of artificial intelligence (AI), as cited in Marsden (2017), is "The science of making machines do things that would require intelligence if done by men." AI allows machines to do humanlike work, behaves smart and insightful by using skills, which are associated with human intelligence. This includes the ability to perceive, learn, act and reason autonomously (Marsden, 2017). AI can select the correct data from the stored data to solve problems. It has been therefore, successfully used in fraud detection by identifying suspicious people, activities, and information. According to Potapov (2019) digital technologies and AI are enabling mining companies to extract minerals in complex geological and extreme weather conditions. Through digital technology, Potapov confirmed that previously inaccessible ore deposits can be developed without endangering lives and minimal human error. AI is currently applied in the following fields in the mining industry:

Exploration

According to Potapov (2019), 90% of Canada's Goldspot Discoveries Inc.'s gold extraction is from detailed geological, topographical and mineralogical data of its gold deposit. This is achieved through analysing data from multiple sources and using algorithms to identify areas where minerals are most likely to be found (Imran, 2019). The use of AI in the exploration field has resulted in more accurate data and prevented the loss of money drilling boreholes to obtain minerals in areas without valuable resources.

Transportation

Autonomous haul trucks and trains are widely used in both surface and underground operations. Rio Tinto, an open pit iron ore mine, uses autonomous trains which can independently travel up to 1 700km. Each train is more than 2km in length consisting of 240 ore carrying cars (Potapov, 2019). In addition, Walker (2019) states that these autonomous fleet are safer and 15% more cheaper to operate than trains operated by humans. These fleet run uninterrupted 24/7 without delays due to toilet breaks and shift changes.

Granulometry and Sorting

Smart sensors are used to separate valuable minerals from waste rock by means of X-rays and infra-red rays. These smart sensors are also able to detect rocks which are too big for the crusher thus preventing downtime caused by blockages in the crusher. The Boliden mining company has used this sorting technology and achieved a 12% reduction in ore mass to be moved (Walker, 2019). This has in turn resulted in a reduction in the fuel and energy required during the sorting process.

Security

Sensors are widely used to monitor ground conditions and temperature changes to warn employees of potentially dangerous situations. In addition, AI can predict when equipment may fail, and this cuts equipment replacement costs by attending to it before it fails. In line with promoting safety, Caterpillar has installed fatigue detection sensors on its mining trucks to prevent mining accidents due to driver drowsiness.

Robotics Systems

Kamble, et al. (2018) predicts that robots will eventually start interacting with each other and with humans, and even learn from them. Robotic systems do not have physical constraints which humans have and therefore, have the potential to replace people where humans are incapable to fulfil those positions without compromising their health and safety. The difference between AI and robotics is that AI is intangible in its manifestation while robotics has physical manifestation as it involves mechanical engineering, electrical engineering, and computer science (Stankovic, et al., 2017). Autonomous systems tend to combine both AI and robotics. An autonomous machine has AI, which drives the intelligence of the machine to be able to independently make decisions, while the robotic component of the machine refers to the mobility of the machinery.

3.5.6 Internet of Things

Kamble, et al. (2018) defined the Internet of Things (IoT) as machine-to-machine interaction without human intervention and, human to machine collaboration to improve productivity, efficiency, and reliability. IoT collects, analyses, and manages data. The captured data is processed and communicated with other physical systems and humans. IoT can also be described as the connection of different physical and smart devices. Maasz and Darwish (2018) revealed that IoT involves different kinds of sensors, assets, devices, systems, and people connected via a wired or wireless high-capacity network, which is connected to the internet. IoT connects people, machines, assets, and other services for a flow of information, which assist in shortening schedules, reducing costs, and improving safety (Dehran, et al., 2018).

IoT does not only involve machine to machine communication but also involves machine to infrastructure, machine to environment and machine to man communication (Stankovic, et al., 2017). IoT can be thus referred to as the technology which connects all things. While Big Data deals with the processing and storage of data, IoT increases the amount of information that is available by enabling the connection of digital tools such as CPS, AI, VR and AR together. CPS can, therefore, be thought of as the bridge that connects IoT with other services. IoT then enables predictive maintenance and remote monitoring, hence improving efficiency.

According to Parviainen, et al. (2017) the benefits of digitalising using sensors and software include:

- A reduction in operating costs as more can be achieved with less manpower and resources;
- Better understanding of the product and risks associated with it as information on the product is updated regularly;

- Increased economic growth and an improved quality of life as people and communities will be digitally equipped with necessary twenty-first century skills;
- Brings new business opportunities in the digital and manufacturing industries and;
- Allows government and private companies to perform with better transparency and efficiency, as accurate information will be at their disposal.

3.6 Mine of the Future

How can the South African mining industry begin to design a mine of the future when it has never fully experienced the digitalisation phenomena? According to Alan Kay "the best way to predict the future is to invent it" (Deloitte, 2018a, p. 2). The mine of the future is an intelligent mine because modern and advanced technology is used which can independently make decisions to enhance productivity and improve safety without or with minimal human intervention. The mine operates in real-time using sensors and software made possible by IoT. A wireless or wired network enables the constant flow of information from the underground environment to the surface operation to power the mine. Such data generated from IoT is helpful in accident investigations where real-time information can be used, rather than relying on human's version of events, to ensure such accidents do not happen again.

3.6.1 Characteristics of the Mine of the Future

The mine of the future aims to remove miners from dangerous underground mining conditions to a versatile and comfortable working environment. Mining 4.0 digitalises the process of drilling and blasting through VR and AR. Rock drill operators can be removed from close proximity to the stoping face to a remote location or at a safe working distance where they can safely drill the face (Lööw, et al., 2019). Because of digitalisation, the mine of the future has fewer employees in the operation as work processes will be automated. The remaining miners underground wear devices that can sense and monitor their health vitals. The location of underground miners is also logged in real-time to track their location underground, which can be useful in tracking workers should they be lost or injured.

Digitalised mining operations such as Aitik Copper Mine in Sweden have fewer miners. This has the added benefit of better supervision and monitoring of workers together with their working places (Lööv, 2019). Humans will not be entirely replaced by robots and automation but will be working alongside these machines. This is because AI does not have the empathy that humans have therefore, human intellect and touch is still needed in the workplace. IoT, AI and robotics will be merely providing consistent and accurate monitoring of underground working places where humans are unable to access. In addition, the mine of the future is a gender-neutral environment where the soft skills of employees supersede the need for physical strength. The available equipment can be used with ease catering for all genders and even the physically challenged.

The equipment, machinery and other essential assets in a digital mine can be tracked underground through geo-position devices. This can be helpful to ensure equipment is located quickly and made available for utilisation. When an equipment is due for service or requires repairing, the information is logged immediately in the system and the manufacturer is made aware. This in turn reduces the costs that would be spent on replacing the equipment or parts of the equipment due to premature failure caused by delaying the repair of necessary breakdowns in the equipment. Tracking the performance of equipment has become easier with digital twinning. According to Stoddard (2019), digital twinning is when equipment virtually mirrors its digital twin such that if there are delay between the virtual machine, which performs optimally, and the one performing in the mining environment, immediate attention can be given to the equipment as it signals that it requires repairs.

According to Sganzerla, et al. (2015), drones can be used to inspect areas which cannot be easily accessed by miners due to falls of ground or presence of toxic gases. This means such working places can be monitored better without any human intervention. Hence, the workforce in the mine of the future is digitally equipped with the necessary tools to operate a twenty-first century mine thus redefining the future of work. This digital transformation of the industry can be expected to improve skills development by training workers to handle digital tools and improve their computer literacy. Because of the transmission of data in real-time, the mine of the future is constantly updated in order to achieve the following outcomes:

- Improved performance through predictive analysis;
- Reduced operating costs by reducing labour;
- Reduced occupational accidents; and
- Reduced equipment downtime.

3.6.2 The Zero-Entry Mine

Johansson, et al. (2010) argued that the only way that zero-harm can be achieved in the underground mining industry is when there is no one working underground. In a zero-entry mine, all the machines are self-regulating and remote controlled from surface. Any mechanical breakdown of machines underground is attended to by remote-controlled robots. Should the machine require the manufacturer for repairs, a remote-controlled vehicle loads the machinery and transports it to surface. Johansson, et al. (2010) further revealed that since there are no humans present in these zero-entry mines, there is no need to worry about environmental conditions such as noise, dust, radiation and temperature, so long it does not affect the functionalities of the machines. Although the concept of a zero-entry mine is far ahead compared to where the industry is today, it is a prediction of where the mining industry is heading in the next few decades. The mine of the future will ultminately be a zero-entry mine where everything is remotely controlled from surface. The zero-entry mine could be the start of another revolution, Mining 5.0.

3.7 Future of Work and the Need for Mine Modernisation

Mining as we know it is changing. The future of work involves less workers and having a workforce with a higher skillset. The best miner in a Mining 4.0 environment is no longer one with the most physical strength but one with recognisable soft skills such as emotional intelligence, creativity, communication, critical thinking, and complex problem solving (World Economic Forum, 2019). Due to twenty-first century technology, digital mines such as the Aitik mine in Sweden have achieved a nearly equal number of male and female employees. Mining 4.0 also transforms the mining environment into a continuous education and learning system. In this environment, there are new demands for teamwork and collaboration of different disciplines to solve complex problems (Lööw, et al., 2019).

Mining 4.0 is an environment where the miner solves mining problems as they occur whilst in communication with other operators, experts, customers, and suppliers working jointly as a team. Hence, it can be concluded that digital systems do not entirely remove the mining workforce and teamwork. Teamwork in this environment takes a different form as various experts connected via IoT can conduct work remotely. Although work can be done remotely, partnership and teamwork between the different mining disciplines is vital. However, some argue that the work of the future in a digital environment will be more isolated as work will become more remote, resulting in less contact between employees. Liversedge (2019) revealed that this is likely to induce loneliness and anxiety amongst employees.

According to *Deloitte (2018b)*, two-thirds of five-year olds will have jobs in fifteen years' time, which currently do not exist. The location of these jobs might also be not what we are used to today. Work in the future is predicted to be more remote and digital therefore, 4IR should be thought of as a unique opportunity to be embraced rather than a problem. Workers will become digital operators who use wearable devices empowered by VR and AR to monitor the workplace. Miners will be overseers and supervisors of the systems in place rather than slaving hard at work as it is today (Sganzerla, et al., 2015). The decline in the number of people required at work across different industries is confirmed by *World Economic Forum (2017)* estimating that 5% of the workforce may be lost due to digitalisation in the next decade. This is because repetitive work will become obsolete and redundant as the work can be assigned to robots.

According to *Deloitte (2018a)*, work in the future will be highly digitalised and technology driven; the workforce will be digitally connected and most importantly, leaders in the mine of the future will be diverse, agile and dynamic. As the mine of the future is developed, the nature of work in such an environment must also change. This is because there exist a correlation between an environment and the type of work conducted. Changes to the mining environment will also require appropriate changes to be done on the workforce, enforcing a better relationship and understanding between man and machinery. According to *Deloitte (2018b)*, the future of work in a digital space involves the following changes:

- Work- changes to the type of work done on surface and underground;
- Workplace- the environment and systems in place will no longer be the same; and
- Workforce- enforcing the partnership between man and machinery and, having man relying on sensors and software to enable a safer and productive environment.

3.7.1 Automation in the Mining Industry

Automation is the use of machinery operated remotely to do work without human intervention (Ghodrati, et al., 2015). Automation minimises employee exposure to risks and hazards by removing them from dangerous working conditions thus increasing safety. The removal of workers from dangerous working places does not only improve safety and efficiency, but it also means operations will require fewer personnel at the operation. Therefore, labour costs can be reduced, and company resources can be allocated where required. According to Ghodrati, et al. (2015), human error in the working place can be eliminated as automation involves the use of robots and machines, which are able to constantly self-correct and issue feedback. Ghodrati, et al. further describe the following four forms of automation mining operations can consider to automate production:

Remote Controlled

In this scenario, mining machinery and equipment is controlled through handheld remote controls. The operator stands in full sight of the machinery and working place. The remote control is used to control the functionality of the machinery. The restrictions that come with this kind of automation is that it has reduced machine productivity, as the operator does not have full visibility and feel of the machinery. However, this technology is suitable to use in dangerous mining conditions such as actively blasted faces and unstable ground conditions with high chances of falls of ground.

Teleoperation

This technology uses VR and AR enabled by sensors, cameras, and software. The operator is at a remote location and operates the equipment having full visibility of the working place. The operator uses hand-held devices such as joysticks to control the machinery. Miners for example, can be removed from dangerous working places to safe controls rooms where they have full view and control of the mining environment as it is in real-time.

Semi-Automation

Here the mining process is partially automated. Some functionalities are fully automated, and the machinery can independently function on its own and in other instances, an operator controls the machinery remotely from a safe location. An example of this is a semi-automated LHD machine; it requires an operator to remotely control the loading and unloading of ore however the machinery is fully automated to independently haul and transport ore between the loading and unloading points.

Full Automation

The machinery in this case is independent and can function without any human intervention. Robots in a fully automated machinery can manage the functionality of the machinery such as the ignition, steering, acceleration and braking of the equipment. Fully automated systems display the highest rate of productivity and efficiency as the element of human intervention is eliminated. Operators can only supervise and monitor the efficiency of the entire process. This high level of efficiency is experienced at the Rio Tinto mine in Australia where the autonomous fleet runs independently without any human intervention.

3.7.2 Miner 4.0

Lööw, et al. (2019) uses the term Miner 4.0 to refer to a digital miner of the 4IR. The Miner 4.0 has access to a wide range of data through IoT resulting in quicker and efficient response time to maintenance issues and breakdowns (Sganzerla, et al., 2015). Through Mining 4.0, the Miner 4.0 has enhanced human skills, senses, memory and increases awareness made possible by sensors. The Miner 4.0 is safely located at a designated control room with full access to mining data and resources throughout the underground system. The advanced miner can remotely connect maintenance officers with manufacturers who can then work together in assisting each other to repair problems thus, reducing down time as a result of breakdowns. The Miner 4.0 has increased limb movements, strength, and endurance due to biomechanical support. The digital miner also uses AR to transform information from a digital form to a physical form using special glasses such as 3D glasses.

The Miner 4.0 uses smart assistants for interfacing with computers, machines, databases, and other information systems. Robotics can be used to perform repetitive and strenuous work-related tasks and are controlled by the intelligent miner remotely. According to Rojko (2017), there are currently studies being conducted in collaborative robotics where special designed robots and humans work together to complete complex tasks in the production line giving rise to machine to human interaction based on AR technologies. The Miner 4.0 initially teaches the machine a certain path and thereafter, the machine automatically follows such that the operator only oversees the activity. The Miner 4.0 uses Big Data to store and discover new information and can use such information to predict future events.

Jeffery (2018) revealed that the remaining gold reserves in South Africa are located below 3km where workers are potentially exposed to hazards such as high temperatures, seismicity and falls of ground. In such a dangerous working environment, the Miner 4.0 can use intelligent sensors to detect any atmospheric hazards present such as toxic gases and fires, as well as check the competence and closure of the hanging wall. This can be done remotely from the control room without putting the health and safety of the miner at risk. Using robotics empowered by sensors and software to conduct work which would otherwise endanger the lives of humans, is the primary reason operations are opting to digitalise because no production is worth the lives of others.

3.7.3 Opportunities Presented by Mine Modernisation

Deloitte (2017) report that Industry 4.0 has resulted in the production of smart factories and smart mines where a virtual copy of the physical world is possible therefore, offering real-time monitoring of the systems in place. The sensors and software in Industry 4.0 enable machines to be linked to all the different systems within the value chain allowing the product to be traced hence, improving product and service quality. Resources can be networked and located at anytime and anywhere thus, discrepancies in the system can be logged and breakdowns can be dealt with immediately. *CGI (2017)* has found that the use of sensors can determine when an equipment needs to be serviced thus preventing breakdowns and reducing maintenance costs by addressing breakdowns way before they occur.

Wear and tear on machinery can also be monitored efficiently therefore, reducing waste by repairing machinery before the damage is irreversible. This results in an overall reduction in operating costs. Through digital twinning, equipment can virtually mirror its digital twin to detect inconsistencies. When the equipment operating in real-time does not perform optimally as its virtual twin, it signals that the equipment may need immediate attention and require repairs. According to Gillespie (2015), the ability to detect when an equipment requires repairs before its performance deteriorates is referred to as condition-based maintenance and exponentially saves time and resources.

Morrar, et al. (2017) reported that digital transformation brings economic competitiveness, an improvement in resource utilisation and performance through the creation of smart mines. 4IR is bringing global competitiveness as industries are now challenged to digitalize their operations to result in production which is collaborative, customer specific and individualised (Deloitte, 2017). Mining 4.0 solutions tend to improve operational efficiency, asset utilization, productivity, environmental sustainability, and inventory management. *CGI (2017)* confirmed that digital solutions also manage energy consumption resulting in greener operations, cost cutting and more consistent quality. With Mining 4.0 technologies, mines can be transformed into becoming smarter and sustainable.

According to *Society of Mining Professors (2019)*, the mining industry has been male dominated for decades and the removal of systematic barriers will allow both genders to have equal opportunities in the industry. The barriers that exist are due to the physical nature of work (Botha & Cronjè, 2015). Work in mining is often streneous including lifting heavy objects, working in confined spaces and hot temperatures for long periods of time. Due to this, Botha and Cronjè (2015) revealed that 43% of female recruits are not physically fit for the nature of work in the mining industry. Therefore, the introduction of Mining 4.0 to the South African mining industry will make the industry even more appealing to women. Miners who have previosuly been seriously injured in the line of duty and as a result deemed unfit to work underground, can return to work and be able to support their families once again.

According to a report by *CGI (2017)*, industries adopting 4IR will be working smarter rather than harder. Systems can be controlled remotely with great service speed therefore, eliminating the need for human presence in dangerous working places. This can be useful in environments containing occupational hazards such as deep-level mines by removing the workforce from areas of potential harm. Kamble, et al. (2018) revealed that using digital systems, hazards in the workplace can be monitored and mitigated. According to Maasz and Darwish (2018), the use of Mining 4.0 technologies has also resulted in better employee ergonomics and satisfaction leading to better employee efficiency. This is because employees are no longer subjected to the harsh mining environment for long periods of time.

The workforce in a Mining 4.0 operation is trained and developed with skills required for twenty-first century technology and mining. Muir (2015) state that an illiterate workforce dominates the conventional mines of South Africa therefore, as mines begin to digitise their operations mining companies will be compelled to improve their current training methods and facilities. This will enhance the level of competency and knowledge of mine workers. This in turn creates competition amongst workers to constantly develop their career and remain relevant in the mining industry by acquiring the relevant skills and training. In addition, the implementation of Mining 4.0 in the mining industry can be expected to restore competition in the slowly deteriorating industry.

From the above-discussed benefits of adopting mine modernisation, the following can be concluded:

- Operations become remote yet connected more than ever before through IoT;
- Employees experience a healthier working environment of constant learning;
- The mining industry will become more inclusive of females and the physically challenged;
- Equipment will perform optimally; and
- Operating costs will be reduced.

3.7.4 Challenges Presented by Mine Modernisation

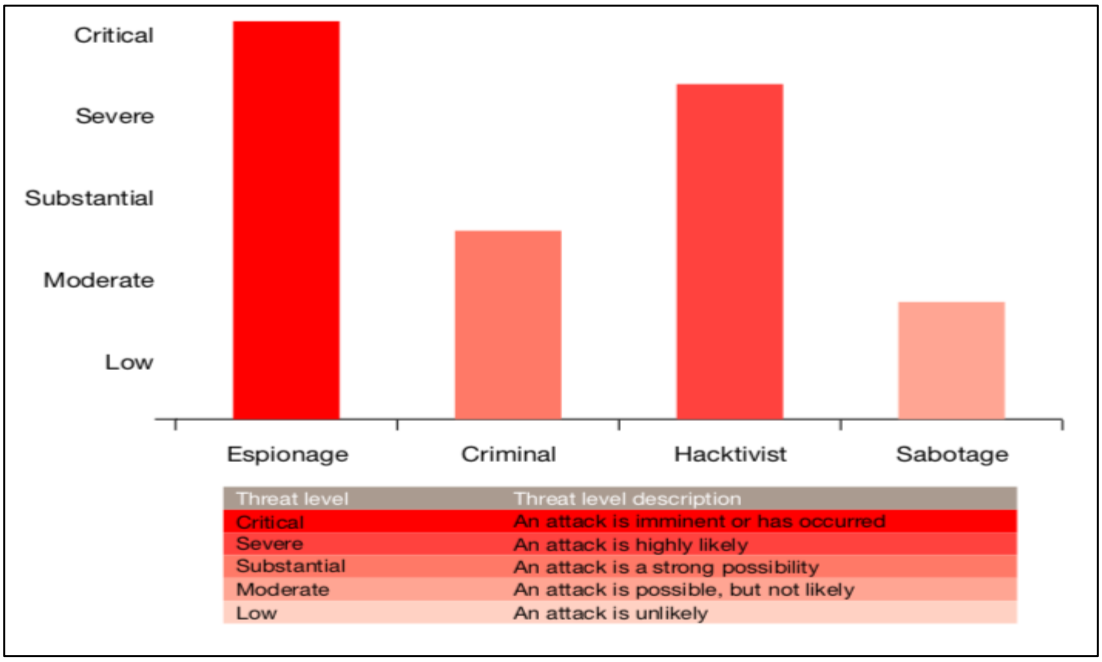
Deloitte (2017) reported that Industry 4.0 technologies require connectivity in order to communicate with each other and with humans. This connectivity can be through a wired or wireless network. Therefore, accessibility to a strong connection to the internet is required. There are ICT infrastructure required for such connectivity; either new or upgraded infrastructures can be used however, they are currently non-existant in most mining operations. In addition, ICT infrastructures are depedent on a constant and reliable supply of electricity. Electricity is also used underground for ventilation and cooling, hoisting activities, lighting of tunnels as well as pumping of water out of the mine (Cornish & Kotze, 2015). However, electricity in South Africa is said to be a major concern. The mining industry electricity tariffs have increased by over 523% since 2006 and a 30% increase is expected in the next three years (Minerals Council South Africa, 2019c). This may be too expensive for the mining industry to afford, as the industry is responsible for 30% of the total national consumption.

In December 2019, Eskom announced it had moved to stage 6-load shedding and requested mining companies to reduce their load on the national power system. Stage 6 entailed mining companies operating only their essential services such as pumps and ventilation (Seccombe, 2019a). Due to this power shortage, major gold mining companies stopped their mining crews from going underground, as mining companies could not risk having thousands of workers trapped underground with no means of returning to surface due to power cuts. According to Seccombe (2019a) the inability to keep a stable and affordable electricity supply in the mining industry has previously led to the closing of many gold operations. As power cuts in the country continue, the mining industry is not immune to the effects of power shortages.

In recent years, the South African mining industry has lost attractiveness to investors due to regulatory uncertainty. A survey found that that of the 15 countries in Africa that have significant mineral resources, South Africa is the third worst country to have mining interest in after the Democratic Republic of Congo and Zimbabwe (Vegter, 2019). Therefore, it comes as no surprise that Jeffery (2018) found that there are no new investments going into the mining industry due to unstable government policies and regulations. This is despite mining legislation such as the Minerals and Petroleum Resources Development Act (MPRDA) of 2004 and the Mining Charter of 2002 which were introduced in the post-apartheid era to ensure the country's minerals also serve to benefit those who were unfairly treated in the past. Such legislations have also made it difficult for investors to gain confidence in the industry. *Eunomix (2018)* explains that post 2002, the mining industry tends to focus on production than long term investment. *Eunomix* also revealed that when amendedments are made in mining policies such as the Mining Charter, which was amended in 2018, the industry tends to be fragile due to uncertainity investors have in the potential growth and direction of the industry.

There is also a general reluctance to invest in new technology as the economic climate forces industries to cut costs rather than spending on innovation. Another concern with the implementation of Mining 4.0 is the cost implications associated with it; to fully digitise an operation may run over hundreds of millions of rands yet also carrying uncertainity regarding the benefits of the adoption of the technology (Sukiennik, 2018). Before investing in new technology, mining companies are also considering the fact that there are limited gold reserves left in South Africa and the uncertainty regarding the rate on investment (ROI) because of this. Omarjee (2016) confirmed that there are limited gold reserves and estimated the remaining reserves to last up to 39 years.

As industries make the digital transformation, protection is necessary against the many cyber-threats such as espionage and spying, hacktivist and sabotage (PwC, 2017). There are cyber risks and privacy concerns associated with the use of Industry 4.0 technologies, as they are dependent on the transmission of information via a network connected to the internet. A survey conducted by *PwC (2017)* shows that cyberattacks in the form of espionage are becoming critical in the mining and metals industry. This is highlighted by Figure 9. The breach of security in a mining operation has the potential to halt the operation, as daily activities are dependent on the transmission of data via a network. In addition, there are threats of losing confidential information because as the world becomes connected, it has also become easier to access information (Maasz & Darwish, 2018).



Threat level	Threat level description
Critical	An attack is imminent or has occurred
Severe	An attack is highly likely
Substantial	An attack is a strong possibility
Moderate	An attack is possible, but not likely
Low	An attack is unlikely

Figure 9: Cyberattack Threats Identified in the Mining and Metals Industry Worldwide (PwC, 2017)

According to *Deloitte (2018b)*, the types of cyber threats that can occur include:

- Inside threats- refers to employees within the organisation who have access to confidential data and intentionally use it for their own financial gain by selling information;
- Espionage- this is the theft of sensitive information for insider trading to promote the interest of competitors;
- Hacktivism- an individual or organisation which executes cyberattacks in order to promote societal change; and
- Data manipulation- refers to fraudulent use of emails through phishing to convince individuals into paying money or revealing their confidential details to fraudsters.

As of today, *CGI (2017)* revealed that there is no single vendor that can deliver Industry 4.0 systems an operation needs as these devices run on different networks. Therefore, there must be an ecosystem of vendors within the operation so that the systems are integrated and can communicate with each other. The collaboration of different vendors will ensure that one system's output becomes another system's input thus, ensuring a continuous flow of information in real-time. *Deloitte (2017)* revealed that there is a global shortage of Industry 4.0 professionals. Although the current experienced workforce has deep industry knowledge, the aged workforce may find it difficult to work with digital tools (World Economic Forum, 2017). Therefore, there is a need to train or retrain the existing workforce in order to operate the new

4IR technology tools. The training and reskilling of the current workforce is necessary as Morrar, et al. (2017) concludes that the qualification requirements and skills required for future jobs will be stricter and different from what is currently expected today.

The skills and literacy rate in conventional mines as compared to mechanised mines has been reported by Muir (2015) to be considerably low. Therefore, conventional mines have a choice to either recruit employees from a sector which has a higher skillset or to invest in the training of their current labour. Retrenching the current labour force in conventional mines to make way for higher skilled personnel is likely to be opposed by employees and labour unions. This may give rise to labour unrest and strikes within the gold industry once again. There also exists a mind-set that embracing technology will accelerate job losses in the mining industry resulting in unemployment and uncertainty in the future of the millions of dependents relying on the mining industry. It was estimated by *This is Gold (2018)* that each mine worker supports between five to 10 dependents for every mining job created such that the gold mining industry indirectly supports between 1.1 million and 3.4 million dependents. This perception of job losses associated with adopting new technologies has brought fear such that industries are not fully geared on the implementation of 4IR. The unemployment rate in South Africa stood at 29.1% during the third quarter of 2019, which is the highest recorded by *Statistics South Africa (2019b)* since 2008.

In addition, there are fears that technologies brought forth by the latest revolution will divide an already unequal nation (Morrar, et al., 2017). According to *Statistics South Africa (2018)*, South Africa is one of the most unequal countries in the world with great division between the rich and poor. Morrar, et al., (2017) stresses the fact that embracing Industry 4.0 will highlight inequalities that exist in unequal countries. Inequality in the world is so prominent that Anker (2018) estimated that almost 30% of the world population has access to a cell phone than basic sanitation. Therefore, before the South African conventional mining industry can decide to digitalise operations, it is important to consider the following:

- Availability of skilled personnel;
- Availability of the necessary infrastructure;
- Available funds towards innovation and technology;
- The effect of digitalisation on the South African unemployment rate;
- Cyber-threats and associated risks of using the internet; and
- The readiness of the mining industry to embrace technology.

3.8 Summary and Conclusion

After considering the information in this chapter the underground gold mine of the future will have the following fundamental attributes:

- There must be a business case for such change;
- The operation will be mechanised with machines doing the hard labour;
- The machines will be digitalised and connected to a central computer system;
- All activities and decisions will be monitored;
- Operations will be monitored remotely through IoT;
- There will be better employee ergonomics;
- A less labour-intensive environment hence gender neutrality;
- Reduced operating costs;
- Improved performance through predictive maintenance;
- A reduction in occupational accidents;
- Increased life of mine through mining of lower grade and complex reserves and;
- It will be staffed by appropriately qualified personnel and very likely by professions that do not exist today.

While many narrow reef gold mines today still use conventional methods, some operations have advanced to mechanisation. Mechanisation, however, was not the optimal solution for a majority of gold mines due to the complex geology of the reef found in the Wits Basin. Mining 4.0, unlike mechanisation, can be integrated into the operation without changing the mining layout. The mine of the future through Mining 4.0 brings many opportunities and the most vital findings are summarised in Chapter 3.8. The mine of the future is no longer a concept of tomorrow but is currently happening today in operations which opted to embrace technology. Failing to adopt 4IR in the narrow reef mines of South Africa, the gold mining industry will ultimately fail to mine the remaining deep and complex orebodies at a profit. This will result in the sterilisation of resources and accelerate mine closure. The next chapter details the research methodology and discusses the methods the author will use to achieve the research outcomes. The author will conduct a case study of a conventional gold mine to determine the required resources to successfully implement Mining 4.0 in the production phase of the MVC.

4 Research Methodology

4.1 Introduction

Chapter 3 summarised the literature on twenty-first century mining and the mine of the future. The major findings were summarised, and these attributes will be used to measure the success of the strategy of the research. Chapter 4 explains the author's research methodology. This research discusses the consideration that must be considered as deep-level conventional gold mines begin digital transformation. It is critical for the mining industry to gear itself and anticipate the challenges brought forth by the implementation of Mining 4.0. This study is important as it offers insights on the current Mining 4.0 technologies available while taking into consideration the restrictions that occur during the production phase of a conventional gold mine. This research considers the distinct geological, socio-economic, political, and environmental factors of the South African narrow reef deep-level mines.

4.2 Hypothesis

The implementation of Mining 4.0 into the South African deep-level mining environment is an option for deep conventional gold mines to work towards achieve zero harm and extend mine life. The premature closing of mines has a detrimental effect on the economy and the hundreds of thousands of people who are dependent on this industry for their survival. This research aims to save the decaying industry by proving the following hypothesis regarding the digitalisation of the conventional deep-level gold mining industry:

4.2.1 Achieving Zero Harm

The implementation of Mining 4.0 in the labour-intensive gold mining industry will result in the industry employing fewer miners underground as innovation will result in many mining jobs becoming obsolete or redundant. This in turn will decrease the number of people working underground who are exposed to hazards and risk. The remaining miners underground will be distanced from occupational hazards and will be digitally equipped to handle workplace risks through digital tools such as IoT.

4.2.2 Regaining Profitability in Mining Operations

According to Jeffery (2018), South Africa has one of the highest labour costs in the world with labour costs contributing 53% of total working costs. By increasing efficiency and reducing the number of employees, the mining industry can be expected to significantly reduce operating costs and therefore, regain profit.

4.2.3 Increasing Life of Mine

Mining 4.0 can convert resources into reserves by allowing the mining of lower grade reserves. Because of the reduction in operating costs due to digitalisation, an operation can then be able to mine lower grade reserves at a profit. Reducing the cut-off grade also means an operation can mine working places it had previously abandoned due to low-grade mineralisation thus, increasing the life of mine. Ranjith, et al. (2017) reported that traditional methods of mining will be obsolete below a depth of 6 000m and currently deep-level mining in South Africa is below a depth of 4 000m. Therefore, to access these complex deep reserves profitably and safely, advanced methods of extraction through digitalisation must be implemented. Thus, the research includes actual technologies that can be implemented to increase mine life.

4.3 Research Method

The research uses literature and case studies to conceptualise the mine of the future. To successfully implement the concept, the research aimed to answer the following questions:

- What challenges are encountered in deep-level gold mining?
- Which critical factors should be considered as deep-level conventional mines make digital transformation?
- Will the implementation of Industry 4.0 technologies and solutions in the production phase of a deep-level mature gold mine improve production efficiencies, life of mine, profitability as well as health and safety in the workplace?
- How can such a concept strategy be successfully introduced?

4.3.1 Safety and Production Reports

The research relied heavily on South African mining data and statistics available on public platforms. These safety and production reports include materials found from websites, journals, and books. Because South Africa became a democratic country in 1994 and the Mine Health and Safety Act (MHSA) came into effect in 1996, the author mostly used mining safety and production data from post the apartheid era. This is because there was better transparency in the mining industry regarding the reporting of injuries and fatalities after MHSA came into place. The safety and production reports collected were mainly from the Department of Minerals and Resources (DMR), Mine Health and Safety Council (MHSC) and the Minerals Council of South Africa (MCSA).

The overall safety performance of the gold industry for the past decade was compared to where the industry ought to be to achieve zero harm. From the industry’s health and safety reports, it was possible to determine the leading causes of fatalities and injuries in the mining industry. Drawing experience and lessons gained from other digital mines across the world, the author then applied digital solutions available in modern mines to the conventional mining industry to address the safety concerns raised in narrow-reef mines.

4.3.2 A Conventional Deep-Level Gold Mine Case Study

A gold mine was selected and used as a case study focusing on the production phase of the MVC. The selected gold mine was one that is also referred to as ‘mature’ as it portrays the characteristics of a mine which has been operational for several decades. The properties of a mature operation include outdated infrastructure, long distances to working places and several abandoned working places due to low-grade mineralisation. Site visits were conducted to the mine to understand the production phase of the MVC. The name of the conventional gold mine remains anonymous throughout the study; however, permission has been obtained from the company to use their data as part of this research.

The case study of the conventional gold mine was conducted to prove the outlined hypothesis of the research. The author used a mining cycle to track the activities that occur in the production phase of a working stope panel. The obtained data was used to create a blueprint to modernise the conventional deep-level mine by adopting automation and digital systems. This conceptual mine modernisation blueprint was used to address the zero-harm hypothesis as the selected digital technologies address occupational hazards by distancing workers from harm. The author aims to prove that the application of Mining 4.0 can achieve zero harm by distancing workers from occupational risks and hazards that occur daily in the production phase of the MVC. The digital technologies selected in the blueprint are innovations currently implemented in different mines across the world and at DigiMine.

According to Schwab (2016), the use of digital technology in any industry reduces the number of employees required as repetitive work can be automated. *This is Gold (2018)* report that the South African gold mining labour costs are the highest costs in an operation. The author attempts to prove that a reduction in labour costs can indeed result in profitability. In addition, the author attempts to prove that increasing efficiencies will reduce operating costs thereby, increasing the operation’s profits. The last hypotheses that will be proven through the case study of the conventional mine is that Mining 4.0 will enable the operation to mine lower grade reserves at a profit therefore, increasing the life of mine. This is because the low-grade reserves that were previously not mined can now be mined without compromising costs.

4.3.3 DigiMine Case Study

The case study of the Sibanye-Stillwater Digital Mining Laboratory (DigiMine) provided innovative solutions, which can be implemented into the South African deep-level conventional gold mines to address production and safety concerns. These digital solutions considered the distinct geological attributes of conventional mining. In addition, the selected technology was fit-for-purpose solutions specifically addressing the safety and production concerns encountered at the conventional gold mine where the case study took place. Not only were the benefits and challenges of these digital systems highlighted but the author also mentioned the challenges that can be expected with the installation thereof. Currently, studies conducted at DigiMine focus on real digital solutions to real life mine problems to various mining fields such:

- Health, safety and security sensing;
- Survey, mapping and navigation;
- Wireless communications systems and;
- Integration for smart mining.

Regular visits to DigiMine were conducted to collect reports and information to understand the functionality of the installed digital systems. DigiMine has also collaborated with different vendors who sponsors the laboratory with software and offer assistance with the installation and training of the use of the systems. The installation of digital systems at DigiMine provided the author an opportunity to draw lessons learnt thus far from the implementation and use of digital systems. The author also used the DigiMine blueprint of the production phase of the MVC and applied it to the implementation of digital systems within a narrow-reef mine context.

4.4 Research Limitations

This research relies on South African mining statistics available on public domains as supporting literature. In some instances, recent data was not yet available, which could be seen as a constraint. For example, the DMR did not publish the Mine Health and Safety Inspectorate (MHSI) report for the years 2008/2009 and 2018/2019 to date. Because of this, the author could only obtain detailed health and safety statistics during these years. In addition, the DMR stopped compiling the average gold grades mined in the industry from 2013. The author had to compile average gold grades from the leading gold mining company’s resource and reserves annual reports from 2014 until 2019. There was also limited access to data from the conventional mine where the case study was conducted, as some information was considered confidential. Moreover, not all of the collected information from the mine could be published in this dissertation due disclosure limitations brought forth by the mine.

4.5 Summary and Conclusion

The author used post-apartheid era mining statistics; this was important as there was better transparency in the mining industry after the country's democracy in 1994. Although the research encountered several limitations, the author was able to collect all necessary data to continue with the study. The research did not require any testing of human subjects. Through conducting the case study of DigiMine and a conventional deep-level mine, the author was able to answer the fundamental research questions stated in Chapter 4.3.

This research aimed to prove three hypotheses:

- The implementation of 4IR in conventional deep-level mines will result in the industry achieving zero harm;
- The adoption of 4IR will increase profitability; and
- Mining 4.0 has the potential to increase life of mine.

In conclusion, Chapter 4 described methods which the author used to prove the above stated hypotheses. The most important findings from this chapter are that this study seeks to address the two most critical factors in the mining industry; safety and profitability. Therefore, the implementation of innovative solutions brought forth by Mining 4.0 is important to ensure the industry can be sustained for the future. To find digital technologies suitable for the mining industry, the author first described the challenges encountered in the deep-level mining industry in Chapter 5. Digital technologies are also highlighted in Chapter 5 to address the concerns in the South African gold mining industry. These technologies are from smart mines which have adopted Mining 4.0 to promote safety and efficiency in their operations.

5 Identification and Description of Current Solutions Informed by Challenges in Deep-Level Mining

The previous chapter, Chapter 4, discussed the research methodology the author used to achieve the research outcomes. The hypothesis presented is that the implementation of Mining 4.0 to the South African conventional deep-level gold mines can improve safety in the workplace by reducing the number of employees exposed to occupational hazards. In addition, Mining 4.0 can be expected to reduce operational costs and therefore, increase the efficiency and life of mine of operations. The research uses the case studies of a conventional deep-level gold mine and DigiMine to support the above hypothesis. Chapter 5 seeks to find digital solutions suitable for the conventional deep-level mining industry by first understanding the operational challenges encountered in the industry.

5.1 Challenges Encountered in Deep-Level Mining

Minerals Council South Africa (2019b) uses the phrase “if it is not grown, it is mined” as a reminder that mineral reserves are non-renewable and reasonable care should be taken to protect the environment and to ensure mining is sustainable. This is because mining in South Africa is important; *Minerals Council South Africa (2019b)* revealed that the mining industry contributed 7.3% and 8.1% in 2018 and 2019 respectively towards the GDP. The industry also managed to pay R24.3 billion in company taxes to the fiscus in 2019 (Minerals Council South Africa, 2020a). While South Africa takes pride in having some of the deepest mines in the world, deep-level mining has many operational challenges.

The industry has sought to adopt 4IR technologies to make mining operations safer and more profitable. Although each blast underground generates occupational risks and hazards, digital sensors and software constantly monitor ground conditions in order to eliminate and mitigate potential harm as a result of blasting activities. As production declines and gold mines fail to meet production targets to cover operational cost, all gold mines will eventually close. The effect of closing down shafts has a detrimental effect on surrounding mining towns which are likely to be plagued by unemployment and crime. According to Vegter (2019) without a skills shift in the mining industry, the surrounding mining towns will eventually become ghost towns. The challenges encountered due to mining at great depths slow the rate of production and compromise the health and safety of miners working underground. The following section discusses the following operational challenges encountered in the deep-level conventional gold mines of South Africa:

- Mining at depth;
- Mining low-grade reserves;
- Unauthorised access to mine facilities; and
- Labour disputes.

5.1.1 Mining at Depth

Van Wyk (2010) refers to mining depths beyond 2 250m as deep-level mining while Malan and Basson (1998) refers to ultra-deep mines as mines located at depths between 3 500m and 5 000m. According to Ranjith, et al. (2017), the average South African gold mine has reached a depth of 2 000m. For the purpose of this research, deep-level mining will be referring to mining depths below 2 000m. There are several challenges associated with deep-level mining such as difficulty in accessing deeper reserves, decreased production and employment while operational costs increase. Mining at depth is also associated with occupational hazards such as seismicity, toxic gases, and high temperatures. As a result, deep-level mines have a higher fatality rate than shallower mines.

Accessing Deeper Reserves

Accessing deeper reserves has proven to be a difficult and costly challenge for the gold mining industry. Viljoen (2009) revealed that the Wits Basin still contains about 35 000t of gold located between 2.5 and 5km with the remaining shallow resources at a much lower grade. *Minerals Council South Africa (2019b)* estimate that accessing deeper reserves through modernisation has the potential to extend mine life by 15 to 25 years. Modernising mines serves the purpose of extending mine life to preserve employment, improve health and safety, mine deeper and complex orebodies as well as extracting lower grade reserves at a profit. Adopting modern technology is therefore, essential for the gold mining industry to remain sustainable.

Declined Production

Due to the challenge of accessing deeper reserves, the gold mining industry has experienced a significant decline in gold production as illustrated in Figure 10. Although South Africa has the third largest gold reserves after Australia and Russia, annual gold tonnes produced in the country have decreased significantly over time. South Africa had previously led as the largest gold producer in the world from 1904 and, by 1970 it was producing close to 1 000t of gold annually (Phillips, 2013). According to Neingo and Tholana (2016), China overtook South Africa in 2009 as the leading gold producer and South Africa currently ranks as the sixth largest gold producer (National Accounts, 2015). Figure 10 shows the decline in gold production from 1970 to 2020. According to Figure 10, the gold industry produced 989t and 90t in 1970 and 2020 respectively. This amounts to a 91% decrease in production over the past five decades.

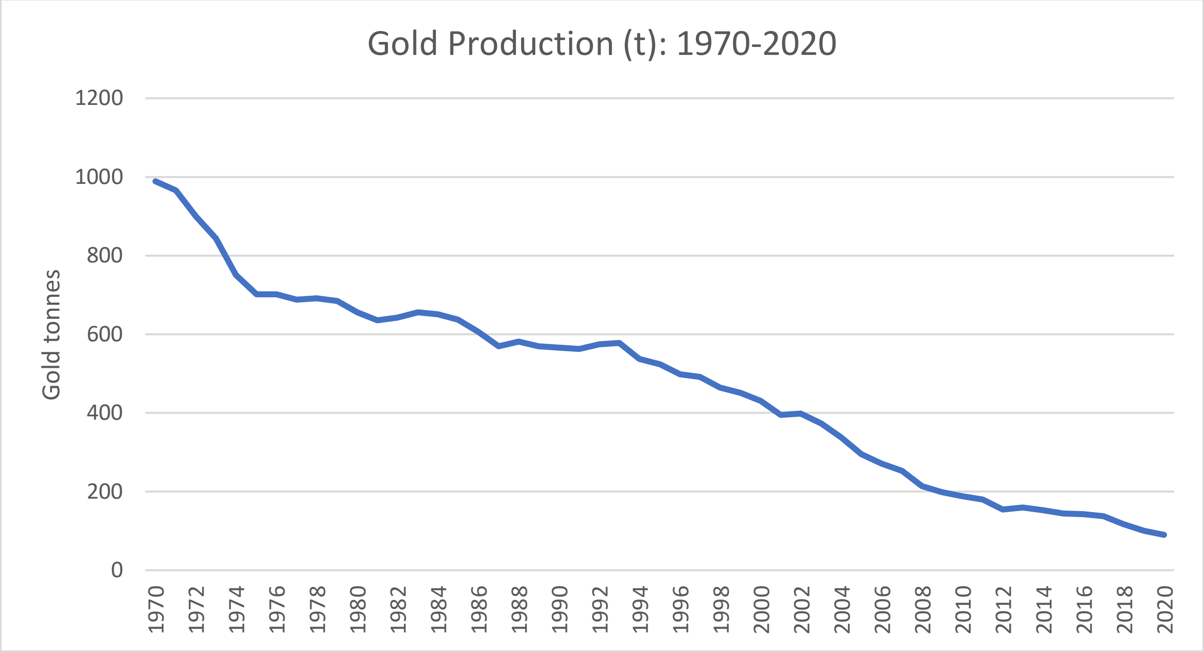


Figure 10: Gold Production: 1970-2020 (Chamber of Mines, 2016; Minerals Council South Africa, 2019; Minerals Council South Africa, 2020a; Minerals Council South Africa, 2021)

The South African gold mining industry is mature with deep-level mines that have been operational for several decades. These mines are characterised by old infrastructure, working places which are remote from each other and long travelling distances to the working panels. Mines which inhabit these characteristics are referred to as mature as they consist of attributes similar to mines which have been long operational. Mature deep-level mines tend to have a decline in production due to poor productivity because of long travelling distances to the working places. The long distance travelling underground is because the high-grade reserves closer to the station have been mined out and are now located several kilometres from the level station. Hence, more time is spent travelling to the working place and this significantly reduces the effective shift time (Neingo & Tholana, 2016). Cornish and Kotze (2015) report that long travelling distance from the station to working places can also cause a delay in the delivery of requested material and services as well as the repairing and maintenance of infrastructure.

Another cause of declined production in deep-level mines is safety stoppages. Ruffini (2010) cites Viljoen, highlighting the severe impact of safety stoppages handed out by the Department of Minerals and Resources (DMR) on the mining industry. On routine visits to a mine or after an accident has occurred, DMR safety inspectors have the authority to halt a section of a mine that was visited and can also issue a Section 54[1] which halts the entire mine's operation. According to McKay (2016), Section 54 safety stoppages between 2012 and 2015 resulted in a R13.63 billion loss in revenue in the industry. These stoppages have contributed to the decline in gold production as McKay revealed that the average length of these stoppages can be between five days and two weeks. However, it is also fair to note that due to DMR's intevention, a significant decline in fatalities has been achieved in the mining industry, as illustrated in Figure 11. Figure 11 also shows that if occupational fatalities are to continue declining at this rate, zero-harm is an achievable milestone in the next few years. However, from hereforth a step change is required to achieve zero harm by implementing technology and increasing skills in the mining industry.

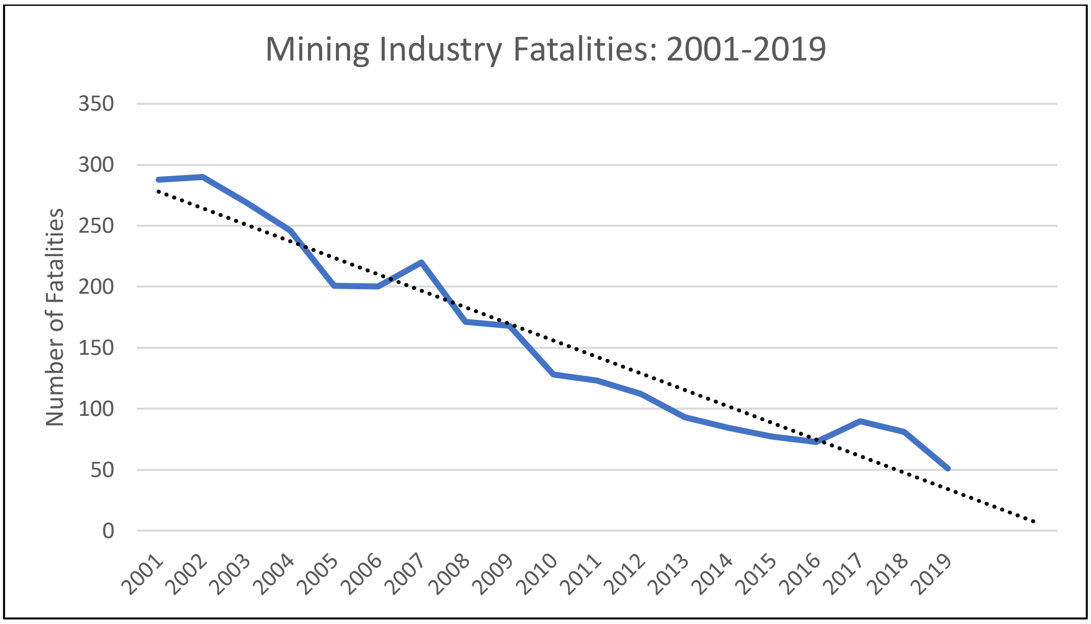


Figure 11: Mining Industry Fatalities: 2001-2019 (Minerals Council South Africa, 2018b; Minerals Council South Africa, 2020a)

High Operational Costs

While the gold mining industry struggles to maintain steady production, operating costs in deep mining operations remain higher. This is due to the costs of ventilation, support and electricity. The geothermal gradient, which is the increase of temperature with depth, is estimated to be 35ºC per kilometer in the Wits Basin (Phillips & Powell, 2015). Therefore, more cooling power

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[1] Section 54 instructions of the MHSA are issued to a mining operation when an Inspector of Mines firmly believes that any occurrence, practice or condition at the mine endangers, or may endanger, the health and safety of any person at the mine (Mine Health and Safety Inspectorate, 2019). Section 54 instructions issued by the Inspector of Mines can result in a complete halt of the mine, partial closure of the mine or any act at the mine.

is required for deeper mining operations hence, higher costs of ventilation. Cornish and Kotze (2015) revealed the cooling of mine environments is more than 20% of the mine's working costs due to geothermal gradient. In addition to the cost of ventilation systems, deep-level environments require strong support systems to support the surrounding rockmass. Hence, some ground has been left underground as support pillars which reduces mineable reserves. According to *Minerals Council South Africa (2019a)*, there is an estimated 160Mt high-grade gold ore left underground as support pillars in the Wits Basin.

In addition, the availability and cost of electricity in South Africa has become a serious concern. According to Ratshomo and Nembahe (2018), Eskom is the main electricity supplier in South Africa producing 90% of the electricity while the remaining 10% is supplied by municipalities, redistributors, and private generators. *This is Gold (2018)* revealed the mining industry consumes 16% of Eskom's annual electricity supply, 6.7% of which is consumed by the gold sector alone. The report also states that the price of electricity has more than trebled since 2009. In 2019, the National Energy Regulator of South Africa (NERSA) granted an annual electricity tariff increase of 9.4%, 8.1% and 5.2% from 2019 until 2022 (Minerals Council South Africa, 2019f).

Minerals Council South Africa (2019f) estimated that the tariff increase will result in a 29% increase in production costs over the three-year period from 2019 and could put over 95 000 jobs at risk. The high electricity costs would result in some operations unable to afford electricity and accelerate mine closure as well as job losses. Eskom's inability to maintain a steady electricity supply has also resulted in major mining operations having to temporarily halt production due to load shedding. In December 2019, leading mining companies had to temporarily halt production and prevent their mining crews from going underground as Eskom was unable to supply electricity as usual (Kotze, 2019). Losing an unplanned production shift reduces the operation's production and millions of Rands are lost.

Gold mines in South Africa are mainly conventional and labour intensive; as a result, the industry employs a large number of people. The high cost of wages together with mining low-grade reserves has resulted in mines unable to break-even during times of depressed gold prices. According to *This is Gold (2018)*, labour costs are 53% of the total working costs. Due to the high costs associated with deep-level mining, the report further states that for the rest of the world, operating costs are estimated to be US818/oz while in South Africa the rate is significantly higher at US1035/oz. This in turn has accelerated the closure of many gold mines and also brought uncertainity in the remaining operating mines.

Declined Employment

Figure 12 illustrates that as gold production decreases, so does the number of workers employed in the sector. In 2009, 159 926 people were employed and the industry managed a gold output of 198t; while in 2019 the industry directly employed 95 130 people and produced just over 100t of gold as shown in Figure 12. During this ten-year period, the industry saw a 49% decline in production and a 40% decline in employment. This is because as mining operations fail to breakeven and operational costs outweigh revenue, the mining industry begins to retrench workers as means of cutting costs. The continual decrease in employment in the gold industry has also had a massive impact on the millions of people who are dependent on the gold mining industry for income.

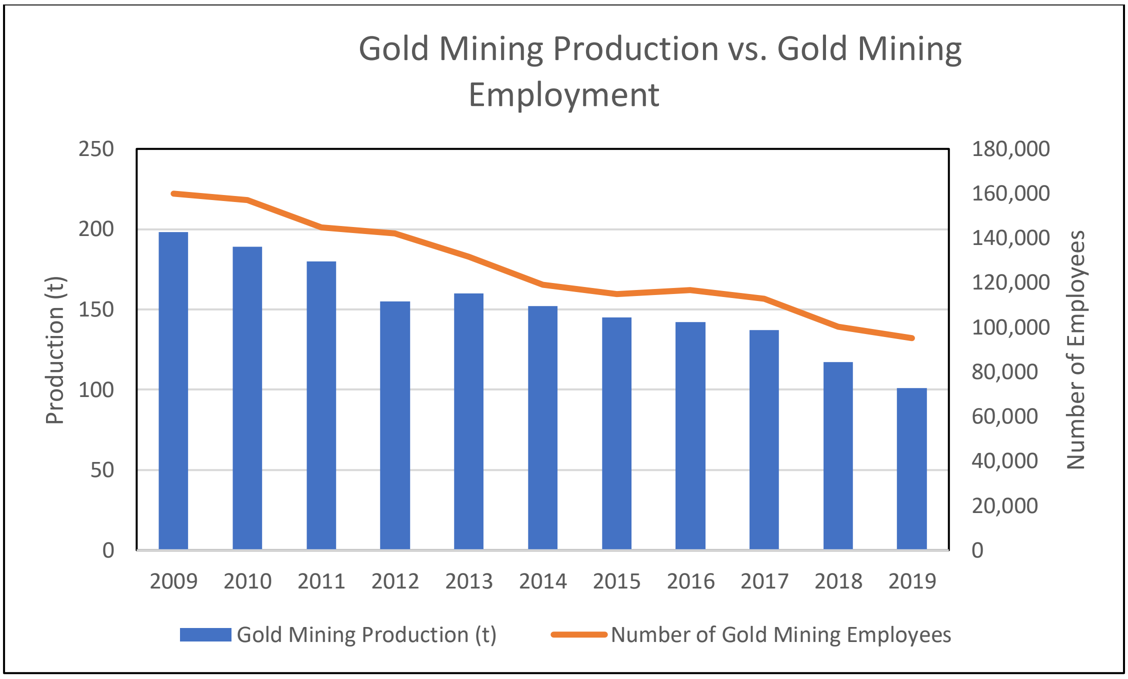


Figure 12: Gold Mining Production vs. Employment: 2009-2019 (Minerals Council South Africa, 2019b; Minerals Council South Africa, 2020a)

This is Gold (2018) estimated that for every mine job created, a further two more jobs are created in the downstream and supporting industries. *This is Gold (2018)* also estimated that each mine employee supports between 5 and 10 dependents and as a result, the industry indirectly supports between 1.1 million and 3.4 million dependents. The decline in employment in the gold sector also influences the unemployment rate; *Minerals Council South Africa (2020a)* reported the gold industry to be the second largest mining employer after the platinum industry. Bronkhorst (2020) revealed that the South African unemployment rate stood at 29.1% during the last quarter of 2019 which is the highest recorded since 2008.

Although the coal and iron ore mining industries have mechanised their operations, these industries have had an improvement in the number of people employed in their sector over the years, Figure 13. Over the 15-year period from 2004 until 2019, the coal and iron ore mining industry has had a 45% and 62% increase in employment respectively. Figure 13 shows that it is possible to introduce technology to an industry and yet achieve an increase in employment as technology opens more opportunities in the sector. The introduction of technology also allows for mining operations with low-grade reserves to become viable by lowering operating costs and bulk mining. Therefore, the introduction of technology in the gold mining industry can be the answer to sustaining employment while improving skills and socio-economic welfare of employees.

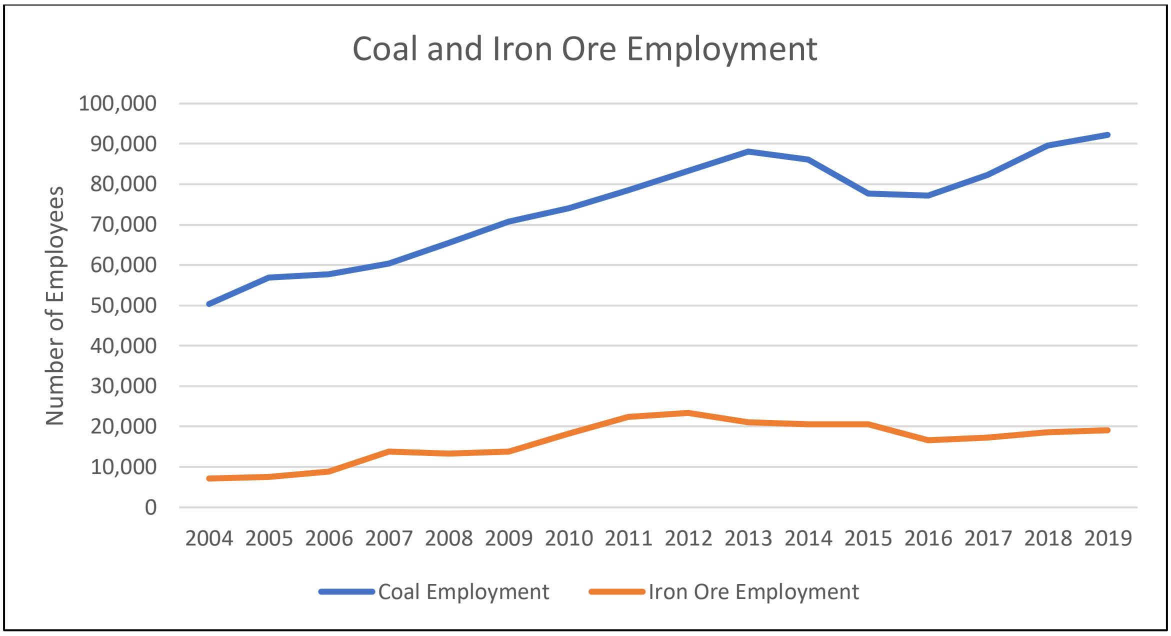


Figure 13: Coal and Iron Ore Mining Industry Employment: 2004-2019 (Minerals Council South Africa, 2014; Minerals Council South Africa, 2018b; Minerals Council South Africa, 2019b; Minerals Council South Africa, 2020a)

Although Figure 12 shows the decline in production and employment rate in the gold industry, the industry has improved its safety performance, as illustrated in Figure 14. It can be argued that the gold industry has been performing well with regards to safety because the industry employed fewer people than it did ten years ago. The gold mining industry employed 40% less people in 2019 compared to 2009 and achieved a 78% reduction in occupational fatalities during the same period. From Figure 14, it can be observed that as the gold mining industry employs less people, the industry reports fewer fatalities. Therefore, by having fewer employees at work the gold mining industry reduces the number of people exposed to occupational risks and hazards thereby, recording fewer fatalities. It is therefore critical for technology to be introduced to distance workers from hazardous working places.

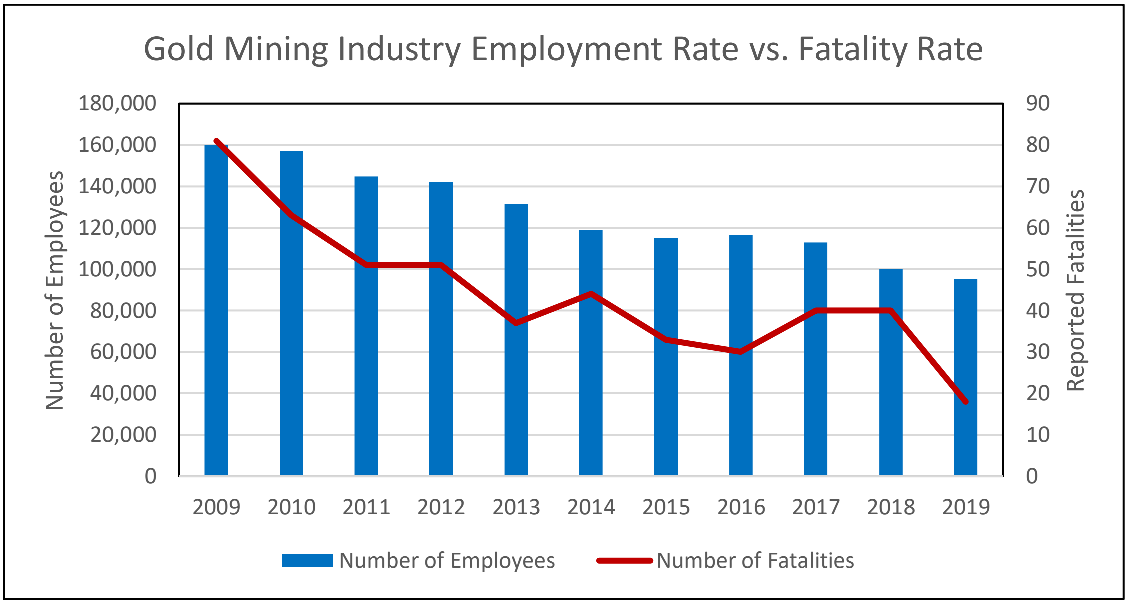


Figure 14: Gold Mining Industry Employment Rate vs. Fatality Rate: 2009-2019 (Minerals Council South Africa, 2018b; Minerals Council South Africa, 2020)

High Occupational Hazards

Deep mining environments are characterised by vertical virgin stresses which range from 95MPa to 135MPa (Malan & Basson, 1998). As a result of high stress induced on the overburden, failure of rockmass can occur resulting in falls of ground leading to injuries and fatalities. The higher the stress due to overburden, the higher the likelihood of rockmass failure (Ranjith, et al., 2017). To contain deformations, closure and falls of ground, stopes have to be supported adequately. Compared to shallower mines, deep level mines are more likely to encounter rockbursts, falls of ground and large inflow of water and harmful gases (Ranjith, et al., 2017). These events are difficult to forecast and control due to their complex nature.

This is Gold (2018) defined falls of ground as the sudden and unexpected release of rockmass as a result of rockbursts or gravity. Seismicity in the gold mining industry has caused much concern to the health and safety of mining employees who work underground. The gold mining industry is seismic due to the depth at which mining operations take place as there are high stresses, and the surrounding rockmass has been weakened. Figure 15 confirms that over the past two decades falls of ground has been the leading cause of fatalities in the mining industry. Although seismicity in deep-level mining is a concern, a report by *Mine Health and Safety*

Inspectorate (2019) revealed that a majority of fatalities that have occurred as a result of falls of ground were induced by gravity.

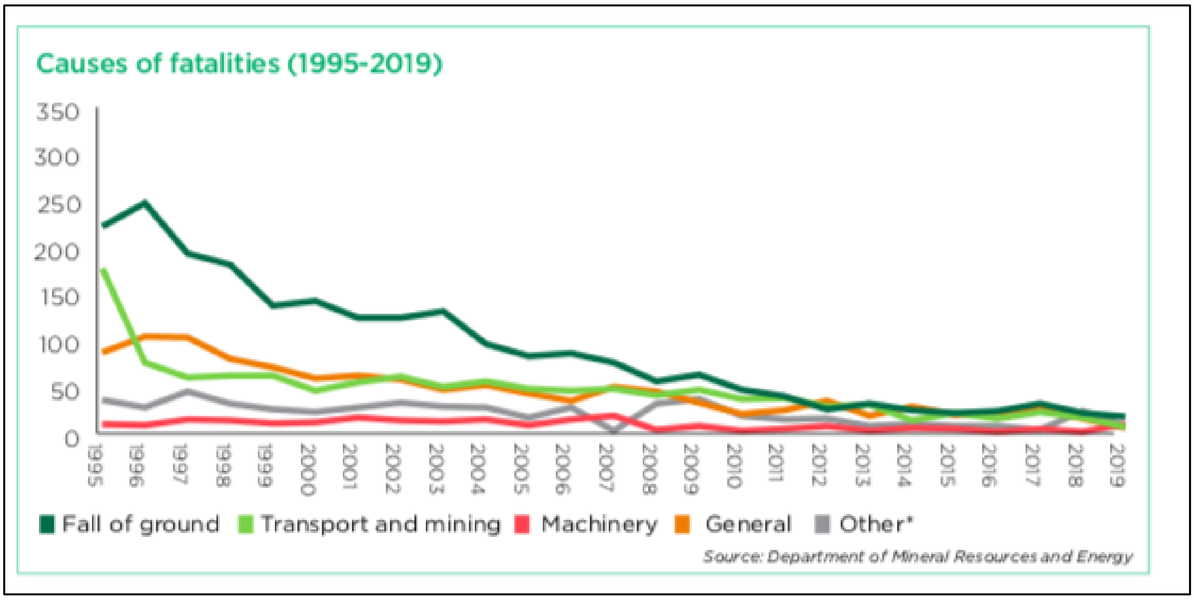
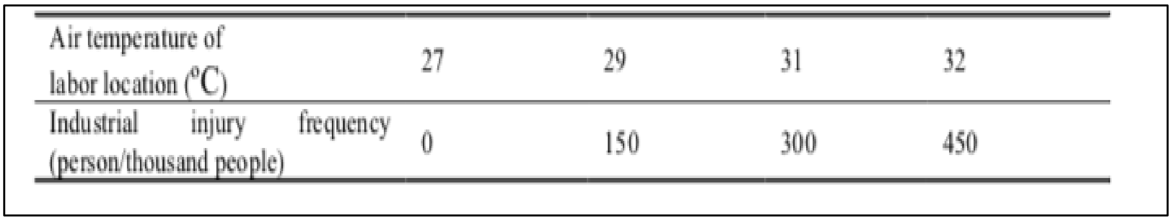


Figure 15: Causes of Mining Fatalities: 1995-2019 (Minerals Council South Africa, 2020a)

Moreover, temperatures underground can reach 60° C and extensive cooling methods are required to regulate these high temperatures. Miners working in high temperatures are subjected to heat stress which can result in cramps, rash, heat exhaustion and heat stroke (Maurya, et al., 2015). Zhao-hui, et al. (2009) revealed that above a body temperature of 41ºC heat stokes can occur and working in temperatures above 43ºC may result in fatalities. Zhao-hui, et al. (2009) revealed that when miners are exposed to hot temperatures for long periods of time, there are long term side effects such as disordering the central nervous system resulting in constant fatigue, loss of attention, slow coordination and easy to slumber.

According to Zhao-hui, et al. (2009), high temperatures also contribute to miners having low efficiency at work. To reduce the risk of heat illnesses and enhance labour productivity, Webber, et al. (2003) reported that work is not permitted in any place underground where the wet bulb temperature exceeds 32.5° or the wet bulb temperature exceeds 37° in the deep-level mines of South Africa. However, Zhao-hui, et al. (2009) argued that wet-bulb temperatures between 30ºC and 34ºC have 3.6 times more accidents than temperatures below 30ºC. Table 2 shows that ideally underground environments should be kept at a temperature below 27ºC to ensure safe and comfortable working conditions. Above a wet-bulb temperature of 30ºC, worker efficiency is said to decrease significantly. There is a correlation between high temperatures and injury rate and is shown in Table 2.

Table 2: Relationship Between Underground Temperatures and Mining Accident Rate (Zhao-hui, et al., 2009)



Air temperature of labor location (°C)	27	29	31	32
Industrial injury frequency (person/thousand people)	0	150	300	450

Some stope panels are referred to as "Precautionary Special Areas" as they are remnant areas and night shift is prohibited. Esterhuyse and Malan (2018, p. 1285) cites Jager and Ryder defining a remnant area as "an unmined block of ground surrounded by extensive mining." Remnant areas require special support and tend to be very seismic because they are associated with geological features, poor ground conditions and rockburst damage (Esterhuyse & Malan, 2018). Geological discontinuities such as brows, faults, dykes and sills, jointing, key blocks, bedding planes and rolls pose serious production challenges for stoping crews. Mining through geological features result in unstable mining conditions as well as poor face shape. This is because the stope face consists of weaker zones which advance faster and are easily fragmented during a blast (Russo-Bello & Murphy, 2000). Thus, an unequal stress distribution along the face is experienced due to an uneven face shape.

Another challenge facing the mining industry is unsafe underground transportation. Although occupational hazards caused by underground transportation such as rail-bound equipment (RBE), winches and trackless mobile machines are independent of depth, it remains a concern in the deep-level mining industry. Figure 15 above shows that underground transportation has been the second highest cause of fatalities in the past two decades, while Figure 16 highlights that transportation was the third highest cause of mine injuries from 2010 until 2017. The "general" class in Figure 15 and Figure 16 includes incidents such as being struck, drowning, falling, mudrush, inadation, scalding and burning; while the "other" classification includes electricity, fires, heat exhaustion, explosions and miscellaneous (Minerals Council South Africa, 2019g). Conventional mines use RBE which can either be battery, diesel or electrically powered, to transport men, materials, and ore to their destinations. *Department of Mineral Resources (2015, p. 6)* defined RBE as "all self-propelled and other equipment used for transportation purposes having wheels running on rails underground and within the surface demarcated bank area at the mine. This includes locomotives, hoppers, material cars, explosive cars, guard cars, drill carriages and all other items of equipment on rails."

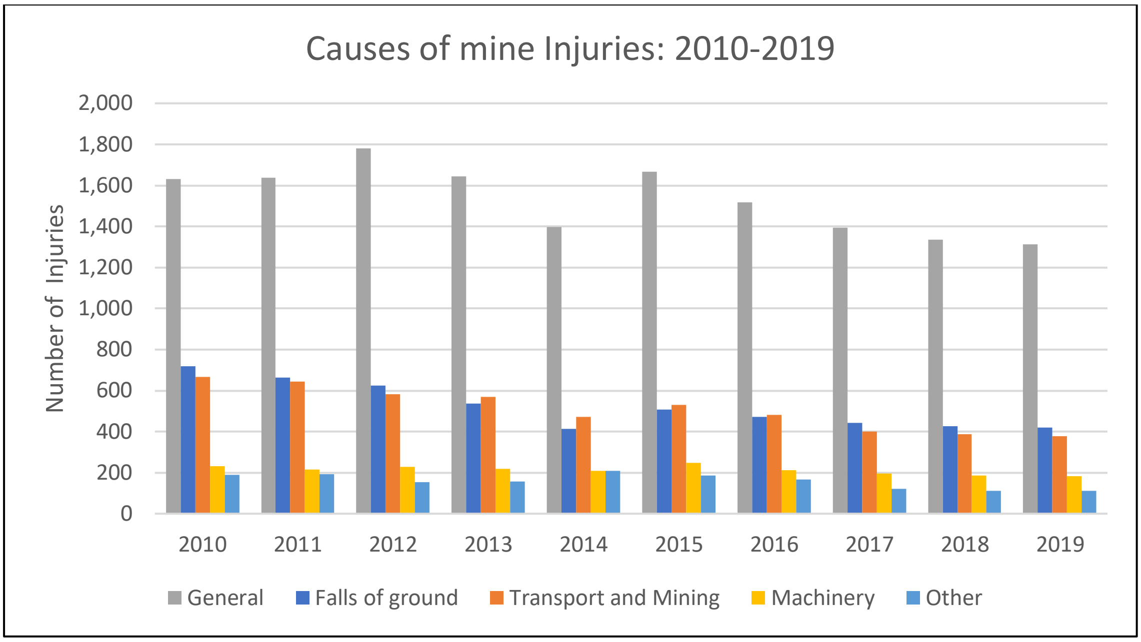


Figure 16: Causes of Mine Injuries: 2010-2019 (Mine Health and Safety Inspectorate, 2013; Mine Health and Safety Inspectorate, 2019)

Gold mines still record the highest cases of exposure to occupational diseases. According to *Mine Health and Safety Inspectorate (2019),* the gold mining industry accounted for over 47% of the reported exposure to occupational diseases in 2017. The three major occupational diseases miners are exposed to are silicosis, tuberculosis (TB) and noise-induced hearing loss (NIHL). Figure 17 shows that although there has been a decline in the reported occupational diseases in the mining industry since 2008, cases of TB are still over the thousand mark annually. The mining industry continually promotes occupational health and safety to ensure employees not only go home everyday, but live longer and healthier lives. Hence, attention was focused towards eliminating miner's exposure to dust and noise during the 2014 Mine Health and Safety Council (MHSC) Tripartite Summit. During the Summit, mining industry stakeholders agreed on new occupational milestone for dust and noise exposure; exposure to respirable crystalline silica should not be more than 0.05 mg/m^3 and noise exposure should not exceed 107 dB(A).

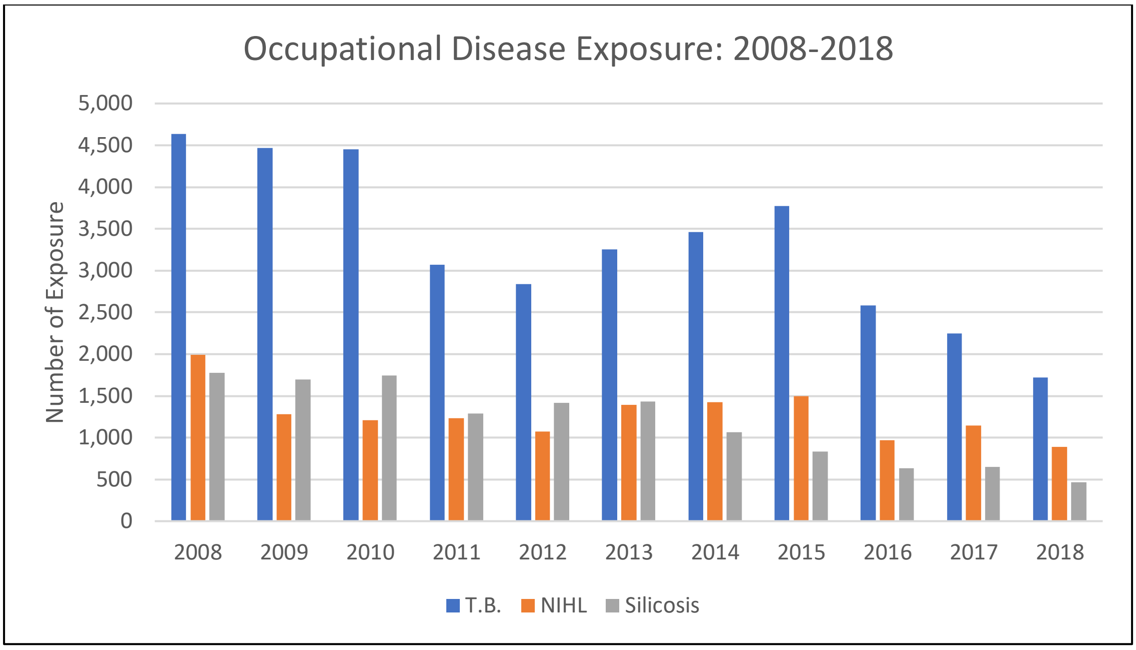


Figure 17: Occupational Disease in Mining: 2008-2018 (Minerals Council South Africa, 2018b; Minerals Council South Africa, 2020a)

High Fatality Rates

As a result of the high occupational hazards that exists in deep-level environments, the industry experiences high fatality rates. *The Mine Health and Safety Inspectorate (2019)* revealed that the platinum and gold mines of South Africa stand as some of the deepest mines in the world and employ the highest number of mining employees therefore are also responsible for majority of the mining industry's fatalities. A majority of gold and platinum mines still resort to conventional means of production as these operations are labour intensive consisting of several individuals working within the crews. As a result, a high number of employees tend to be exposed to occupational hazards underground. Figure 18 compares the safety performance of the gold and platinum mining industry compared to other mining commodities and shows that the gold and platinum sector remain the leading contributors to mine fatalities.

According to Figure 18, 1 080 miners lost their lives from 2009 until 2019; 488 of which were gold miners. This means in the past 10 years the gold industry alone has accounted for over 45% of the mining industry's fatalities. In 2019, the mining industry recorded its lowest fatality rate in history with only 51 fatalities. Of these 51 reported fatalities, only 18 were gold miners which is a 55% improvement in the gold mining industry's safety performance compared to the previous year (Minerals Council South Africa, 2020a). Based on industry safety statistics reported by *Minerals Council South Africa (2020a),* 2019 was the first time in history another mining sector, the platinum industry, surpassed the gold mining industry to have more reported fatalities. However, it is also fair to note that one of the largest gold mining company in the country was on a labour strike for the first four months of 2019 (Jamasmie, 2019).

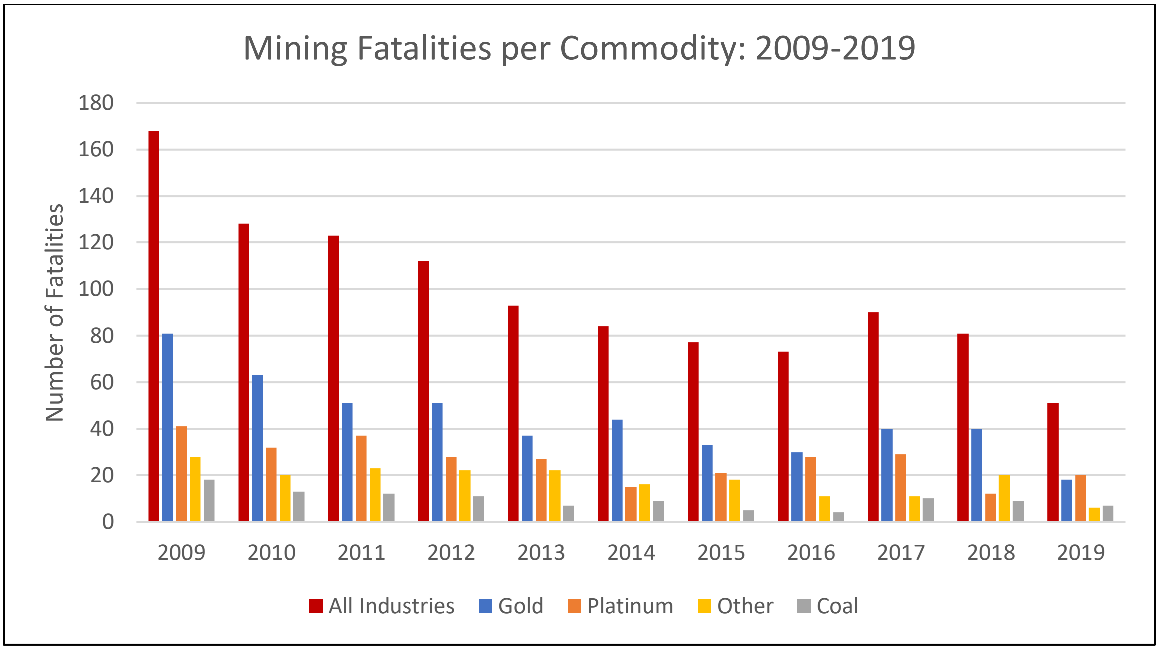


Figure 18: Mining Fatalities per Commodity: 2009-2019 (Minerals Council South Africa, 2018b; Minerals Council South Africa, 2020a)

5.1.2 Mining Low-Grade Reserves

The gold mining industry is characterised by declining grades with higher grades now located within deeper deposits. Figure 19 illustrates that by 2013 the average gold grade reported by MCSA had decreased to 2.91g/t. The MCSA has not published the average grades mined in the gold mining industry since 2013. Hence, the author compiled the grades mined by the top five gold mining companies in the country; Gold Fields, Harmony, AngloGold Ashanti, Sibanye-Stillwater, and Pan African Resources. This is because these companies account for more than 90% of gold output in the country (Minerals Council South Africa, 2019i). The compiled grades are from 2014-2019 and were obtained from each company’s annual integrated report. Figure 19 shows a drastic increase in the gold grades mined from 2014. This occurred because of mining companies increasing their pay limit to capitalise on the low gold price during this period.

Neingo and Tholana cited Müller and Frimmel estimating that if the gold grade is extrapolated from 1968 into the future, the grade may be found to be as low as 0.9g/t by 2050. Currently, there is an estimated 400Mt of low-grade ore which has been left underground as it cannot be mined at a profit with the current methods of today (Minerals Council South Africa, 2019a). Neingo and Tholana (2016) reported that this is because the lower the grade of ore, the higher the costs of production because of greater consumption of energy, water, reagents and other consumables per unit of gold produced. The ability to mine lower grade reserves at a profit would increase profitability, life of mine and ensure job securing for thousands of mining employees.

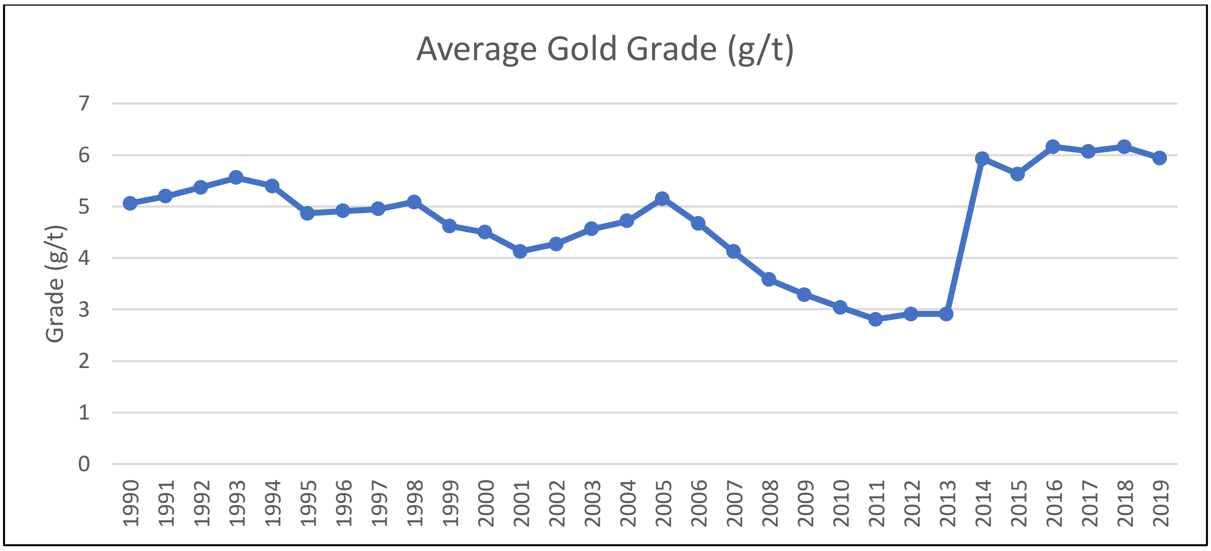


Figure 19: Average Gold Grade: 1990-2019 (Chamber of Mines, 2016; Minerals Council South Africa, 2011; Minerals Council South Africa, 2014)

5.1.3 Unauthorised Access to Mine Facilities

Although the unauthorised access and use of mine facilities and equipment is strictly prohibited, the lack of proper surveillance and monitoring of mining assets has given rise to theft and created opportunities for illegal mining. Without adequate surveillance, mining assets cannot be rightfully allocated and used to their full potential. In addition, personnel monitoring in deep-level mines is important due to the long travelling distances to working places. This is because there is potential for mine employees to get lost in old or abandoned working areas which poses a danger to their health. The wandering off of employees' underground can also be intentional, they can be aiding and abetting illegal miners.

Illegal Mining

Illegal mining has been difficult to eradicate in the gold mining industry and has been described by *Minerals Council of South Africa (2019h)* as a well-managed syndicate; an organised crime consisting of many individuals. Gold produced from illegal mining is sold to regional buyers who are licensed under the Precious Metal Act 37 of 2005 to trade in precious metals (Minerals Council South Africa, 2019h). Since these buyers are licensed to be trading in gold, eradicating illegal mining has been a near impossible mission because there is a platform for buyers to legally trade in precious metals. According to *Minerals Council South Africa (2019h)* illegal mining is estimated to be a R7 billion industry. It was further revealed that 70% of illegal miners are illegal immigrants from neighbouring countries such as Lesotho, Zimbabwe and Mozambique.

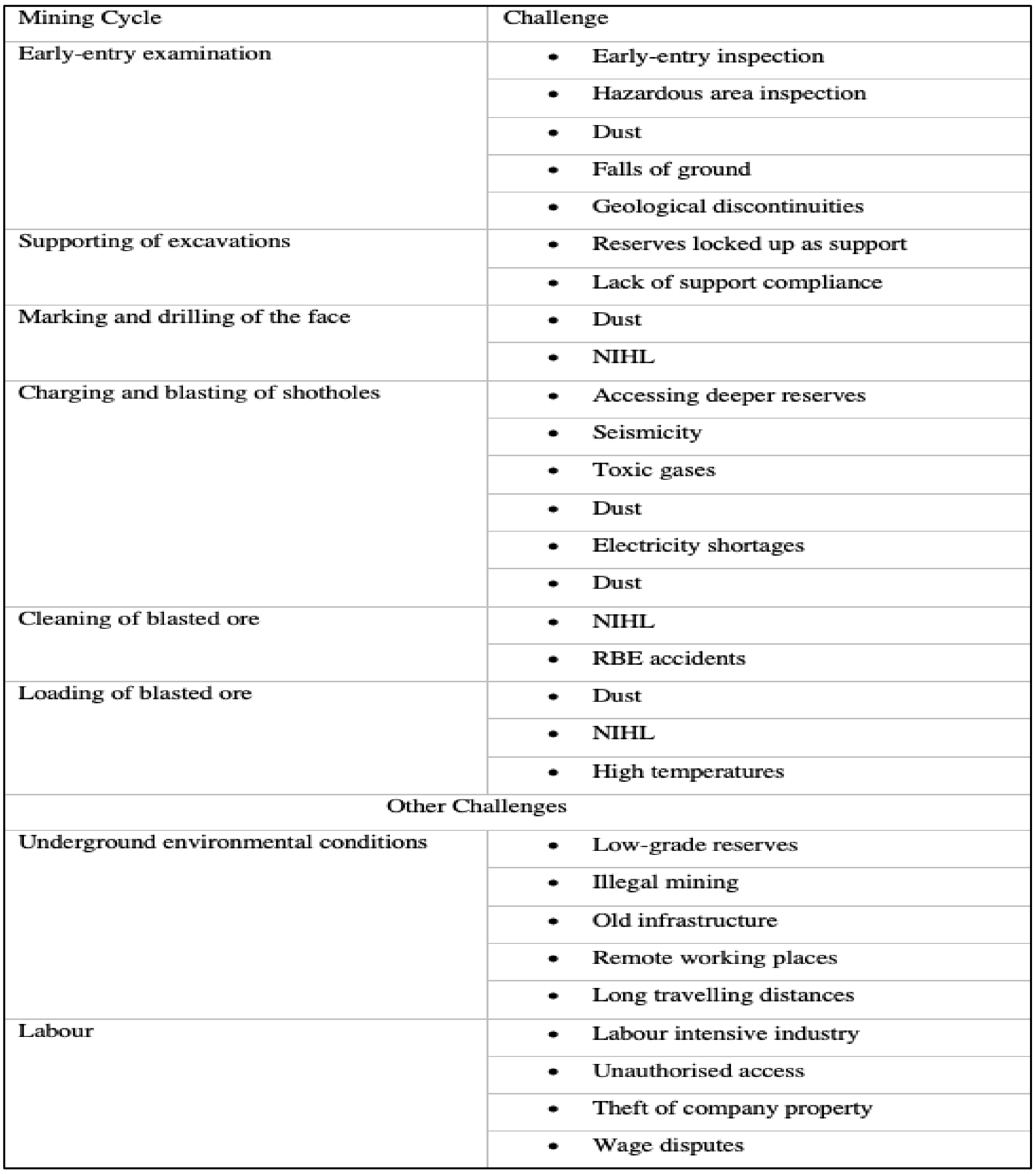
Illegal miners can stay several days and even months underground in abandoned mines (or in mines which are in operation) working in dangerous areas which have not been declared safe. In operating mines, illegal miners are often heavily armed and pose a major threat to the health and safety of the mine's employees. Illegal miners also involve mine employees in acts of violence, bribery, and theft as they need assistance to carry out their illegal activities. They recruit mining employees into helping them with food, contraband, equipment, and necessary intel. Once a mine employee becomes entangled with illegal miners, it is hard for them to stop as they become victims of intimidation. Illegal mining does not only put lives in danger but has a detrimental effect on mining companies as they lose revenue, taxes, and employment opportunities. *Minerals Council South Africa (2019h)* reported that illegal miners use the mine's facilities and resources illegally such as water, electricity, equipment, and machinery thus, adding to the operating costs of the company.

5.1.4 Labour Disputes

The gold mining industry has also encountered operational stoppages and a decline in production due to labour unrest as workers demand higher wages and better benefits. In recent years, unprotected strikes have resulted in uncontrollable violence and forced mining companies to halt operations. A defining moment in South African mining labour disputes was the Marikana massacre which left 34 miners dead and 78 wounded (Davies, 2015). This was during the platinum labour strike in 2012. Workers who still resume work during labour strikes often face intimidation and threats of violence hence operations are completely stopped and function with fewer essential employees. Therefore, labour strike cost the industry billions of Rands as operations are temporarily halted. According to Seccombe (2019b), the five month labour strike at Sibanye-Stillwater in 2018 resulted in the company losing R2.2 billion. Labour strikes are said to be coming more frequent and taking longer to resolve, which Hart (2014) reported has the long term effect of reducing investor's confidence in the South African mining industry.

Hence, the South African gold mining industry has been struggling to remain afloat in the past decades due to decreased production and escalating operating costs. While mature gold mines are characterised by long travelling distances, working places which are remote from each other and old infrastructure, the industry also faces safety concerns because of the depth at which these operations take place. The gold mining industry therefore needs to strive for change and adopt new technologies to become profitable and safer as deeper resources are explored. Table 3 summarises the challenges encountered in the mining industry in each stage of the mining cycle. Table 3 also includes other challenges which have an influence on daily production but do not fall under the mining cycle that has been illustrated in Figure 6. These factors include: underground environmental conditions, labour, and reporting and communication.

Table 3: Challenges Encountered in the Mining Cycle



Mining Cycle	Challenge
Early-entry examination	Early-entry inspection
	Hazardous area inspection
	Dust
	Falls of ground
	Geological discontinuities
Supporting of excavations	Reserves locked up as support
	Lack of support compliance
Marking and drilling of the face	Dust
	NIHL
Charging and blasting of shotholes	Accessing deeper reserves
	Seismicity
	Toxic gases
	Dust
	Electricity shortages
	Dust
Cleaning of blasted ore	NIHL
	RBE accidents
Loading of blasted ore	Dust
	NIHL
	High temperatures
Other Challenges	
Underground environmental conditions	Low-grade reserves
	Illegal mining
	Old infrastructure
	Remote working places
	Long travelling distances
Labour	Labour intensive industry
	Unauthorised access
	Theft of company property
	Wage disputes

5.2 Digital Solutions Informed by Industry Challenges

The following section highlights digital solutions which can be implemented to address safety and production concerns in the deep-level mining industry. The implementation of Mining 4.0 has potential to ensure the industry achieves zero-harm and profitability through the creation of digital mines. Walsh, et al. (2017) described a digital mine as one where autonomous vehicles are used to improve safety, productivity and reduced cost by having lower fuel consumption; drones for data collection, inspection and monitoring of adherence to safety standards. A digital mine consists of digital twinning of equipment allowing early detection of malfunctions in the equipment hence, decreasing maintenance costs. Moreover, wearable technologies are used in a digital mine to monitor the health and safety of employees. According to *World Economic Forum (2017),* the adoption of digital technologies has the potential to save an estimated 1 000 lives and prevent 44 000 injuries over the next ten years in the mining industry.

5.2.1 Real-Time Reserves Monitoring

Today, open pit mines use digital technology to monitor reserves; an example of this is the OZ Minerals company. Klein and Walsh (2017) revealed that the company uses drones in its Prominent Hill copper-gold mine to map and measure the reaps of run-of-ore mine as well as remaining resources. Underground mines such as Rio Tinto's Pilbara Iron Ore mine have adopted a visualisation tool called Rio Tinto Visualisation (RTVis). *Mining Technology (2014b)* reported that this image tool works like an ultrasound to deliver real-time 3D images of underground ore deposits. This technology can accurately identify the size, location, properties, and quality of the ore in real-time. The software is then able to direct workers where to locate high-grade reserves therefore, enabling accurate drilling and blasting as well as higher recovery rates (Crawford, 2018). The adoption of this technology in the South African deep-level gold mines would ensure a higher pillar extraction rate is achieved as *Minerals Council South Africa (2019a)* estimated that 160Mt of high-grade gold ore has been left as support pillars in the Wits Basin.

5.2.2 Infrastructure Inspection and Monitoring

Mature deep-level mines are characterised by old infrastructure such as old rail tracks. The Council for Scientific and Industrial Research (CSIR) is currently conducting research and has a working prototype on the use of a railway robot for surveying and inspecting underground trackwork. According to Campbell (2018), the robot patrols the rails and checks their condition to prevent derailments of RBE. Rupprecht (2011) cites Binks revealing that derailments and track clearance are amongst the causes of RBE accidents in underground mines. To monitor the performance of other mining assets, Akyildiz and Stuntebeck (2006) reported that the installation of smart sensors can assist in tracking the efficiencies of mining assets. For example, the sensors can be installed along the path of underground pipes to detect air and water leaks quickly and report to the control room. Early detection and reporting of malfunctions reduce maintenance costs as attention can be immediately given.

5.2.3 Connectivity

Goldcorp's Éléonore gold mine teamed up with Cisco to install a multi-service, secure IP network throughout the mine. This has enabled full Wi-Fi connectivity at the mine. *Cisco (2015)* reported that underground employees and machinery have been fitted with radio frequency tags which transmit their unique ID number and location to the control room via the Wi-Fi network. The installation of the Wi-Fi has resulted in a connected workforce as miners can go underground with iPads and iPhones with which they can communicate with each other underground as well as the surface environment (Crawford, 2018). Deep-level environments consist of working areas which are far from each other; communication between miners in different working places is mainly through phones which are located at the level station, waiting place or refuge bay. Therefore, the installation of this network would ensure miners are in constant communication with each other and the control room; any concerns encountered during the shift can be immediately reported to the relevant persons without waiting for the shift to end to give a report.

5.2.4 Autonomous Hauling Systems

Rio Tinto's Cerro Verde, an open pit copper mine in Peru, sought to automate their hauling process to increase efficiencies and reduce costs. According to *SAP (2017),* hauling costs at the mine previously accounted for half of the mining costs. The mine now runs on a smaller number of trucks yet run more frequently. In addition, these trucks have built-in software which enables problems with the truck to be detected earlier resulting in a reduction in maintenance costs. Rio Tinto's Pilbara Iron Ore mine has also implemented autonomous hauling systems (AHS). The automated fleet operates nearly 24 hours a day, 365 days a year without needing to stop for shift changes or breaks; stopping only for refuelling and maintenance (Crawford, 2018). Automation of the fleet has resulted in better efficiencies and reduced costs. Operating costs at the operation have now reduced by 13%. Since mature deep-level mines are associated with long travelling distances to the working places, automating the hauling process would ensure better allocation and scheduling of RBE to increase efficiencies.

5.2.5 Ventilation-On-Demand System

Cornish and Kotze (2015) reported that ventilating mine environments is expensive, contributing more than 20% of the mine's working costs in deep-level mines. Temperature of virgin rock below 2 000m can be as high as 40ºC in the Wits Basin (Minerals Council South Africa, 2019c). To reduce energy costs, the Goldcorp Éléonore mine installed an intelligent ventilation system to conserve energy and to improve airflow at the mine (Cisco, 2015). This ventilation-on-demand system allows for ventilation supply to be sent where it is needed depending on the presence of people and machinery. An automated fan responds to signals sent from tracking devices worn by all employees and machinery underground thereby monitoring air flow in relation to people in real-time. The system then powers the fans to supply adequate fresh air as people and machinery travel through the mine.

The system is also able to adjust the fan speed based on carbon emissions from underground vehicles. The installation of the ventilation-on-demand system at Éléonore mine has cut ventilation requirements by 50% therefore, reducing energy costs also by 50%. *World Economic Forum (2017)* state that the system has resulted in a greener operation as it leaves a minimum footprint on the environment by having less carbon emissions. The Éléonore mine has also installed smart sensors which work together with geospatial tracking of workers and machines, to turn lights on or off and electricity depending on the presence of workers and machines. This has resulted in a significant reduction in electricity costs; *World Economic Forum (2017)* reported that the mine now saves between $1.5 million and $2.5 million each year on energy costs.

5.2.6 Hazard Monitoring

There are safety concerns such as seismicity and high temperatures when accessing deeper reserves. To forecast underground hazards such as rockbursts and water inflow in deep-level mines, Mira Geoscience provides 3D and 4D earth modelling for exploration, resources evaluation and geotechnical hazard assessment (World Economic Forum, 2017). Mira forecasts geotechnical hazards in real-time considering all the relevant geological and geotechnical characteristics such as depth of workings, rock type, seismicity rate, deformations, etc. The ability to predict hazards before they occur ensures that extra precautions are taken, and miners are evacuated from that particular area in time.

To maintain safety in the deep-level mines of South Africa, CSIR has developed small safety robots which are able to identify hazards such as loose rocks and toxic gases during early-entry examination after a blast. These small machines, measuring less than 30cm in diameter, can map deep-level mining environments and are fitted with gas sensors, cameras, and scanners (Perold, 2013). The robots can perform work under dangerous working conditions without hassles. A special feature of the robots is that they can identify loose rocks on the hangingwall after blasting activities. According to Campbell (2018), loose rocks on the hangingwall are slightly cooler than surrounding solid rocks and the thermal cameras fitted in the robots can identify this temperature difference. Although the temperature difference between these rocks is small, it can be detected by the thermal cameras installed on the robot.

The robots are also fitted with an acoustic sensor which can identify loose rocks based on sound; the sound made by loose rocks is different from sound made by solid rocks. According to Campbell (2018), the robots are designed to enter the stope first and examine the condition of the panel thereafter give feedback to the crew. Although there is no longer active research done on these robots at CSIR, the implementation of these robots in the deep-level mining industry would significantly reduce fatalities and injuries because of falls of ground. Contrary to popular belief, falls of ground due to seismicity is not responsible for causing the highest fatalities; it is falls of ground induced by gravity which claims more lives as shown in Table 4. The implementation of these robots to conduct early-entry examination would ensure falls of ground due to gravity are eliminated as the robot would identify loose rocks first-hand and the crew would then ensure proper barring takes place. AR technology would make it possible to control the robot remotely as it enters the stope panel. As the robot conducts the examination on the face, the operator would be able to see the stope panel via cameras installed on the robot.

Table 4: Falls of Ground Induced by Gravity vs Seismicity (Mine Health and Safety Inspectorate, 2019)

Year	**2015**	**2016**	**2017**
Falls of ground induced by gravity	16	15	21
Falls of ground induced by seismicity	7	9	12
Total falls of ground fatalities	23	24	33

Drawpoints such as orepasses cannot be accessed without compromising the health and safety of employees. To address this, an autonomous drone company called Emesent has developed “Hovermap” technology that allows the inspection and survey of dangerous underground working places. For example, the drone allows for the inspection of orepasses in case of hang-ups by creating 3D maps, videos and images as well as recording environmental conditions of the area. Hovermap uses light detection and ranging (LiDAR) to measure the time taken for each pulse to be reflected off the surroundings and return to the sensor. The data is then processed by simultaneous localisation and mapping (SLAM) algorithm to create a high resolution, 3D point cloud and accurate digital representation of the underground environment (Hrabar, 2019). Hence an estimation of the motion and location of the drone can be detected even in inaccessible areas without the need for GPS for navigation.

Seismic Monitoring

To address falls of ground induced by seismicity, the mining industry has introduced seismic monitoring. According to Mendecki, et al. (2010, p. 1), "routine seismic monitoring in mines enable the quantification of exposure to seismicity and provides a logistical tool to guide the effort into the prevention and control of, and alerts to, potential rock mass instabilities that could result in rock bursts." Mendecki, et al. (2010) sites Mendecki revealing following as the objectives of seismic monitoring:

- To detect and locate seismic events to rescue personnel;
- To make corrections on the rock mass response based on the comparisons of the observed and expected seismicity;
- To monitor seismic changes and classify them according to a seismic hazard rating system;
- To detect unexpected seismic changes that could result in instability of working places immediately or long term; and
- To improve seismic monitoring and mine design based on historic data in order to understand the behaviour of rock mass.

Wireless underground sensor nodes (WUSN) are sensors used for underground seismic monitoring. The use of these sensors underground is important in understanding the behaviour of the rockmass in response to seismicity. In addition, this also assists in predicting the magnitude and location of the next seismic event (Akyildiz & Stuntebeck, 2006). The advantage with the use of WUSN is that it does not have coverage restrictions, the monitoring field can be extended by adding new sensor nodes without disturbing the current nodes that exist. From an experiment conducted at the DigiMine mock mine, Zaman and Förster (2018) revealed that WUSN can still establish communication with trapped miners in a disaster scenario where the sensor node is buried under rockfall. This is because the sensor can still communicate with other sensor nodes while buried under debris through a wireless network.

Anti-Collision Systems

According to *Mine Health and Safety Inspectorate (2019)*, the most common cause of RBE accidents underground is the collision of RBE with each other, people as well as vent doors. The Schauenburg SCAS II Collision Warning System uses radio frequency to warn underground vehicle drivers of pedestrians, other vehicles, and hazards in the vicinity. Mohapi and Zarske (2018) reported that this system can be installed both in trackless and rail-bound equipment. The system also warns pedestrians of incoming vehicles by means of an LED light and an audible alarm installed on the underground vehicles. Sensors installed on the vehicle can detect hazards on the front, rear and both sides of the vehicle. The Schauenburg anti-collison system has been designed in such a way that it is able to stop when it detects a collision is about to occur even without human intervention. The equipment can also be programmed to slow down when travelling in restricted areas where there is minimal clearance between the RBE and sidewall.

Environmental Monitoring

The Schauenburg SCAS II Schaulicht SmartLite is an underground headlamp fitted with sensors which can warn personnel of dangerous working conditions such as toxic gases, fires and seismicity in real-time. Mohapi and Zarske, (2018) reported that the headlamp also comprises of collision warning and a distress call feature which underground workers can use to contact the control room and seek assistance in the case of an emergency. Schauenburg has also developed a fixed environmental system which offers continuous monitoring of environmental conditions underground including temperature and air quantity. The sensors in this system convey the retrieved data from underground to the control room. The control room can then issue a warning to miners underground should there be a need.

Underground Surveying

According to Shahmoradi, et al. (2020), drones serve multiple purposes in underground inspection and monitoring. Drones can be used to monitor face conditions such as face shape, limit lines and mining direction; determine support compliance and to a lesser extent underground surveying. Although the Emesent Hovermap drone can be used for underground surveying purposes, there are accuracy concerns that require more research. Hrabar (2019) revealed that stopes are currently mapped using a boom-mounted laser scanner which requires surveyors to be close to the working face and exposes them to hazards such as working under brows. The Hovermap drone has definite potential because it can be launched from a safe area to survey the stope.

5.2.7 Personnel and Equipment Monitoring

DAQRI is an American based company that manufactures smart helmets. The helmet connects the user to their work environment and comprises of a high-definition camera and audio array for advanced communications (World Economic Forum, 2017). Sensors on the helmet can also communicate with WUSN underground to locate personnel. Akyildiz and Stuntebeck (2006) confirm that the connection of WUSN to an audio sensor can assist in the location and rescuing of trapped miners in the event of an accident. Another technology of this kind has been implemented by Goldcorp in its Éléonore mine. Éléonore has partnered with AeroScout Industrial which manufactures tags that are worn by all employees and underground machinery.

The tag allows for people and equipment to be tracked throughout the mine in real-time. According to *Cisco (2015)*, the tracking systems reduces evacuation time drastically; people underground can now be evacuated 45-50 minutes faster than before. Éléonore mine has not only installed tracking devices on their machinery but telemetry boxes as well. *Cisco (2015)* reported that the telemetry boxes transmit vehicle information directly to the control room. Any malfunction with the equipment is immediately addressed before damage is irreversible and this reduces maintenance costs. According to Crawford (2018), sensors have also been installed in the vehicles to send information regarding the engine's functioning to the control room and any fault in the equipment can be detected quicker. The monitoring of equipment also ensures that only trained persons use the equipment therefore preventing injuries and damage as a result of unauthorised incompetent people.

The tracking of underground employees in South African deep-level mines will not only assist in locating employees quicker in case of emergencies but also help fight against illegal mining. *Minerals Council South Africa (2019h)* revealed that illegal miners involve mine employees in acts of violence, bribery, and theft in exchange for money. Without assistance from mine employees to obtain food supplies, contraband and necessary intel about the mine, illegal miners will not be able to operate. Eliminating the relationship between mine workers and illegal miners prevents illegal miners from obtaining necessary essentials to survive the underground environment. Therefore, the monitoring of employees' whereabouts underground through sensor powered tags will enable the detection of suspicious movement of workers, thereby prompting necessary investigations. In addition, the monitoring of equipment underground through tags will allow for the control room to be made aware of any attempts to use equipment when mine employees are no longer underground.

5.2.8 Transparency Through Digital Applications

One of the causes of labour disputes is caused by lack of transparency between companies and stakeholders. To solve this, Antofagasta Minerals, a Chilean mining company uses social media platforms to engage with surrounding mining communities to build trust (World Economic Forum, 2017). The company engages with their employees and those affected by mining activities via digital applications to understand their concerns therefore addressing these issues quicker. Within South African gold mining context, addressing labour issues, and finding resolutions before matters escalate into unlawful labour strikes can save the industry billions of Rands and save countless jobs as well. By enforcing better communication and transparency between mining companies and stakeholders, both parties can be able to find common ground without resorting to violence and unlawful strikes.

5.3 Towards the Digital Mine

The installation of digital systems will remove workers from dangerous working places. A decline in the number of employees within an operation is likely to reduce operating costs. This is because Jeffery (2018) estimated labout costs in South Africa to be 53% of the total working costs. Operating costs may also be reduced by having less ventilation requirements through the use of the ventilation-on-demand systems. The use of this system, in combination with the installation of sensors to switch the system on and off automatically depending on human or machine presence, may result in a reduction of energy costs.

According to Birch (2016), cut-off grades are used to classify a mineral as a resource or a reserve. By significantly reducing operating costs, an operation can then reduce its cut-off grade and be able to mine lower grade reserves at a profit. This can be achieved through recalculating the net present value (NPV) using the new lower total fixed costs. The total fixed costs will be reduced as a result of decreased labour costs, electricity cost and maintenance costs, etc. The ability to mine these lower grade reserves at a profit would enable the industry to increase production and its life of mine therefore, saving thousands of jobs. Gold production can also be expected to increase as accessing deeper reserves will be easier through real-time monitoring of reserves. The use RTVis can offer the exact location and properties of the remaining reserves. The use of this imaging tool can also offer ways to have a better pillar extraction rate.

Safety in mining operations can be expected to improve through the use of robots for inspecting dangerous areas and the use of digital systems for hazard prediction. An increase in safety compliance reduces safety stoppages handed to mining operations by the DMR. Production stoppages due to labour strikes can also be minimised through better communication and transparency between mining companies and stakeholders. This is possible through the use of digital applications which can be accessed by mine employees and those affected by mining activities. In addition, the gold mining industry will be able to eradicate illegal mining by having better surveillance and monitoring of mine workers and equipment underground.

Although some work may become redundant and obsolete as a result of Mining 4.0 and automation, Menon (2019) argued it will influence the reskilling and reshaping of the current workforce and new jobs will emerge in other industries such as manufacturing. A decline in employment in the mining industry is inevitable; production declines due to the dangerous and complex nature of work associated with working at depth make it difficult for operations to remain viable. However, reducing the number of employees underground also reduces the number of people who are exposed to occupational hazards and this will ensure countless lives are saved and hundreds of injuries prevented. The use of personnel protective clothing (PPE) is not eliminated by the implementation of digital systems, workers should still don their full PPE as per standard to reduce exposure.

Appendix 1 is an expansion of Table 3, and summarises digital solutions currently available to address the safety and production challenges experienced in the mining industry. The “remarks” column in Appendix 1 highlights additional comments regarding the execution of the activities. Although some systems can be used by themselves, others need to be used in conjunction with other systems to achieve the desired output. For example, the geospatial tracking of employees alone will not combat the presence of illegal miners. There is need for additional surveillance in the form of live feed cameras in underground and surface environments. Other systems do not mitigate hazards but only forecasts their occurrence; in such a case, another system would have to be used to attenuate the effects of the hazard. Hence, such comments have been included in the remarks column of Appendix 1.

5.4 Summary and Conclusion

The operational challenges encountered in the industry are mainly as a result of:

- Mining at depth;
- Mining low-grade reserves;
- Unauthorised access to mine facilities; and
- Labour disputes.

Although the South African mining industry still has a long way to go before it can achieve zero harm, the sector continues to drive this initiative. The rest of the world has begun to adopt Mining 4.0 to increase efficiencies and safety while reducing costs. As a result, the conventional deep-level mining industry has been challenged to digitalise their operations. This is because as mining operations continue mining at great depths, operations are struggling to remain viable. Mining 4.0 is therefore adopted to have operations which consists of:

- Modern mining;
- Real-time data capturing and feedback;
- Drones for inspection and monitoring;
- Wearable devices for maintenance; and
- A digitally connected workforce.

In conclusion, research makes it possible to understand the causes of mining accidents and how to prevent them from occurring. There are currently systems available on the market that address the safety concerns in the industry and mining companies need to consider the implementation thereof. The most vital finding from this chapter is that the installation of smart sensors and software underground connects the workforce together to have an environment of constant communication and awareness. Underground workers are no longer isolated from the surface environment but are provided with the necessary assistance at any given time through wearable devices. The next chapter is the case study of a conventional deep-level mine highlighting the production phase of the MVC in order to understand the considerations that need to be taken into account prior the implementation of digital systems. The purpose of the next chapter is to introduce digital technology in the production phase of a conventional mine to enhance productivity and safety.

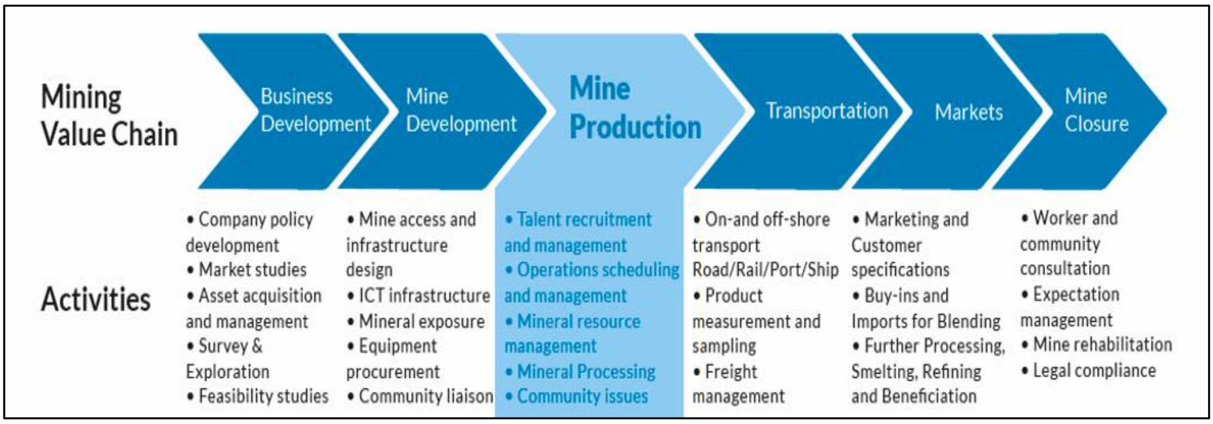
6 Mining Cycle Industry 4.0 Considerations for An Underground Conventional Deep-Level Gold Mine

The previous chapter, Chapter 5, aimed to find digital solutions to address the safety and production concerns based on the challenges encountered in deep-level gold mining. To further understand what it takes to modernise the mining cycle through automation and digital systems, this chapter uses a deep-level mine case study to understand the work processes that occur during the production phase of the MVC. Understanding the nature of work enables appropriate selection of suitable technology to the activities conducted during the different stages of the mining cycle in a working stope panel. The case study is also used to determine the digitalisation considerations of the industry ought to make prior the adoption thereof.

6.1 Phases of the Mining Value Chain

This research focuses on the production phase of the MVC. This phase occurs when a mining operation begins extracting valuable minerals. According to Sebutsoe and Musingwini (2017), it is during this phase that mining operations achieve the primary objective of making profit by extracting, processing and selling minerals. Song, et al. (2013) add that it is during the production phase that profits are made and stakeholders can recover investments. The different stages of the MVC are illustrated in Figure 20 and are dependent on each other; requiring processes in each stage to be completed for the next stage to be successful (Sebutsoe & Musingwini, 2017).

The production phase unlocks mineral value and because of this, it has maximum impact on the MVC. The production phase also determines the rate at which the stages downstream can be accomplished. Hence, Sebutsoe and Musingwini further reported that it is crucial for this stage to be well designed, planned, optimised and managed in order to prevent choking downstream. Mineral extraction is often associated with uncertainity due to technical and human factors as mentioned in Chapter 5.1. Although there are different templates that illustrate activities under the MVC, Song, et al. (2013) revealed that there are four basic stages which include: exploration, development, production and closure. Figure 20 illustrates a template of the various stages in the MVC; prior and after the extration of mineral resources.



Mining Value Chain	Business Development	Mine Development	Mine Production	Transportation	Markets	Mine Closure
Activities	• Company policy development • Market studies • Asset acquisition and management • Survey & Exploration • Feasibility studies	• Mine access and infrastructure design • ICT infrastructure • Mineral exposure • Equipment procurement • Community liaison	• Talent recruitment and management • Operations scheduling and management • Mineral resource management • Mineral Processing • Community issues	• On-and off-shore transport Road/Rail/Port/Ship • Product measurement and sampling • Freight management	• Marketing and Customer specifications • Buy-ins and Imports for Blending • Further Processing, Smelting, Refining and Beneficiation	• Worker and community consultation • Expectation management • Mine rehabilitation • Legal compliance

Figure 20: Mining Value Chain (Cawood, 2019c)

6.2 A Conventional Deep-Level Gold Mine Case Study for A Typical Mining Cycle

The conventional gold mine that has been selected is in the production phase of the MVC and is located within the Wits Basin. Due to operational challenges and low-grade reserves, mining activities take place only in some of the developed mining levels located through a sub-shaft. This case study investigates the work process that currently occur during the production phase of a working stope panel by unravelling the work conducted during each stage of the mining cycle. The case study also seeks to understand where safety and efficiencies are compromised during the line of work. The following section details work that is conducted during each stage of the mining cycle.

6.2.1 Early-Entry Examination

The shift starts when the crew assembles at the waiting place to discuss the work planned for the day as well as issues concerning safety and production, Figure 21. Although stope panels are not fitted with communication devices, intercom telephones are available at the waiting place. While at the waiting place, the crew is also reminded of refuge bay[2] procedures should life-threatening situations occur. The miner and safety representative are to report the condition of the refuge bay to the control room daily. On completion of the waiting place meeting, the crew must conduct early-entry examination from the entrance of the stope. Should working places contain methane and carbon monoxide levels exceeding 1.4% and 100 parts per million

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[2] A refuge bay is the primary location miners take refuge in should there be emergencies such as the presence of toxic gases, fire or falls of ground. Underground refuge bays have been designed such that they are located within 500m from stope panels and are equipped with compressed air, sealed door, water, latrines and a telephone to be life sustainable.

respectively, crews must be evacuated. Mining employees are also issued with hand-held whirling hygrometers to measure temperature[3] and gas detecting instruments (GDI) prior going underground. Underground working places must be declared safe by a miner before crews commence with any work. Once the crew is satisfied with the conditions at the stope, they must declare the stope safe and sign the miner's logbook. Any observed hazards should be recorded in the miner's logbook and a risk assessment should be conducted. If the crew is unable to deal with the observed hazard immediately, the area is to be barricaded off and reported to the immediate supervisor.

Figure 21: Underground Crew Assembling at the Waiting Place (Petra Diamonds, 2019)

6.2.2 Supporting of Excavations

Underground stopes are supported to contain deformations, closure and falls of ground. Support is transported into the stopes via mono winches. Support installed inside the stope panel should be 90º from the footwall to the hangingwall to ensure the rockmass is sufficiently

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[3] Mining operations are ventilated to provide fresh adequate air to underground working places, to remove heat and moisture and, to dilute toxic gases and airborne pollutants (Bluhm, et al., 2003). Heat is controlled in the stope by installing ventilation fans, curtains, centre gully brattices and venturis. Ventilation controls in the crosscut include ventilation doors and cooling cars. The mine standard, as stipulated by *Department of Mineral Resources (2017)*, state that the air velocity in a stope should not be less than 0.25 m/s over the working height. In addition, the measured wet bulb and dry bulb temperatures in a working stope should not exceed 32.5ºC and 37ºC respectively.

supported. Table 5 was conceived from the support standards at the mine and illustrates the required support for an updip stope panel that has a minimum stoping width of 1.2m and a maximum stoping width of 2.2m. In such scenarios, 0.9m long roofbolts must be installed not less than 70º to the hangingwall strata. Gully mesh is to be installed not more than 10m from the face. Crews are to also install temporary support such as nets and mechanical props, not more than 0.5m from the face, before installing permanent support. There is also support in the form of reef pillars to offer extensive excavation support.

Table 5: Underground Permanent Support Standards

Support Type	**On dip distance**	**On strike distance**	**Distance after a Blast**
Packs	1.9m	1.9m	4.2m
Roofbolts	1.0m	1.5m	0.5m
Elongates	1.5m	1.5m	2.5m
Mechanical props	1.5m	1.5m	0.5m

Figure 22 shows the various underground permanent support such as packs, mechanical props and roofbolts. The support illustrated in Figure 22 is installed according to the mine standard highlighted in Table 5. According to Daehnke, et al. (2001), the following factors determine the type of support used underground:

- Depth of mining;
- Mining method;
- Geological features; and
- Characteristics of the reef such as dip, stoping width and length of the panel.

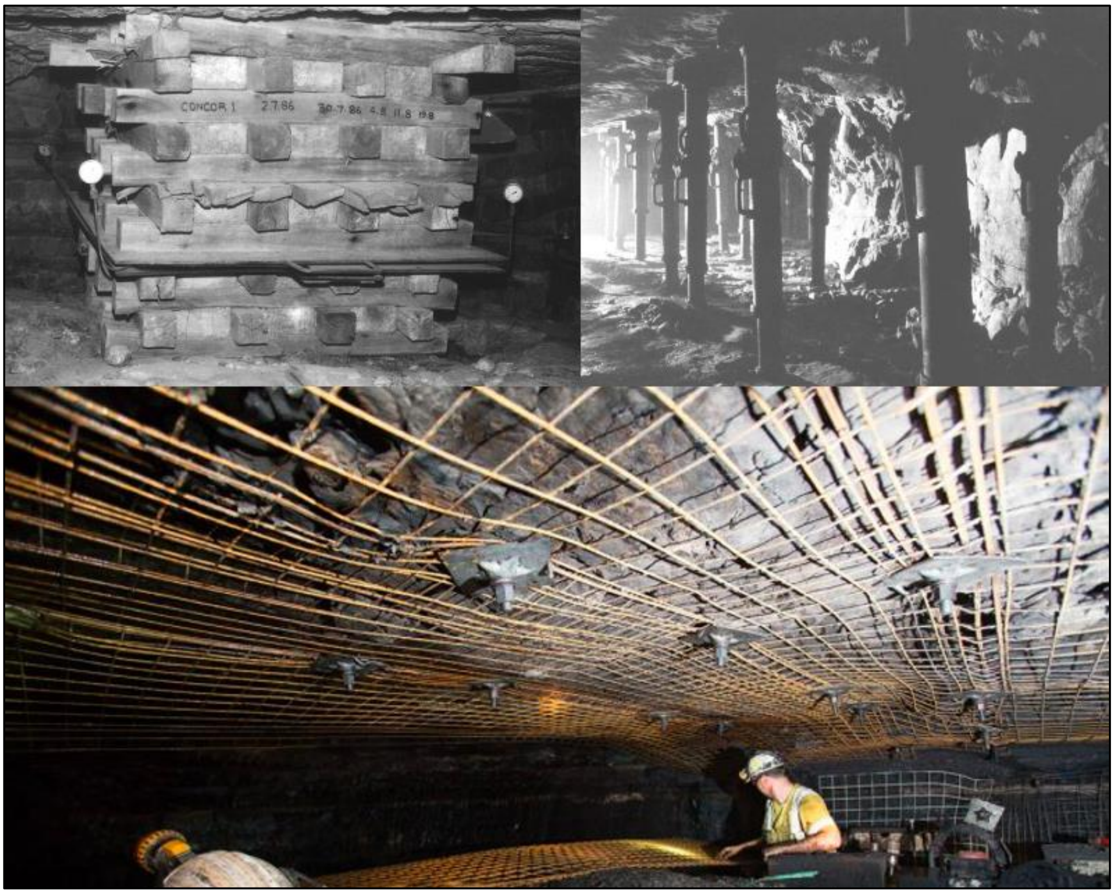

Figure 22: Underground Permanent Support (Bhowan, 2019; Daehnke, et al., 2001)

6.2.3 Marking and Drilling of Shotholes

Production holes are marked in a pattern which considers the stoping width, reef channel and the overall length of the panel. The characteristics of the stope have been outlined in Table 6. The marking of stope panels is also influenced by the direction of the reef as well as the presence of geological discontinuities. Miners are handed out survey notes that indicate limit lines and mining direction to maintain mining on reef. Production holes are drilled with 1.2m drill steel while preconditioning holes[4] are drilled 2.4m deep.

The expected face advance after a blast when using 1.2m drill steel is about 0.9m. This is because the 1.2m drill steel has an expected 0.3m socket. However, in reality a 0.9m face advance is hardly achieved; typically, a 0.8m advance is recorded after each blast. This is because the face advance is dependent on the angle at which production holes are drilled.

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[4] Preconditioning is done to destress the face ahead and has become mandatory to drill with each blast. Zvarivadza and Modisha (2015) revealed that preconditioning mitigates face bursts, and mining stopes which have been preconditioned tend to be much safer than those which are not.

Production holes drilled at an angle less than 70º to the face tend to give a lower advance rate. Rock drill operators often struggle to achieve this angle of drilling due to the condition of the footwall, overall confinement of the stope and stoping height restriction. Figure 23 illustrates the stage of marking and drilling of shotholes in an underground stope.

Table 6: Stope Characteristics

Stope Characteristics	
Face Length	17m
Stoping Width	1.7m
Channel Width	1.62m

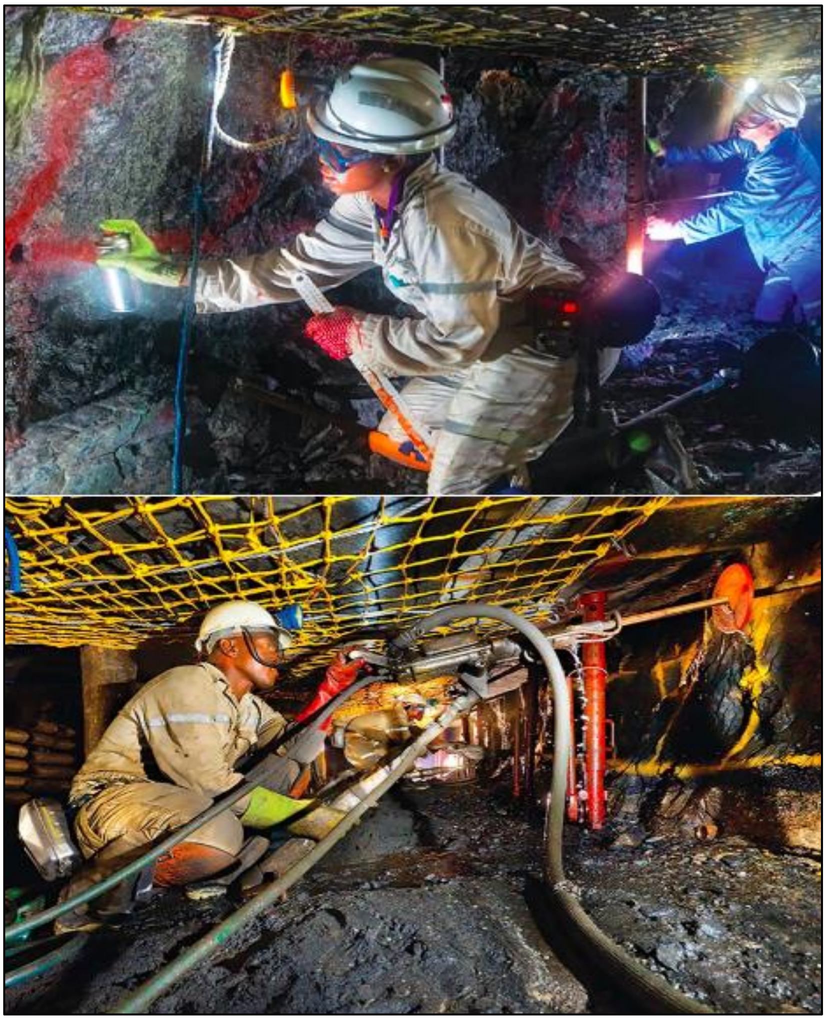

Figure 23: Marking and Drilling of an Underground Stope (Minerals Council South Africa, 2019j)

6.2.4 Charging and Blasting of Shotholes

The drilled production and preconditioning holes are primed, loaded with cartridge explosives and tamped, Figure 24. The charged holes are timed using fuses and thereafter connected to electric switches. Electric current is carried through blasting cables to the blasting box. The system is armed on surface using the centralised blasting system. Blasting is initiated at the surface control room once the morning shift has been cleared. Blasting time is 18:00 and the shift clearance time is 17:00 however, this is hardly achieved as mining crews tend to exit later than this. Due to this, there are delays in the blasting time. These delays further prevent the entry of night shift crews from going underground on time. This is because a re-entry period of three hours is compulsory before the next shift can gain entry to any underground working place where blasting has taken place. In addition, blasting delays in one operation affects the blasting of other operations linked together in the central blasting system. This is because these mining operations must blast around the same time.

Figure 24: Charging an Underground Stope with Cartridge Explosives (Dyno Nobel, 2010)

Crews can blast, clean, and support the panel on a cyclic routine. Without any breakdowns or unforeseen circumstances, the crew can blast four times a week. Every fifth day is designated to installing a line of permanent pack support along the entire face length and to advance the strike gully closer to the face. Therefore, of the available 23 production shifts in a month, mining crews can blast only on 16 of those shifts. This gives panels an average face advance of 12.8m a month when assuming a face advance of 0.8m. Therefore, without any disruption the stoping panel with characteristics outlined on Table 6 can achieve a call of about 218m^2. Hence, stope panels achieve higher square metres if they have a longer face length.

6.2.5 Cleaning of Blasted Ore

Cleaning inside stoping panels is through a high-water pressure sweeping tool in conjunction with scrapper winches. As the scrapper winch pulls ore away from the face, the sweeping tool blows the remaining ore towards the direction of the scraper scoop for easier and faster cleaning. Scraper winches are used to clean the face, strike gully and centre gully; these scraper winches run concurrently. The panel consists of three 37kW scraper winches which are attached to a two-tonne scraper scoop. Figure 25 illustrates a scraper scoop while it pulls broken ore. Blasted ore from the face is directed to the strike gully by the face scraper winch. The strike gully scraper winch then feeds ore to the centre gully thereafter, the centre gully scraper winch tips ore into the orepass. Orepasses can only accommodate limited number of tonnes. Hadjigeorgiou and Stacey (2013) argued that this is because orepass systems were initially designed during the early phases of the mine when there was insufficient data available to execute better orepass design. Since the orepass can be quickly filled to its maximum capacity, it is important to empty the orepass before there is large accumulation of ore in the gullies which can hinder cleaning the stope face.

Figure 25: Scraper Winch Scoop Pulling Ore (Phakathi, 2017)

There are safety and production concerns associated with the use of traditional scraper winches. Scraper winches are responsible for a high number of injuries and fatalities. *Mine Health and Safety Inspectorate (2019)* identifies scraper winches and rigging as the third largest contributor to fatalities after falls of ground and RBE. Scraper winches are also associated with delays daily which reduce the cleaning rate of the panel. According to Rupprecht (2013), the delays include time spent establishing the scraper path, filling the scraper scoop, breaking large rocks, repairing broken winch ropes, re-rigging and travelling in the gully. The cleaning rate of the scraper winch is also affected by the face shape and condition of the footwall, which are usually poor and uneven thus resulting in poor cleaning efficiency (Rupprecht, 2013).

Recently, the mine has reintroduced water jets. These had been previously withdrawn as the use of the equipment resulted in several injuries and fatalities due to high-pressured water from the jet. Although water jets come with safety concerns, they result in a tremendous reduction in the time spent cleaning the face as compared to using scraper winches in conjunction with sweeping tools (Gauert, et al., 2013). The face cleaning rate is improved by over 50% when scraper winches are used together with water jets (Rupprecht, 2013). It is mandatory to clean panels thoroughly as Rupprecht further reported that without doing so additional costs would have to be assigned to sweeping and vamping crews to reclean panels. Leaving blasted ore behind also decreases the mine call factor (MCF). Tetteh and Cawood (2014) cite Storrar confirming that the accumulation of ore and sweepings underground has a negative impact on the MCF[5].

6.2.6 Loading of Blasted Ore

Locomotives can be diesel or battery powered and are assigned for the transportation of workers, materials, and ore. A locomotive is operated by two people; a driver and a guard. Drivers working together in a station level communicate with each other through radios. The dimensions of main haulages in this conventional mine typically are 3.5m by 3.5m and crosscut dimensions are 3.5m by 3.0m hence there is only a single rail lane for RBE to travel, Figure 26. Not only does this cause restrictions and congestion in the haulages but also results in poor scheduling of RBE as time is lost coupling and shunting RBE. The lack of proper scheduling of locomotives causes the delay of supply and delivery of materials and ore. In addition, RBE

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[5] Xingwana (2016, pp. 150-151) defined MCF as “the ratio, expressed as percentage, of the specific product accounted for in the recovery, plus residue, and the corresponding product called for by the mine’s measuring and evaluation methods.” The MCF evaluates the inconsistencies in the ore tonnage and gold content along the mining system. An MCF of 100% means there is no gold lost underground and at the plant. This means all the process within the MVC are operating efficiently. However, conventional methods of cleaning result in a lower MCF as scraper winches are unable to thoroughly clean the panel and tend to leave ore behind.

accidents are common underground because of RBE collision with other RBE, men and structures such as ventilation doors.

Figure 26: RBE Transportation Underground (Thorough Tec Simulation, 2020)

RBE are serviced on a weekly basis at the fitter shop located close to the level station. There is also a battery bay for the charging of RBE's that operate on batteries and a diesel bay for the refuelling of diesel-powered locomotives. Breakdowns of RBE is common, and the breakdown of equipment has a detrimental effect on a stoping crew's ability to clean, support and blast the stope. As a result, the panel is likely not to achieve the monthly call due to RBE breakdowns. The long distances from the level station to the stopes result in machinery breakdowns to be only addressed the following day. Breakdowns are usually reported at the end of the shift by the miner to the immediate supervisor who can then escalate the matter to relevant departments.

In some panels, ore from the stope can be retrieved from bottom gullies by rail bound mechanical loaders which directly load to hoppers. Ore in this particular stope is retrieved from an orepass. At the loading point, a chute controls the discharge of ore from the orepass to rail-bound hoppers attached to locomotives, Figure 27. Each hopper carries up to 3 tonnes of broken ore and a locomotive pull not more than eight hoppers at a time. The ore-filled hoppers, consisting of 24 tonnes of ore, are transported to the internal tip located close to the level station. The internal tip is the tip that connects ore from different levels to the lowest operating level.

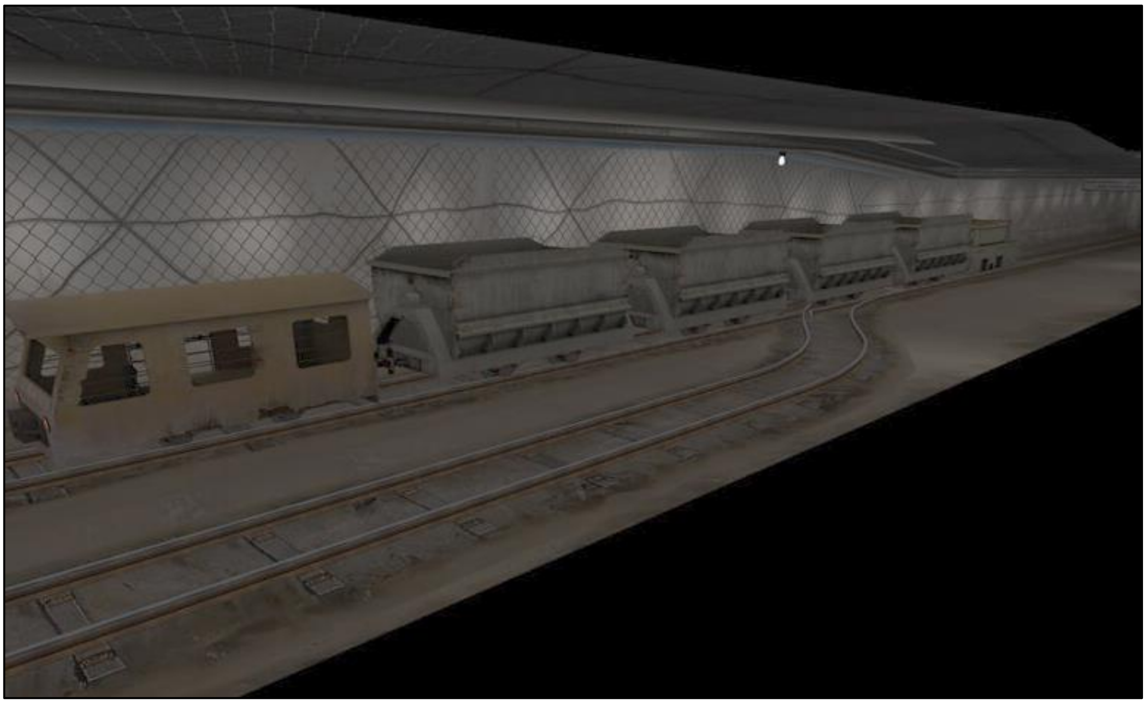


Figure 27: Hoppers Coupled to a Locomotive (Thorough Tec Simulation, 2020)

Blasted reef from the stope panel is discharged at the internal tip as shown in Figure 28. The reef tip is equipped with a grizzly to ensure large rocks do not pass through. In the event that large rocks are present, they have to be broken with a large hammer. This is a hazardous task as fly rock from breaking rocks can injure workers in close proximity to the tip. Although the orepass at the internal tip is fitted with the grizzly, it is common to have hang ups inside the orepass which have potential to cause a mudrush.

Figure 28: Reef Discharging Station (Bethel, 2005)

6.2.7 Underground Environmental Conditions

Most panels in this operation are remnant areas consisting of different geological discontinuities such as faults, dykes, brows, etc. The mining crew was mining towards a reverse fault 250m long, at a dip of 65º. Due to the presence of these geological features, the face shape was uneven which further caused difficult mining conditions as the face consisted of weaker zones which advanced faster than the other parts of the face. To negotiate with the fault, the updip stoping method was used. Some panels have nightshift crews to pull gullies and transport ore. However, due to the high seismic rating of some stopes, night shift is prohibited.

Nightshift crew has also been prohibited from working inside this remnant panel. Therefore, the morning shift is responsible to blast and clean the stope panel during the shift. As this stoping panel is highly seismic, extra precautions are taken to minimise the effect of seismicity and rockbursts; miners are therefore encouraged to check the seismic rating of their working places before proceeding underground. Table 7 is the seismic rating used at the conventional mine and outlines the actions to be taken by miners and supervisors to safeguard employees against seismic events.

Table 7: Seismic Rating at the Conventional Mine

Seismic Rating		**Required Action**
0 to 5	Low short-term seismic rating	No action required
6 to 7	Medium short-term seismic rating	• Rock engineer to notify mine overseer and mine manager Miner and shift boss: • Discuss seismic rating with crew • Discuss escape strategy with crew • Fix all sub-standards
8 to 10	High short-term seismic rating	• Rock engineer to notify mine overseer and mine manager Miner and shift boss: • Withdraw people from the stope • Discuss seismic rating with crew • No blasting should take place

This stope is located approximately 2 750m below surface. Although the cut-off value at the mine is 1 100cmgt, the average value at this stope panel ranged from 500cmgt to 800cmgt. This prompted the closing of this panel as it became apparent the mining thereof was unprofitable. Accessing deeper reserves has also been a challenge in this operation due to the presence of geological discontinuities and seismic events. Unlike the previous digital mines discussed in Chapter 2.6 which were either initially designed for or have been adjusted to accommodate digital technology, this conventional mine consists of old infrastructure such as rails and telephone lines. Hence, there is no effective or real-time communication to reach people inside the stope as the nearest telephone is at the waiting place. In addition, the operation consists of long travelling distances to working places which can be more than an hour. The stoping areas are also remote from each other.

Production shifts are commonly lost due to compressed air and water shortages. The lack of compressed air and water inside the stope affects almost all the activities in the mining cycle. For example, the face cannot be blasted without compressed air, roofbolts support cannot be installed, and production holes cannot be drilled. Compressed air shortages are mainly due to leakages along air columns in the haulages and crosscuts. Water shortages also affect the ability to blast stope panels as it is used to lower temperatures inside the stope and water down to allay dust prior conducting any mining activity. Water shortages are mainly because of reduced water pressure from underground water pumping stations and leakages along the haulage pipes. Another major challenge for the operation is electricity shortages. On the 9th of December 2019, this operation alongside other mining companies had to shut down their underground operations and processing plants due to power failures as a result of technical faults at one of Eskom's major power station. This has led to questioning the ability of the South African mining industry to keep a stable electricity supply.

6.2.8 Labour

The conventional gold mining industry is highly labour-intensive. During the twentieth century, most gold mining workers were migrants from other Southern African countries; for example, Mozambique, Lesotho, Swaziland and Botswana (Harington, et al., 2004). The mining industry traditionally recruited unskilled migrant labour speaking many different languages. A hybrid language called "Fanakalo" was created and used for European supervisors to communicate with African subordinates using a basic vocabulary (Hurst, 2008). Today, Fanakalo remains the primary language of communication. Crews underground conduct safety meetings daily while supervisors have safety and production meetings with management weekly. Although information from management is conveyed to underground crews through "safety and production briefs" written in English, meaning is often lost in translation as Fanakalo can be described as an instructive language with limited vocabulary. This is because the experienced workforce is without any formal education and has very little knowledge of English.

The number of people in a stoping crew is calculated according to the face length. In this particular stoping panel there are 17 people: a miner, team leader, six rock drill operators

(RDO), six scraper winch drivers and four stoping labourers. In addition, there are four people in the construction crew. The construction crew is responsible for equipping and extending mining services such as pipes and columns in the stope. There are no females within the crew. Stoping panels also consist of a shift boss and mine overseer for supervision. Stoping crews work eight-hour shifts, five days a week with two working Saturdays a month. Due to some working places located several kilometres from the station, the effective shift length in the stope is between five to six hours due to time spent travelling underground.

Employees are required to don full protective clothing and are issued with a lamp, self-rescuer, and a gas detection instrument at the lamproom before going underground, Figure 29. The PPE store issues employees with necessary equipment for underground or surface work. However, employees often do not comply with PPE standards before going underground. Due to the presence of illegal miners, employees are individually searched prior going underground and as well as after shift for excessive food, contraband or illegal possession of mine property. To mitigate the ingress of illegal miners, the operation has installed fingerprint identification system turnstiles before the main shaft entrance. However, employees are still entangled with assisting illegal miners in exchange for money.

Figure 29: Self-Contained Self-Rescuer, Cap Lamp and Gas Detection Instrument (Mine Arc Systems, 2020; Golden Future, 2020; Schauenburg, 2018)

Employees are transported underground to their working places via vertical shafts and connecting tunnels. The operation is a deep-level mine consisting of two vertical shafts for access and transportation of men, materials and ore. The primary shaft is the main access to underground working levels and is approximately 2 000m deep. Due to the depth of the explored reef, there exist a secondary shaft which gives further access to mining levels from the primary shaft. The sub-shaft is over 1 000m deep from the primary shaft and more than 3 000m measured from the datum line. It is also common for operations to develop a tertiary shaft to mine deeper reserves depending on the depth of the explored reef (Holl & Fairon, 1973). This tends to be the case for ultra-deep operations.

6.2.9 Reporting and Communication

Shift bosses, miners, team leaders and safety representatives are issued with logbooks for reporting hazards encountered underground. The logbooks are signed daily by the immediate supervisor and kept for records for at least three months. These logbooks are also issued at the PPE store. Working places which have morning shift and night shift have a communication book in which miners from these different shifts sign and communicate with each other. However, the communication book is sometimes not filled as miners tend to forget. In addition, there is an A-hazard book which records all the major hazards that were recorded when the working place was visited by the different mining departments. These hazards are also recorded on a mining software. The software also tracks the operation’s production performance by recording the daily booked and forecasted square metres. The shift boss plots the daily face advance on the production plan on a weekly basis. This is to predict how many square metres the panel is likely to achieve at the end of the month.

There are different departments working together to ensure a mining operation is a success. These include engineering, safety, rock engineering, ventilation, geology, survey, mine planning, grade control, sampling, finance, human resource, and labour unions. These departments visit working panels on a regular basis. The reports from the visits are signed by the relevant supervisors and heads of departments. The survey department conducts monthly visits to the panel to measure the advance of the face and calculate the square metres achieved for the month. The survey department also installs new survey pegs with the progression in face advance to ensure the panel is mining in the correct direction, Figure 30.

Figure 30: Underground Surveying (Tarikh, 2016)

Underground materials are ordered by the shift boss on surface. The shift boss orders materials on the material-ordering book and signs for it. Once the material has arrived on the mine premises, it is loaded in material cars for underground, Figure 31. Material from surface is loaded for underground by the afternoon shift while empty material cars are removed from underground to surface during night shift. In the case of explosives, miners order explosives and accessories in the order book available at the office on surface. The destination of material and explosives cars from surface to underground are marked by a piece of paper hence, it is very common for these cars to end up in the wrong working place or used by another mining crew.

Figure 31: Material Cars to be Transported Underground (Phakathi, 2017)

Although the control room is the heart of the operation, there is lack of integration of the different activities conducted underground and on surface. The control room has operators who work shifts to process and monitor information presented on the available systems and to convey verbal reports as given by mine employees. Table 3 is further expanded in Table 8 to summarise the challenges encountered at the conventional deep-level mine where the case study was conducted. These challenges are arranged according to the stages of the mining cycle. Other challenges have also been included on Table 8 which do not fall under the mining cycle. These include challenges experienced due to underground environmental conditions, labour, and communication restraints.

Table 8: Challenges at the Conventional Deep-level Gold Mine

Mining Cycle	**Challenge**
Early-entry examination	• Early-entry inspection
	• Hazardous area inspection
	• Dust
	• Compressed air shortages
	• Water shortages
	• Falls of ground
	• Geological discontinuities
Supporting of excavations	• Reserves locked up as support
	• Compressed air shortages
	• Water shortages
	• Lack of support compliance
Marking and drilling of the face	• Underground surveying: mining direction and limit lines
	• Compressed air shortages
	• Water shortages

	• Dust
	• NIHL
Charging and blasting of shotholes	• Accessing deeper reserves
	• Low face advance after blasting
	• Seismicity
	• Toxic gases
	• Dust
	• Electricity shortages
	• Low MCF
	• Late blasting
Cleaning of blasted ore	• NIHL
	• Dust
	• Compressed air shortages
	• Water shortages
	• Electricity shortages
	• Insufficient drawpoint size
	• Low MCF
	• Safety concerns with the use of scraper winches and water jets
Loading of blasted ore	• RBE accidents: Collision with other RBE, workers and structures such as ventilation doors
	• RBE breakdowns
	• RBE congestion

	• Short effective shift length due to long travelling distances
	• Insufficient drawpoint size
	• Orepass inspection
	• Rock breaking at the tip
	• Dust
	• NIHL
	• Compressed air shortages
Other Challenges	
Underground environmental conditions	• High temperatures
	• Low-grade reserves
	• Mining in remnant areas
	• Uneven face shape
	• Illegal mining
	• Old infrastructure
	• Lack of monitoring air and water leakages
	• Remote working places
	• Communication only by telephone available at the waiting place or refuge bay
	• Long travelling distances
Labour	• Labour intensive industry
	• Limited education and digital skills

	• Conventional PPE used
	• Lack of PPE compliance
	• Lack of compliance to safety standards
	• Short effective shift length due to long travelling distances
	• Knocking off late therefore delaying blasting time
	• Unauthorised access
	• Theft of company property
	• Wage disputes
Reporting and communication	• Conventional control room set-up
	• Conventional recording of identified hazards (logbook, safety compliance auditing)
	• Lack of regular management and employee engagement
	• Communication only by telephone at the waiting place or refuge bay
	• Lack of reporting refuge bay compliance
	• Inability to report breakdowns and malfunctions during shift
	• Lack of MCF monitoring in real-time
	• Lack of inventory management: Ordering too much materials, material cars getting lost underground, etc.

	- Lack of communication and transparency between different mining departments
	- Lack of adequate communication between different shifts
	- Overbooking: Reporting inaccurate daily face advance and square metres achieved after blast

6.3 Case Study: Digital Requirements

Appendix 2 is an expansion of Table 8, and summarises digital technologies for the conventional mine to cater for the challenges encountered at each stage of the mining cycle. Through digital technology, a conventional mine is transformed into an environment where miners are distanced from hazardous working conditions as such work can either be conducted from a safe distance or remotely through unmanned aerial vehicles (UAV), VR and AR. There is real-time monitoring of environmental conditions, geological features, and face advance of the stope. The implementation of digital systems increases production by using algorithms to offer safer mining methods to extract complex and deep reserves. Production can be monitored in real-time, enabling better efficiencies and ore reconciliation as inconsistencies in ore flow in the system can be detected quicker.

Appendix 2 proposes that miners will no longer rely on telephones available at the waiting place and refuge bays for communication; installing an underground communication network and issuing miners with communication devices will ensure teams can easily communicate with each other and the surface environment. The digital mine offers the surveillance of personnel, equipment, and other assets. The monitoring of personnel and the mining environment ensures the safety of employees and compliance to safety standards. The safety of employees is also improved through the installation of safety devices on equipment and communicating risks. Automating the hauling fleet eliminates congestion of RBE through advanced RBE scheduling for the daily transportation of men, materials, and ore. In addition, digital twinning of equipment reduces maintenance costs as the performance of equipment can be observed in real-time therefore, predicting breakdowns before they occur and allowing for regular maintenance.

Automating the drilling stage of the MVC may be difficult to implement in the narrow-reef mining industry. The characteristics of the stope such as the dip of the reef, height of the stope and stope confinement due to installed support hinders the installation of large equipment such as autonomous drills. As illustrated in Table 5, the distance from the face to the last line of permanent support such as elongates, and packs should not be more than 2.5m and 4.2m respectively after a blast. Therefore, the autonomous drills must not be wider than these dimensions as the equipment would not be able to manoeuvre around the stope. In addition, Table 6 illustrated the stope width as 1.7m therefore, the autonomous drills must not be higher than this as it would require an increase the stoping width resulting in dilution of ore. Another challenge of introducing autonomous drills in narrow-reef mines are the varying dips of the reef and large equipment may find difficulty in manoeuvring through these gradients. To summarise, although the digital technology is ready for autonomous drilling, the drilling machine itself is not yet ready.

It is crucial to modify the drilling process as the average face advance after a blast is only 0.8m. Increasing the face advance by only 10cm to 0.9m would increase the monthly face advance from 12,8m to 14.4m when the face is blasted on 16 of the 23 production shifts. Using the stope characteristics shown in Table 6, the monthly call can be increased from 218m^2 to 245m^2 with a 14.4m face advance. Rupprecht (2013) reported that increasing the face advance to more than one metre per blast would require changes to the cleaning equipment used as scraper winches will be unable to handle the tonnage output from the blast. Therefore, longer drill steels cannot be used before the mining layout is improved. The face advance can be increased by improving the blasting quality to ensure better face and footwall conditions to enable RDO's to drill at right angles to the face. Monitoring the performance of the drilling machine and the stope face in real-time through digital twinning will ensure the face is drilled correctly.

The digital solutions outlined in Appendix 2 cater for the challenges encountered at the conventional mine and have not included the introducing of mechanisation. This is because previous studies have indicated that attempts to mechanise the narrow-reef have been unsuccessful without improving the overall design and layout. The digital solutions presented offer the mining industry better monitoring and surveillance technology to improve production and safety through UAV's, robotics, and smart sensors. Safety in remnant stoping areas can be improved significantly as 4D geotechnical hazard assessing systems can be used to monitor the stope conditions and warn miners of a possible occurrence of a seismic event ahead of time.

The control room is characterised by constant inflow of information from workplaces as received from the installed underground systems. Installing a videowall at the control room will offer live feed display of the performance of different systems. Therefore, the mining environment becomes safer and more efficient through Mining 4.0 as everyone, and everything can be tracked throughout the system. This increases awareness between underground employees and the mining environment. Currently, there is no single vendor that can supply all the needs of an operation hence, the digital technologies outlined in Appendix 1 and Appendix 2 are supplied by different vendors. A mining operation should, therefore, collaborate with different vendors to result in an ecosystem of vendors.

6.4 Considerations for the Digital Mine

According to Macfarlane (2001), the successful implementation of technology in mines has not only been a South African problem but a worldwide problem. Therefore, it is important to learn from experiences of other mines which have also digitalised their operations. It is also said that the mining standards of today are written in blood; people had to die first before measures were put in place to mitigate the hazards. Although technology is adopted to increase safety, any technology that is implemented and not understood becomes a hazard. This should not be the case with the adoption of Mining 4.0. Measures must be in place not only to mitigate the hazards associated with the use of new technology but to also understand and predict them well over time. The following section highlights factors the mining industry should consider prior implementing digital systems in conventional deep-level mines. This was done with the purpose of preparing the industry on what to expect with the introduction of Mining 4.0.

6.4.1 Understanding the Need for Innovation

There must be a clear understanding of the use and functionality of the innovation within the system. Pickering (2007) argued that in many instances such as the implementation of hybrid mining in some narrow-reef mines, there was not a clear understanding of the benefit of the system to the mining process. It was implemented because it was regarded as ‘fashionable’ at the time. However, before implementing technology in any mining operation, there needs to be clear understanding of the need and benefits of the technology. The fit-for-purpose technology which has been chosen should then be implemented to address the current shortcomings of the operation (Pickering, 2007).

According to Macfarlane (2001), the reason behind unsuccessful technology implementation in the mining industry has not been the technology itself but the work system to which the technology was introduced into. It is therefore important to adequately engineer the system; assessing and managing the risks associated with the technology. The selected technology must address real and current needs of the operation and the entire work system must be adequately engineered (Pickering, 2007). For this reason, it would be far better for the mining industry to remain as it is than to prematurely introduce technology which is not understood.

6.4.2 Scale of Innovation for Mining Operations Will Differ

According to Willis, et al. (2004), the measure of success of digitalisation will be independent for different mining enterprises. This is because the effort going into digitalising mines will differ. The amount of effort going to the digitalisation of an operation should correspond to the investment input. Mines will have to consider the remaining reserves in an operation to determine how much investment can go into new technology. A mine should not invest in technology if the fruits cannot be reaped during the life of mine. Therefore, each mine should consider the life of mine of its operation and make investment based on this. Since the digital blueprint of one mine may differ from another, each mine should design its own digital mine blueprint to address the needs of the company. Hence, Pickering (2007) found that the implementation of technology can only be effective if the integration is into a suitable mining system.

Ramdoo (2019) revealed that large-scale mining operations have more financial capability to invest in technology than mid-size or smaller mines and therefore, the scale of technology adoption may be far more intense. In addition, the introduction of technology in the mining industry is also affected by the state of development of the country. This is because governments in developed countries may be less threatened by the rapid adoption of technology and the infrastructure required is available. Developed countries can be expected to advance quicker in introducing technology compared to developing countries. This is because these countries have a better diversified economic base and are equipped with reliable and fast connectivity infrastructures to facilitate the adoption of new technology (Ramdoo, 2019). In addition, developing countries may struggle to obtain skilled workers who are experts in the fields of mining and digitalisation thus, slowing the rate of digital adoption (World Economic Forum, 2017).

6.4.3 Open Innovation Approach

Karo and Kattel (2010) quotes Chesbrough's definition of open innovation as "the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and to expand the markets for the use of innovation, respectively." Karo and Kattel (2010) also quotes Chesbrough revealing that with open innovation "valuable ideas can come from inside or outside the company and can go to market from inside or outside the company as well". Innovation can be defined as deviation from routine work behaviour to carrying out new combinations of work practices that result in optimum output. Open innovation promotes the collaboration of different people and organisations outside the company (Karo & Kattel, 2010). Through open innovation, there are alliances between different companies and academic researchers. This is an approach the labour-intensive gold mining industry should consider in order to have better insights on what to expect with the introduction of Mining 4.0 and also, increase competitiveness in the industry.

There is also need for collaboration of different systems and vendors as Industry 4.0 has brought forth mining technology which is mobile and accessible. Thus, the mining industry must collaborate with various digital vendors to develop new ways of thinking and operating to revitalise the much struggling industry. Industry 4.0 is dependent on the linking of different systems that must work together to produce a highly efficient system. A single vendor is incapable of delivering all the Industry 4.0 systems an operation requires therefore, an ecosystem of different vendors is required within an operation (CGI, 2017). In addition, workers will have to be adequately trained to be able to use these digital systems hence, there should be regular vendor support to assist with the skilling and training of workers.

6.4.4 Influence From Labour

Employees play a major role when mining operations undergo any kind of transformation. Willis, et al. (2004) reported that when new technology is imposed on a mine before ensuring that it will be well received internally, it is bound to fail. Macfarlane (2001) gives an example of the use of geospatial tracking devices in Germany. Although the technology was introduced to monitor the safety of underground employees and to ensure evacuation can be done quicker in the case of emergencies, employees found the use of the technology unethical as they had to now account for their whereabouts. The technology was then perceived as a "policing" measure and interpreted as a threat than a safety measure by employees (Lööw, et al., 2019). Therefore, it is important for operations to engage with employees and fully communicate the benefits of the use of certain technologies to avoid backlash. Early employee participation is thus vital during the planning stages of technology implementation to ensure the workforce is onboard. This is because without employee engagement, the implementation of most systems will be unfruitful.

Mindset contributes immensely to the successful transformation of any industry, so does culture and behaviour. This is because employees must be willing to adapt to change and be prepared for it. Workers in the gold mining industry tend to possess old attitudes and culture of unwillingness to familiarise with new practices and this may hinder the implementation of innovation in the industry. According to Vogt and Hattingh (2016), there is general reluctance from the gold industry to adopt new technologies. This reluctance has been due to worker resistance as well as managerial reluctance and conservatism (Steward, 2013). According to Johansson, et al. (2010), to change workplace culture it is first crucial to begin by transforming most of the workforce which are male miners and mining engineers. The industry can also consider an approach which involves gradual introduction of technology to give employees enough time to adjust to the new ways of working as implementing changes too quickly to the mining environment can cause too much shock to the system (Scalzo, 2019).

6.4.5 Changes in the Workforce

With the adoption of Mining 4.0, new jobs will be created while some will become redundant. The industry must then decide what is to happen to the employees whose jobs have now become redundant keeping in mind that those employees may hold several years of mining experience. Lööw, et al. (2019) warned that although the next generation operators will be trained in using digital equipment and perform well with digital functionalities, they will not have “industry experience”. Therefore, there must be integration of industry knowledge and digital experience. Thus, for this new era of mining to be accepted, there must be collaboration between the leaders of the industry, government, learning institutions and communities (World Economic Forum, 2017).

In the digital mine, there will be new demands for teamwork and responsibility. There will also be changes to the daily mining routine as it is known today. *McKinsey and Company (2018)* reported that the best way to take advantage of new technology is to reorganise workers into “squads” where people are assigned to teams according to varying and complimenting skills. This is because there will be a need for new qualifications, skills, and knowledge (Johansson, et al., 2010). According to Johansson, et al. (2010), the digital mine redefines what a miner is; the best miner will no longer be one with the most physical strength but one with concentration and tactile skills. This is because the roles miners will play will no longer be the same. The miner will have minimal interaction with the direct stope face hence, Johansson, et al. (2010) cites Abrahamsson and Johansson revealing that in a digital mine, miners can return home as clean as they came.

A mining engineer of the future must gain competence in systems thinking, production systems and people (Johansson, et al., 2010). The mining engineer must not only have qualifications and knowledge on digital technology but have industry experience as well. Lööw, et al. (2019) states that although unemployment can increase due to digitalisation, there will be an increase in prosperity and development of the workforce in the digital mine. This is because the mining operation becomes a learning organisation where there is integration of learning and personal development (Johansson, et al., 2010). Therefore, there will be an increase in consumption and growth in the service sectors. Although a mining operation will be characterised by fewer yet high-skilled personnel, employee wages can be expected to be higher.

Schwab (2016) predicts that the introduction of technology may intensify the gender gap even more. This is because new jobs will be created in the fields of mathematics, ICT, and computer technology through Industry 4.0; these fields are already dominated by more men than women. Therefore, job losses may affect women more than men in the future. Johansson, et al. (2010) reported that due to cultural beliefs and stereotypes, some countries have found it difficult to recruit women in the mining industry. Table 9 illustrates that women in mining are only a small percentage of the overall workforce. Although gender-neutrality in the mining industry may not be immediately achieved, more women can be motivated to join the industry and stay longer through digitalisation. Currently, women are often victims of gender stereotyping while the machinery and equipment used underground are still conventional and not suitable for women (Moraka & Jansen van Rensburg, 2015). Therefore, for mining companies to support transformation, Moraka and Jansen van Rensburg (2015) stress that mining companies must also review their human resources practices.

Table 9: Percentage of Women in the Mining Industry (Minerals Council South Africa, 2018b; Minerals Council South Africa, 2020a)

	Gold	**PGM**	**Coal**	**Chrome**	**Iron ore**	**Diamonds**	**Manganese**	**Lime, aggregate and sand**
2017	12	11	13	16	14	14	16	12
2018	12	11	13	17	14	14	16	18
2019	12	12	14	17	15	15	16	14

6.4.6 Changes in the Nature of Work

Gosine and Warrian (2017) predicts that middle-income and middle-skill jobs may be replaced by automation while the demand for high-skill jobs increases. However, Gosine and Warrian (2017) cites Hollinger revealing that machines may not entirely replace human but work together with humans as collaborative robots. Collaborative robots are ideal for work scenarios where human judgement is required while the physical environment has ergonomic challenges. Gosine and Warrian further revealed that human-robot collaboration in some activities is more productive than robots or humans working alone. *McKinsey and Company (2018)* reported that robotics and automation are removing miners from the dangerous mining environment. In Western Australia, miners using autonomous haulage systems have had a 20% increase in productivity. *McKinsey and Company* further reported that technology adoption may help reduce the industry’s footprint on the environment by having operations which are lean with low-energy consumption.

Automation can transform the mining industry to becoming safer, productive, efficient, sustainable and profitable (Husseini, 2018). Therefore, the mining industry will be better equipped to face the challenges it encounters. Through automation, machinery can be able to independently make decisions even when changes occur in the systems. Jacobs and Webber-Youngman (2017) revealed that the implementation of technology such as automation has potential to reduce human error as mines are a very hazardous and inconvenient workplace (Husseini, 2018). Sadullah and Kanten (2009) confirmed that the behaviour and unsafe practices of employees can cause accidents in the workplace hence, automating production has potential to eliminate human error in the workplace.

With the use of an anthropomorphic robot, a robot that mimics human behaviour, human activities which are repetitive can be replaced (Jacobs & Webber-Youngman, 2017). However, Gosine and Warrian (2017) introduces the concept of 'automation anxiety'. This is the fear of the impact of automation on people's work, life, safety, and its capacity to replace human labour and expertise. Lööw, et al. (2019) confirmed the introduction of technology may accompany worker-anxiety. By having fewer employees at the mine site, operators may find themselves working longer hours and often on standby which may create psychological strain and anxiety.

According to Johansson, et al. (2010), working rotative shifts has become more common over the last decade. This is mostly common in mines with fewer employees. There are fears that working rotative shifts will result in working longer hours therefore, inducing fatigue and stress amongst workers. Johansson, et al. (2010) revealed a study conducted by Dembe et al. investigating the impact of long working hours on workers and found that working at least 12 hours a day was associated with a 37% increased hazard rate while working at least 60 hours per week was associated with a 23% increased hazard rate. Employers and labour unions will have to agree upon shift rotation and working hours to avoid overtime and extended work hours (Johansson, et al., 2010).

6.4.7 Upgrade Training Facilities

Mining operations must upgrade their current training facilities as well as change their employee development programmes to include digital technology. There needs to be understanding of the roles that are required in the digital mine and offer the necessary training. This is because the implementation of Mining 4.0 will result in work which is remotely controlled therefore, changing labour relations as well (Lööw, et al., 2019). Higher institutions must also upgrade their curriculum to supply the mining industry with mining engineering graduates who have digital knowledge. The digital knowledge taught in these institutions must align with the digital underground mining environment.

6.4.8 Implement Changes to the Mining Layout

World Economic Forum (2017) reported that the adoption of Mining 4.0 increases productivity. Therefore, there may be changes that must be implemented on the current mining cycle and haulage fleet to accommodate the increased tonnage output. For example, Rupprecht (2013) revealed that the current cleaning methods using scraper winches can only accommodate face advance not more than one metre per day. Any face advance more than this will require changes to the layout and the type of cleaning equipment used. It would defeat the purpose of introducing digital technology in narrow-reef mines if blasted tonnes do not reach the plant timeously. Studies should therefore be conducted to determine which processes within the production phase should be modified to accommodate the higher tonnage output. Through IoT it will be possible to track production in real-time and determine where inconsistencies occur from underground to the plant. This would ensure an increase in MCF and a higher gold recovery rate.

The complex geology of gold mines including presence of low stoping heights and marginal grades have slowed the introduction of mechanisation in the gold mines (Vogt & Hattingh, 2016). Fortunately, Mining 4.0 offers the industry the ability to mine lower grade reserves at a profit thereby, increasing profitability and life of mine. Each mining operation would then have to conduct studies to determine the new cut-off grade. Therefore, extensive studies would have to be done in each operation to determine the changes that will be brought forth in the mining cycle due to the introduction of technology. It should then be expected that digitalising the industry will not be an overnight process, it may take a considerable amount of time.

6.4.9 Upgrade Infrastructure

Maasz and Darwish (2018) have found that there has been less successful technology implementation within the mining industry of South Africa due to the lack of internet connection and communication technology on site. Therefore, there is need to upgrade existing infrastructure. However, there are costs constraints associated with upgrading existing infrastructure that must be considered. The implementation of Mining 4.0 may not come cheap, there will be high costs associated with the installation and maintenance of systems. *Deloitte (2017)* attribute the slow adoption of technology in South Africa to the lack of investment towards new technology. Therefore, the mining industry must be willing to invest in new technology.

Developing underground networks such as Wi-Fi or 5G wireless technology for communication enables real-time communication of personnel. However, this communication would have to be installed and extended as the face advances (McKinsey & Company, 2018). Since the distance to working places can be several kilometres from the level station, it is costly to continuously extend these sensors throughout the mine. Therefore, smart sensors may have to installed only in working areas or abandoned areas which need to be monitored as covering the whole mine boundary may be costly. In addition, because some mining operations are close to each other, it is crucial to also establish communication boundaries in order to prevent different mines from accessing each other's information without permission.

6.4.10 The Impact of New Technology on Mining Regulation and Legislation

Occupational injuries and fatalities have been on a steady decline since 1996. It was in 1996 that the MHSA came into effect and gave rise to legislation such as Section 22 and Section 23 of the Act. Section 22 of the MHSA effectively states that every employee has a right to take care of their health and safety, as well as that of their co-workers (Mine Health and Safety Inspectorate, 2016). Section 23 states that every employee has a right to withdraw from any dangerous situation at work which may threaten their health and safety. Section 22 and 23 of the MHSA have therefore given mine employees a right to withdraw should they believe their safety is at risk. *Minerals Council of South Africa (2019e)* confirmed that the introduction of regulatory structures such as MHSA has contributed to the decline of fatality rates in the mining industry. Although the introduction of new technology may be the step change the industry needs to obtain zero-harm, this may require the amendment of different mining legislation such as the MHSA for provision of new digital technology.

The DMR facilitates the safe mining of mineral resources in South Africa therefore, there will be new amendments required on the existing mine regulations to monitor the safety of employees. The DMR also issues various mining qualifications for the mining industry; these qualifications will also have to be amended to include Mining 4.0. In addition, mining companies and stakeholders will have to work together to amend the current mine standards to improve the safety of employees through Mining 4.0 yet ensure their rights are not violated in the process. This is because adopting certain technologies such as geospatial tracking systems should not be used as a policing measure by the employer, but a safety measure to protect workers. Moreover, because of the change of the nature of work due to Mining 4.0, mining companies will have to upgrade their current training syllabus and facilities to incorporate Mining 4.0. Therefore, the current mining legislation and regulation will have to be amended in the process.

The MHSC was established in 1996 to advice the Minister of Minerals Resources and Energy on issues of health and safety as well as the challenges the industry encounters. Over the years the Council has established several forums and campaigns to influence a safe culture in the mining industry to ensure each mining worker goes home safe after each shift at work. These campaigns are in the quest to "drive and sustain the mining industry's pursuit of zero harm";

these include Zero Harm, Mining Occupational Safety and Health (MOSH) and the recently launched Khumbul'ekhaya campaign (Minerals Council of South Africa, 2019g). Therefore, the MHSC will have to introduce new campaigns and strategies that take into consideration the adoption of digital technology in the workplace.

6.4.11 The Mine of The Future: A Zero-Entry Mine

Ultimately, zero harm can only be guaranteed by not having any miners working underground as no one would be exposed to the hazardous underground environment (Johansson, et al., 2010). Although there have not been sufficient studies done on the subject of Industry 4.0 and Mining 4.0 within South African deep-level mining context, the industry should advance in research to ensure that the zero-entry mine is a possibility in the near future. The concept of a zero-entry mine is a vision that the South African deep-level mining industry should have for the future. Joseph (2020) predicts Industry 5.0 will involve AI therefore, the adoption of Industry 5.0 in the mining environment, Mining 5.0, could be the start of developing zero-entry mines.

Although failure should be expected, the industry should not aim to fail. It should also be considered that not all mining operations will reap the benefits of Mining 4.0. Some mines may attempt to adopt Mining 4.0 but later find the systems too complex therefore, possibility of failure should be considered. Therefore, there must be contingency plans should the implementation and algorithms fail. These measures must be in place to be able to correct these failures before it disrupts the functionality of the mine. The purpose of the system and the problems that can be anticipated with its use have to be known ahead of installation. However, whether the adoption fails or thrives; employees, stakeholders, community will continue having expectations from the industry which put financial pressure on the already struggling industry.

The gold mining industry can learn from previous experiences and failures concerning the implementation of technology in the sector such as the failed attempt of introducing mechanisation in the narrow-reef gold mines (Pickering, 2007). These past experiences will offer guidance on the challenges that can be expected and how they can be solved. There are many lessons that can be drawn from the implementation of mechanisation in the narrow-reef mines. For example, Willis, et al. (2004) reported that mechanisation did not only increase labour efficiency but the overall productivity of the operation as well. However, this was not achieved at lower unit labour costs. The higher skilled labours were paid higher and only a few were required.

Willis, et al. (2004) reported that having fewer employees underground has the additional benefit of easier transport logistics and lower fixed labour overheads. Higher productivity in mechanised operations was achieved through the integration of technologies to ensure higher face advance rates were achieved. A higher face advance resulted in reduced face length which in turn ensured the mine's labour and infrastructure were better utilised. When the face had a shorter face length, there was better supervision and control therefore, made it easier to introduce more technology on the face (Willis, et al., 2004). There was also the benefit of better communication and environmental conditions offered due to fewer personnel present at the face. Willis, et al. further reported that although the introduction of mechanisation did reduce the number of people exposed to occupational risks and hazards underground, the introduction therein also gave rise to other risks.

6.5 Challenges Of Digitalising the Conventional Deep-Level Gold Mining Industry

The gold industry encounters volatile gold prices which make long term strategic planning difficult, Figure 32. This volatility in the gold price is due to external factors such as the world economic climate and is beyond the control of the industry. According to Neingo and Tholana (2016), the gold price influences revenue, cashflow, profitability and mineral asset values. The mining industry is a price taker and is unable to predict commodity prices hence premature mine closures can occur as the industry fails to operate optimally. Although Mining 4.0 is expected to increase safety and profitability in mining operations, volatility in the gold price affects the industry's confidence to invest in new technology. Listed below are other challenges that can be expected with implementing Mining 4.0 in the conventional gold mining industry.

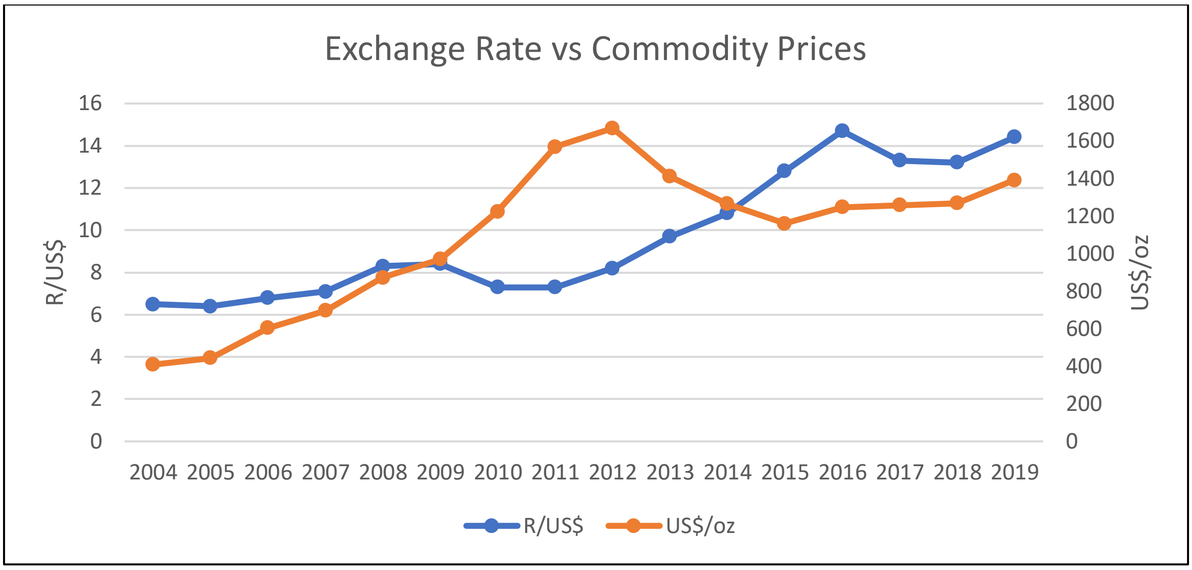


Figure 32: Exchange Rate vs Commodity Prices: 2004-2019 (Minerals Council South Africa, 2014; Minerals Council South Africa, 2020b)

6.5.1 Retrofitting Technology into the Complex Narrow-Reef Environment

Maasz and Darwish (2018) revealed that the South African mining industry has been slow in embracing technology because it is hard to introduce new technology in the complex environment. This is because South African gold mining industry generally has mature infrastructure and underground working places that are remote from each other and far away from the shaft area. The implemented digital systems should consider the characteristics of these deep-level mines such as the depth of underground workings and distances to working places. Therefore, the installed digital systems should be able to operate several kilometres below surface and be able to communicate several kilometres from the level station to the different working areas. The technology implemented should also consider the dimensions of the stope as well as the restrictions inside the panel as illustrated in Figure 33. In addition, the underground gold mining environment is dark, humid, and characterised by seismic events. The systems installed should therefore be suitable to use under these conditions.

Figure 33: Low Stoping Width in Narrow-reef Mining (Montiea, 2015)

Gosine and Warrian (2017) cites Jensen revealing that there are challenges of integrating automation technology in already existing mines. It will therefore be harder to introduce new systems to an existing mine than greenfield projects because the technology must be retrofit to the existing mine (Ramdoo, 2019). Due to the complexity in nature of gold mines, it can be expected that not all activities can be automated. Therefore, an operation should conduct extensive studies to determine work processes which cannot be automated, and what can be done to make work safer for the employees who are involved in that line of work.

6.5.2 Electricity Shortages

Eskom is the main electricity supplier in South Africa and NERSA continuously implements tariff increases. Langenhoven (2019) predicts that high electricity tariffs will accelerate job losses in energy-intensive mines. Figure 34 illustrates that the electricity tariffs implemented by Eskom in the past decade are higher than the inflation rate. In addition to high tariff increases, Eskom faces electricity shortages which affect the ability of mining operations to function. Although the implementation of digital systems may reduce energy requirements and energy costs, digital systems are highly reliant on electricity for communication to transmit information to different systems. Hence, electricity supply must always be available for the mine to run efficiently. Therefore, the ability for the gold mining industry to secure and afford a stable electricity supply comes into question. Mining operations can consider combating electricity shortages by means of large-scale generators as backup.

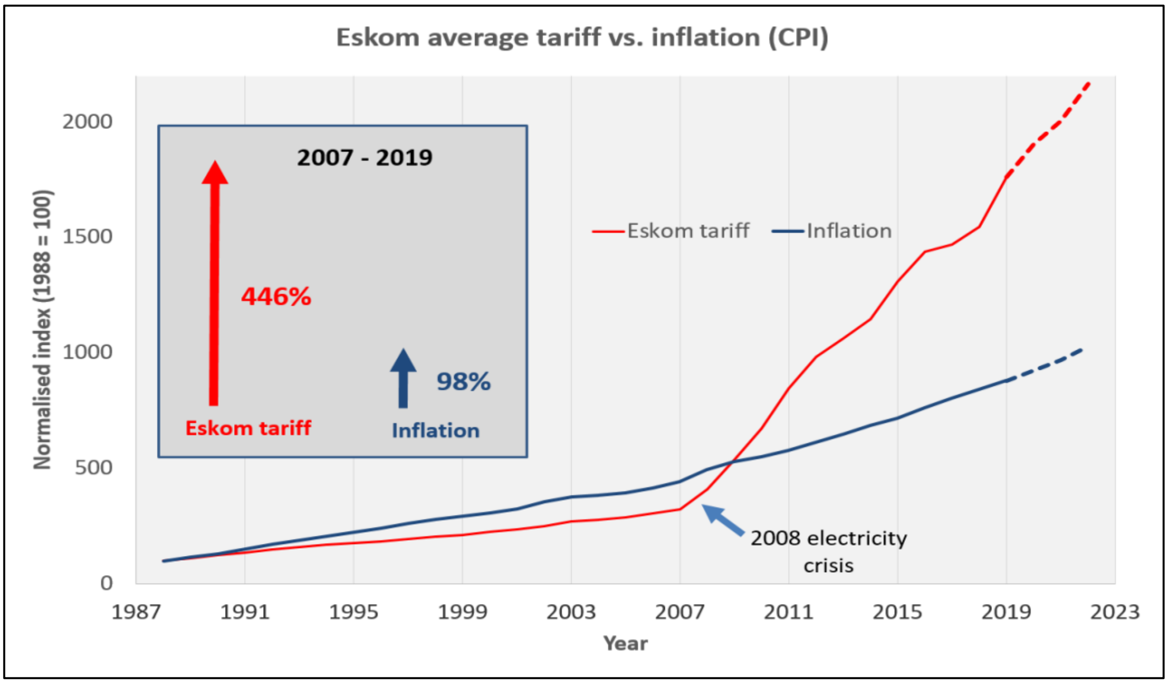


Figure 34: Electricity Tariff Increase (Moolman, 2019)

6.5.3 Cyber Risks

There are cyber risks and privacy concerns associated with the use of Industry 4.0 technologies as they are dependent on the flow of data via a network connected to the internet. By using the internet as primary means of operating and communicating, mining operations open themselves to serious cyber-attacks where hackers can gain access to private information thus, posing a threat to confidential data. Maasz and Darwish (2018) reported that Big Data databases can store huge amounts of data, which can pose a threat to confidential information when breached. This means the traditional information and communications technology (ICT) security measures are not enough to protect an operation. An attack on an enterprise can affect a large area and has the potential to disturb the functionality of the entire operation. This is because the output of one system can be the input to another system. Due to the lack of experience of using digital systems in the South African deep-level mining context, the extent of potential cyber threats and consequences thereof is still unknown. Mining companies are still uncertain regarding the level of protection required against potential cyber threats and attacks. Figure 35 illustrates the various threats that can be anticipated, their consequence and measures to mitigate them.

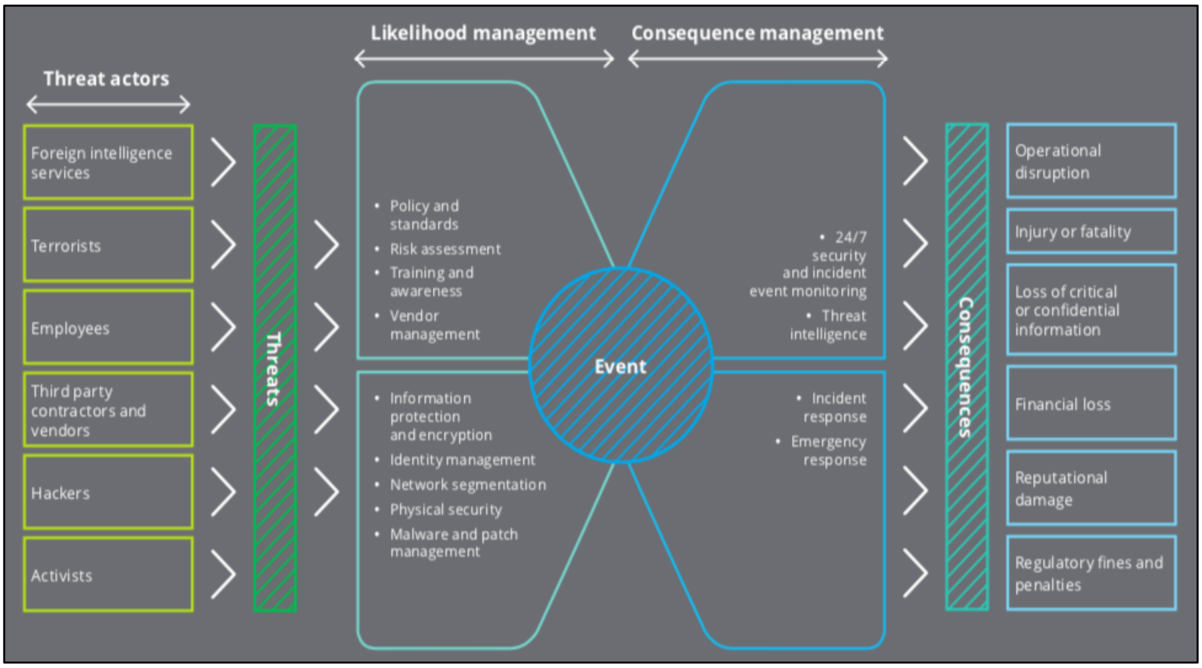


Figure 35: Cyber Risk Bowtie Analysis for Mining Companies (Deloitte, 2018c)

6.5.4 Job Losses in the Industry

Although industries are having conversations about Industry 4.0, the adoption thereof in South Africa is still relatively low compared to the rest of the world. This is because the country is not yet fully geared on implementation and *Deloitte (2017)* attribute this slow adoption to the fear of job losses. According to Muir (2015), the conventional gold mining industry requires a lower skillset compared to other mining sectors and this has caused fear that embracing new technology may accelerate job losses in the industry. Morrar, et al. (2017) reported that it is certain that some jobs in the future will be redundant or obsolete due to the automation and digitalisation of production. Abrahamsson and Johansson (2009) predicts that the implementation of Mining 4.0 into the mining industry may not only see the removal of miners from dangerous working places but also result in fewer employees required to work in a mining operation.

Although some industries such as the coal and iron ore industries have had an increase in the number of employees, the possibility of workforce reduction in the conventional mining industry should be considered. Ramdoo (2019) revealed a study conducted by McKinsey Global Institute revealing that by 2025, 30% of commercial trucks will be automated, reducing accidents by 70-90% while resulting in an 80-90% reduction in employment. Although new employment will be created by technology, the areas in which new employment will be created by technology is so far still unknown (Ramdoo, 2019). The gold mining industry is infamous for long and violent labour strikes and the reduction of labour could possibly induce more labour tension in the industry. The reduction of labour in the gold mining industry will directly affect the employment rate. Figure 36 illustrates that in 2019 the unemployment rate was the highest recorded in the past decade. High unemployment rate has a direct impact on poverty levels and inequality.

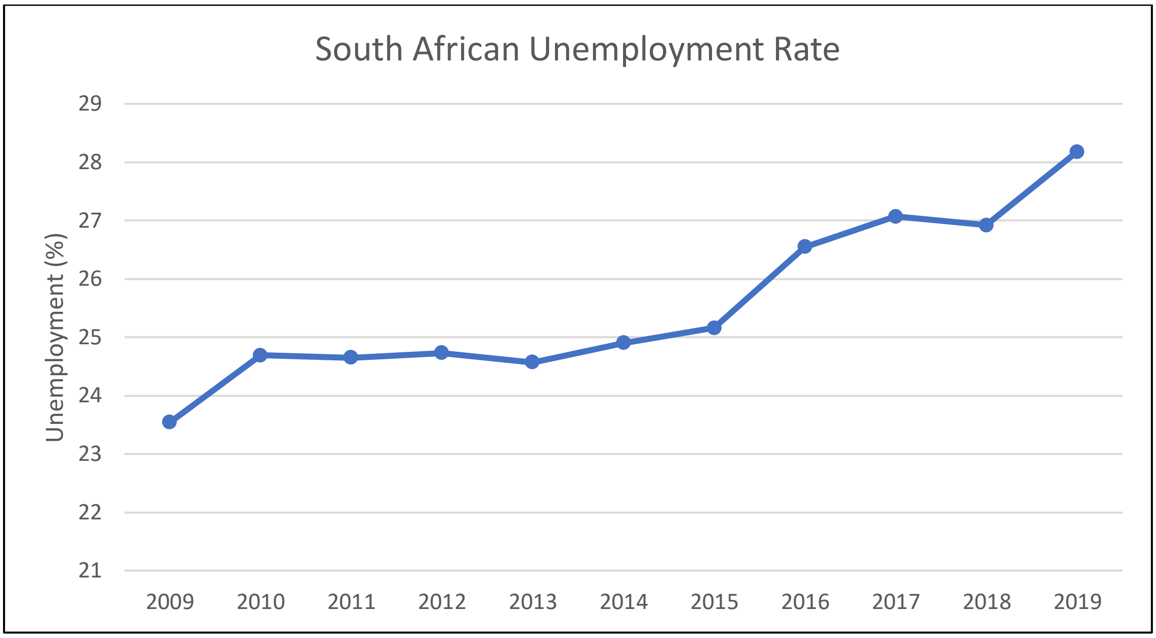


Figure 36: Unemployment Rate in South Africa: 2009-2019 (Plecher, 2020)

6.5.5 The Lack of Digital Skills and Expertise

Although the world has transition to a digital age with artificial intelligence and robotics, Schwab (2016) revealed that the human touch can never be replaced and will always remain fundamental in any industry and institution. It can be guaranteed that employees will not be entirely replaced by machines but will be working alongside them (Lööw, et al., 2019). This is because Industry 4.0 aims to integrate humans and machines through IoT (Sukiennik, 2018). However, Lööw, et al. (2019) argued that low skilled workers are likely to be negatively affected by the introduction of new technology. This is while Muir (2015) reported that an illiterate workforce dominates the conventional mines of South Africa. Therefore, the digital transformation of the industry may further put spotlight on the industry's lack of skilled and educated personnel.

While South Africa is said to produce more mining engineers than any other English-speaking country, Muir (2015) reported that majority of mining engineering graduates tend to leave the country for countries such as Canada and Australia. Muir further reported that of the 75% mining engineering graduates who join the mining industry after graduating, only 15% remain in the industry long-term. This is because employment in the mining industry is not always considered ideal because of the adverse working conditions (Moraka & Jansen van Rensburg, 2015). This has put a massive skills and expertise gap in the industry. According to Husseini (2018), the main barrier preventing the mining industry from attracting new graduates is old technology. This has resulted in stagnation of the job market as the older and aging generation are the only people with industry skills.

The shortage of skills and expertise in the fields of mining and digitalisation in South Africa poses a challenge to the digital transformation of the industry. *Deloitte (2017)* revealed South Africa has also fallen short of Industry 4.0 professionals and although the experienced workforce has deep industry knowledge, the aged workforce may find it difficult to work with digital tools once digital transformation is in full motion (World Economic Forum, 2017). The mining industry has to then decide to either invest in the training of existing employees or find a new workforce, which is familiar with digital tools. It can be expected that the latter will be met with strong opposition from labour unions and may even result in labour strikes in the industry.

Johansson, et al. (2010) states the mining industry needs to attract and recruit young talent by creating attractive mining workplaces that engage and motivates those who are not thrilled at the thought of working in the mining industry today. Johansson, et al. (2010) further revealed that there is a lack of skilled miners and mining engineers while the experienced workforce is ageing, and companies are struggling to recruit young talent. To attract talent to the mining industry, Johansson, et al. (2010) suggests that the industry creates career paths that are also inclusive to women. In addition, Johansson, et al. revealed that well-motivated employees are prerequisite for high productivity. Increasing wages alone is not enough, employees can be motivated by having a clearly defined career path which progresses though training and exposure (Johansson, et al., 2010). Therefore, a cooperation between government and the mining sector is required to address the skills shortages that will be brought forth by Mining 4.0.

6.5.6 Resistance From Illegal Miners

According to *Mine Health and Safety Inspectorate (2019)*, there are on average four dead illegal miners who are retrieved from underground as a result of gassing, illnesses and gang violence every month. There are also an average of a hundred illegal miners who are arrested monthly underground. As the industry makes digital transformation, the industry must also work harder against illegal mining and the prohibited use of company infrastructure. Mining 4.0 has the potential to assist in the surveillance and monitoring of the mine's resources to prevent loss, damage and theft of company resources as a result of illegal mining. However, illegal miners can retaliate towards the installation of underground digital systems as it will interfere with their illegal activities. The mining industry must then have strategies to mitigate resistance from illegal miners.

6.6 Summary and Conclusion

There must be collaboration between the industry, stakeholders, labour, vendors, and government in order to transform the South African mining industry. The level of commitment that goes into digitalising an operation must correspond to the yield in the ROI before the operation depletes its resources. This is because technology is not only implemented to promote safety but also to increase profitability. Therefore, before the industry can be digitally transformed the following considerations must be made:

- Understanding the need for innovation;
- Understanding that the scale of innovation per mine will differ;
- Implementing an open innovation approach;
- The impact the influence of labour towards the innovation;
- The required changes to the workforce;
- The required changes to the nature of work;
- Upgrading training facilities;
- Improving machines so that mechanisation is successful;
- Implementing changes to the mining layout;
- Upgrading infrastructure;
- Understanding the impact of new technology on mining regulation and legislation; and
- Envision the mine of the future as a zero-entry operation.

Although digitalisation may result in new occupational hazards that were previously not there in the underground mining environment, these hazards must be well understood and mitigated. It is also crucial for mining operations to gauge the readiness and willingness of its employees to change. Companies should engage with employees from the early stages to promote transparency. The following challenges must also be anticipated with digitalising the narrow-reef mining industry:

- Attempting to retrofit technology into the complex narrow-reef environment;
- Electricity shortages;
- Cyber risks;
- Increasing job losses;
- Lack of digital skills and expertise; and
- Resistance from illegal miners.

In conclusion, unless the South African mining industry accelerates the introduction of new technology, it will remain unsafe. The digitalisation of the South African conventional deep-level mining industry should also take into consideration the nature and complexity of the industry as the narrow-reef gold mines in the country are some of the deepest mines in the world. The mining industry should also consider that the implementation of some technologies such as geospatial tracking devices can be perceived as crossing privacy boundaries and may not be well received by employees. Therefore, the most vital finding from this chapter is that it is important for mining companies to communicate with their employees regarding the digital transformation of the industry to prevent worker-resistance.

Digitalising the narrow-reef gold mining industry will not be achieved overnight, it will be a process and the industry must gear itself for the changes that will be brough forth. There is a need to understand the need for innovation in the industry otherwise it will only cost the industry money installing systems whose purpose is not understood. In addition, there should not only be funds going into research studies of innovative technology in the deep-level mining industry but there should be initiatives to ensure that such research is implemented. The next chapter, Chapter 7, is a conceptual blueprint for the modernisation of activities within the mining cycle at the conventional deep-level gold mine where the case study took place.

7 Conceptual Mine Modernisation Blueprint

Chapter 6 discussed the nature of work at a conventional deep-level gold mine by conducting a case study at the operation. The chapter also detailed the considerations that need to be made prior the digitalisation of the conventional mining industry. Chapter 6 also included the challenges that are likely to be encountered by the mining industry because of digital transformation. Chapter 7 will further use the data obtained at the conventional mine to create a conceptual mine modernisation blueprint. This conceptual mine modernisation blueprint includes all the activities that occur during the mining cycle and offers digital and autonomous technology to result in safer and efficient production.

7.1 Stages of Mine Modernisation

Mine modernisation can be defined as the use of modern and innovative technology to improve the state of mining operations. Figure 37 illustrates the stages to ensure an autonomous mining operation is ultimately achieved. Based on the data obtained from the case study of the conventional mine, the mining operation can move further up the mine modernisation path, from somewhere between conventional mining and mechanisation to automation, Figure 37. This is because for a mine to be modernised, there needs to be a level of mechanisation that currently does not exist at some conventional mines. After mechanisation, an operation can introduce digital mining and systems can be integrated. Thereafter, algorithms can be used for decision-making. This ultimately results in an autonomous mining operation, a mine of the future. Thus, Figure 37 enables us to understand where a certain mining operation is regarding modernisation and where there is still work to be done.

The International Society of Automation (2020) defined automation as the use of technology to monitor and control production, and the delivery of products and services. To automate production, work systems must be integrated, and this can be achieved through digitalisation. Digitalisation or digital transformation refers to “the changes associated with the application of digital technology to all aspects of human society” (Parviainen, et al., 2017, p. 64). Digitalisation allows collection of vast amounts of data of an operation in near real-time through remote but connected sensors (Husseini, 2018). This data can then be used to analyse trends and make informed decisions about the operation. The mining data that can be collected include how long ore loading equipment queues for ore and therefore, be able to make efficient use of equipment by reducing the idling time of equipment, etc. Through integrating systems, it is possible to determine the number of equipment that should be sent to a location at any given time thereby, reducing energy consumption and maintenance costs.

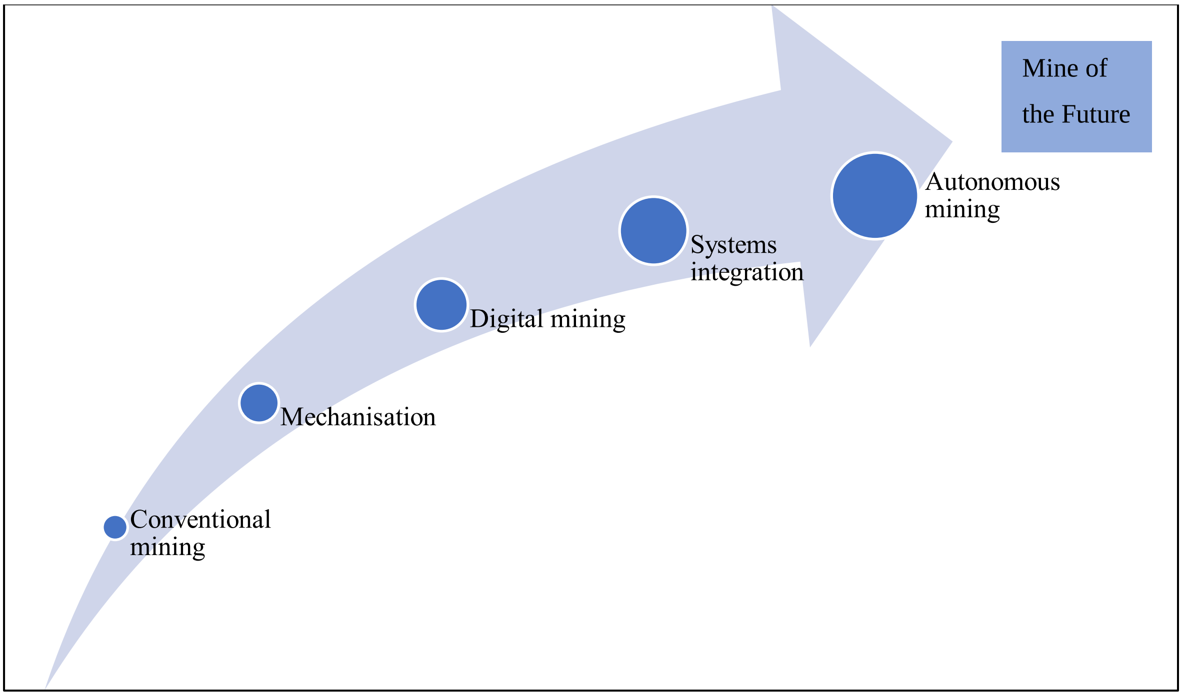
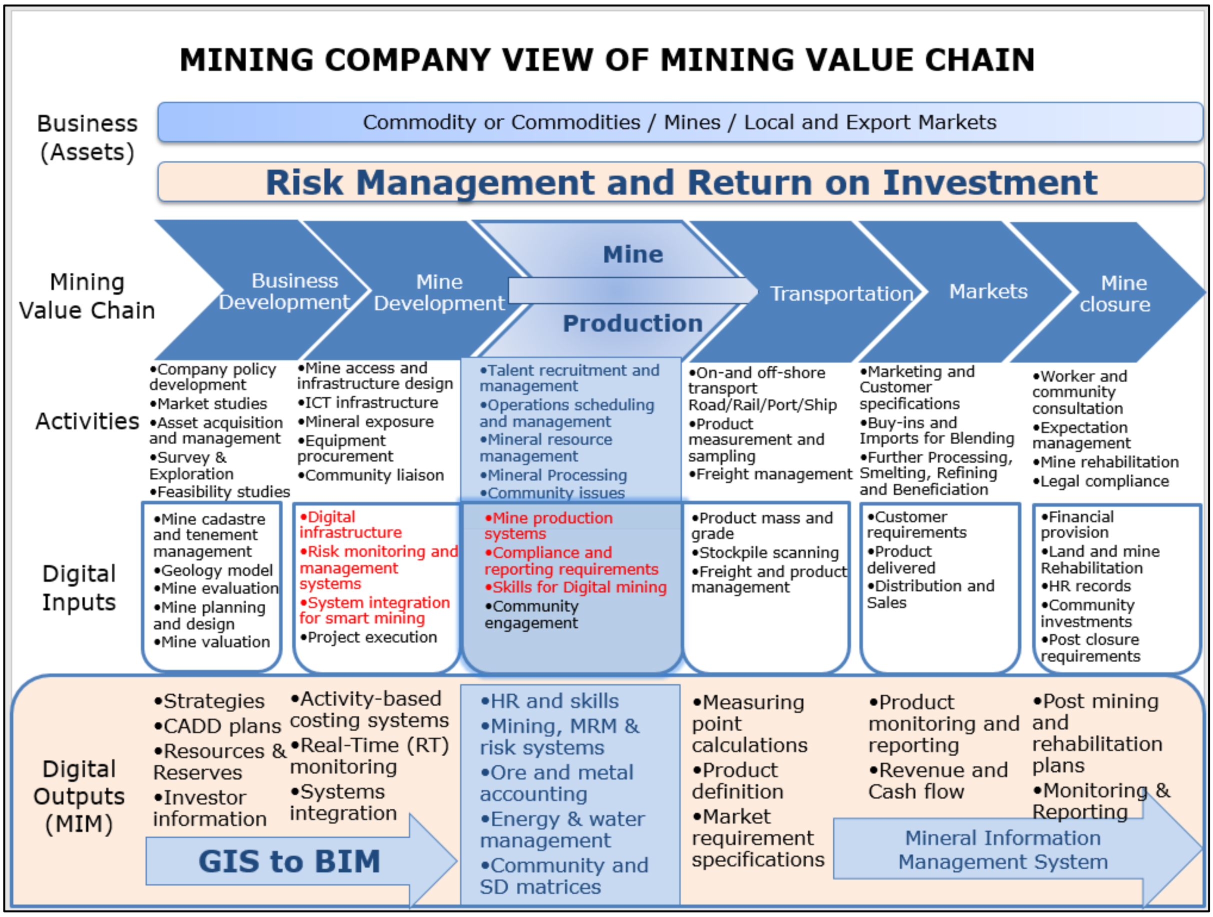


Figure 37: Stages of Mine Modernisation

Lottermoser (2017) added that the use of digital systems for sustainable development purposes includes ensuring environmental integrity, social responsibility and effective government and governance systems. Hargan (2016) echoed the previous author's views on the value proposition of digitalisation and defined digital innovation as "… the application of new technologies to existing business problems or practices." Hargan (2016) cited the following examples of digital innovation:

- Machine to machine communication for predictive maintenance to ensure safe and optimal use with minimum lost time;
- Connecting buyers and sellers in new ways, upsetting existing markets and influencing prices; and
- Extrapolating the abundant digital health products into the heavy industry workplace for worker care and awareness of risk.

In the foreword to the Industrial Policy Action Plan (IPAP) 2018/19 – 2020/21, *Department of Trade and Industry (2018)* reported Minister Rob Davies making an important link between mining and inclusive growth with this statement: "the mechanisation and digitisation of deep-level and above-ground mining processes require the mastery of complex industrial capabilities, including many technologies and disciplines associated with the digital industrial revolution." IPAP is a 'working' policy document with regular updates, it was first approved by Cabinet in 2007 in recognition of the importance of innovation for industrialisation in South Africa. Minister Davis' statement can be interpreted to digitalise beyond the mining stage to cover the entire MVC as illustrated in Figure 38. Minister Davies also emphasised the need for partnerships, tasking all partners to integrate innovation interventions at a firm level. This is because the activities in the mining cycle are linked; the output of one activity becomes the input for another activity. Therefore, there need to be collaboration between different systems to ensure smart mining through integration as an autonomous mine would be built on an ecosystem of various systems.



	Business Development	Mine Development	Mine Production	Transportation	Markets	Mine closure
Activities	•Company policy development •Market studies •Asset acquisition and management •Survey & Exploration •Feasibility studies	•Mine access and infrastructure design •ICT infrastructure •Mineral exposure •Equipment procurement •Community liaison	•Talent recruitment and management •Operations scheduling and management •Mineral resource management •Mineral Processing •Community issues	•On-and off-shore transport Road/Rail/Port/Ship •Product measurement and sampling •Freight management	•Marketing and Customer specifications •Buy-ins and Imports for Blending •Further Processing, Smelting, Refining and Beneficiation	•Worker and community consultation •Expectation management •Mine rehabilitation •Legal compliance
Digital Inputs	•Mine cadastre and tenement management •Geology model •Mine evaluation •Mine planning and design •Mine valuation	•Digital infrastructure •Risk monitoring and management systems •System integration for smart mining •Project execution	•Mine production systems •Compliance and reporting requirements •Skills for Digital mining •Community engagement	•Product mass and grade •Stockpile scanning •Freight and product management	•Customer requirements •Product delivered •Distribution and Sales	•Financial provision •Land and mine Rehabilitation •HR records •Community investments •Post closure requirements
Digital Outputs (MIM)	•Strategies •CADD plans •Resources & Reserves •Investor information	•Activity-based costing systems •Real-Time (RT) monitoring •Systems integration	•HR and skills •Mining, MRM & risk systems •Ore and metal accounting •Energy & water management •Community and SD matrices	•Measuring point calculations •Product definition •Market requirement specifications	•Product monitoring and reporting •Revenue and Cash flow	•Post mining and rehabilitation plans •Monitoring & Reporting

Figure 38: Interdependence of Digitalisation Factors along the Mining Value Chain (Cawood, 2019c)

Using smart sensors and software, worker safety has improved in Rio Tinto's Pilbara mine; workers are no longer exposed to hazards associated with fatigue, noise and dust associated with the use of equipment (Crawford, 2018). Hence, automation through the use of digital technology not only increases production but safety as well. Therefore, it is important for the decaying conventional deep-level gold mining industry to improve the current state of working conditions underground. The following section details the blueprint to modernise the various stages of the mining cycle at the conventional deep-level mine where the study took place.

7.2 Conceptual Mine Modernisation Blueprint for the Mining Cycle

To create a conceptual mine modernisation blueprint for the conventional mine, Appendix 2 was expanded using the Goalscape software. Goalscape is a software that can be used to break down complex challenges in a meaningful way (Baur, 2020). Goalscape enables one to clearly define goals, rate goals according to importance and determine the responsible persons to accomplish the outlined goals. The software also determines the overall progress into achieving the primary goal by calculating the percentage progress of each individual goal. Therefore, the software user can see the impact each individual goal has on the overall system. Goalscape offers a roadmap illustrating the journey towards achieving a particular goal by clearly stating the different inputs and outputs required to achieve the goal.

The purpose of this chapter is to modernise the production phase of the MVC. To determine how activities in the production phase of the MVC can be modernised, Goalscape was used to simplify these activities. This blueprint for the production phase of the MVC consists of four segments, Figure 39. The first segment highlights the various stages of the mining cycle: early-entry examination, supporting of excavations, marking, and drilling, charging and blasting, cleaning and loading of blasted ore. The first segment also includes different factors which have an influence on a working stope panel. These factors include underground environmental conditions, labour and reporting and communication. The work conducted in each of these different stages of the mining cycle was detailed in Chapter 6.2.

The second segment of the diagram illustrated in Figure 39, are the different challenges that occur during each stage of the mining cycle. This section was coined from Table 8. The third segment explains how each of the mentioned challenges on the second segment can be resolved. This allows the Goalscape user to input different subgoals in a simplified manner. The last segment of the diagram identifies autonomous and digital solutions to address the challenges addressed by the second segment. Goalscape also enables the user to rate the importance and progress to achieve a particular goal. For the purpose of this study, the importance of all the subgoals was equalised. Hereinafter, Figure 39 is used as a legend to illustrate the stage each autonomous production blueprint represents. The particular stage will be highlighted and shown on the top right corner of each blueprint.

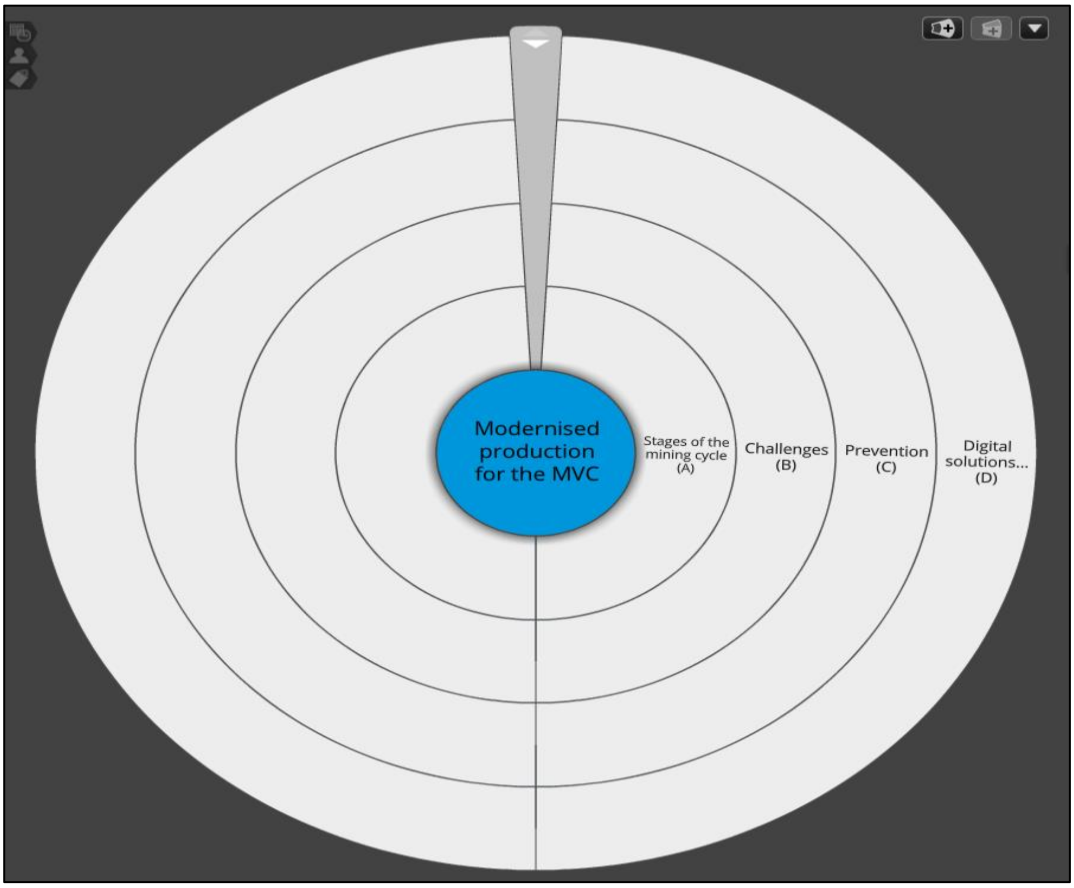


Figure 39: Autonomous Mining Cycle

Improving safety and production of deep-level mines can be achieved through the development of smart mines where Industry 4.0 technologies such as IoT, big data, CPS, VR, AR and AI are the backbone of such an operation. As this section details the conceptual mine modernisation blueprint for the activities in the mining cycle, each stage of the mining cycle was divided into subgoals to determine how automation and digital systems can be implemented in the various activities within the mining cycle to minimize risk and increase efficiencies. In order to determine the current state of modernisation at the conventional gold mine where the study took place, the author estimated the percentage progress on the adoption of each of the mentioned digital technologies highlighted in the fourth segment of Figure 39. The rating shown in Table 10 was used to measure the scale of modernisation at the operation. A 100% rating would mean the activity has been fully modernised. It was found through the case study that a partial adoption of modernisation of 50% was the highest achieved at this particular mine.

Table 10: Current State of Mine Modernisation in the Mining Cycle: Conventional Gold Mine Case Study

Progress rating criteria	**State of technology adoption (%)**
Only conceptual studies have been done on the adoption of the technology	15%
A similar yet conventional technology has been implemented	20%
Advanced technology has been implemented	25%
Automation/ digital technology has been adopted	50%

7.2.1 Early-Entry Examination Blueprint

The first stage of the mining cycle is early-entry examination. Figure 40 illustrates the various challenges that are encountered during the early-entry examination stage of the mining cycle. Early-entry examination is conducted to declare the stope safe prior proceeding with mining activities. If this stage is improperly done, miners can be exposed to many hazards such as falls of ground, toxic gases, dust, and heat strokes. During this stage, production can be also compromised if compressed air and water flow to the stope panels are not monitored. This is because leakages along the pipes can cause significant disruption in the delivery of compressed air and water to working places. Figure 41 shows the output the proposed technology should have to address the challenges raised in Figure 40. The installed digital systems should enable the inspection of hazardous workplaces without compromising the health and safety of employees. There should be monitoring and mitigation of hazards because of falls of ground and geological discontinuities. In addition, the supply of water and compressed air to the stope should be monitored.

Figure 40: Challenges During Early-entry Examination

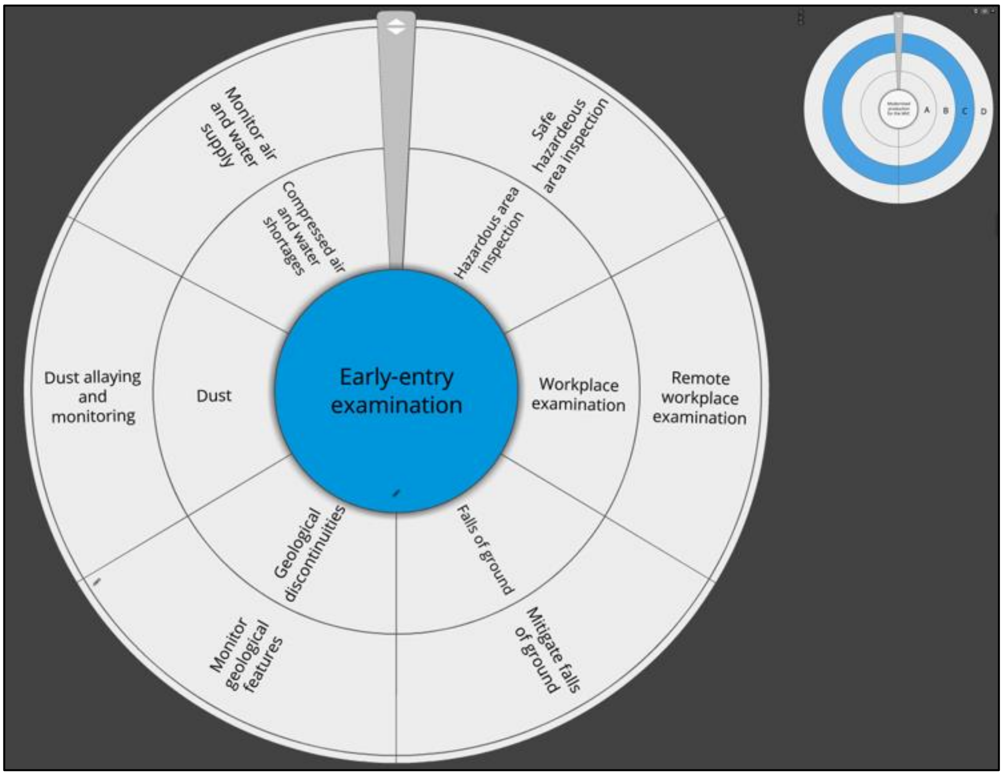


Figure 41: Output of Proposed Technology During Early-entry Examination

Figure 42 illustrates technology which can be adopted to achieve the outputs shown on Figure 41. The technology selected in Figure 42 relies on the installation of smart sensors and software. UAV's and safety robots can be used to remotely conduct early-entry examination before the crew enters the stope. CSIR has developed a remotely controlled safety robot small enough to maneuverer in narrow-reef stopes. This safety robot can detect loose rocks on the hangingwall through a thermal sensor. This is because loose rocks tend to be cooler in temperature than solid rocks. (Campbell, 2018).

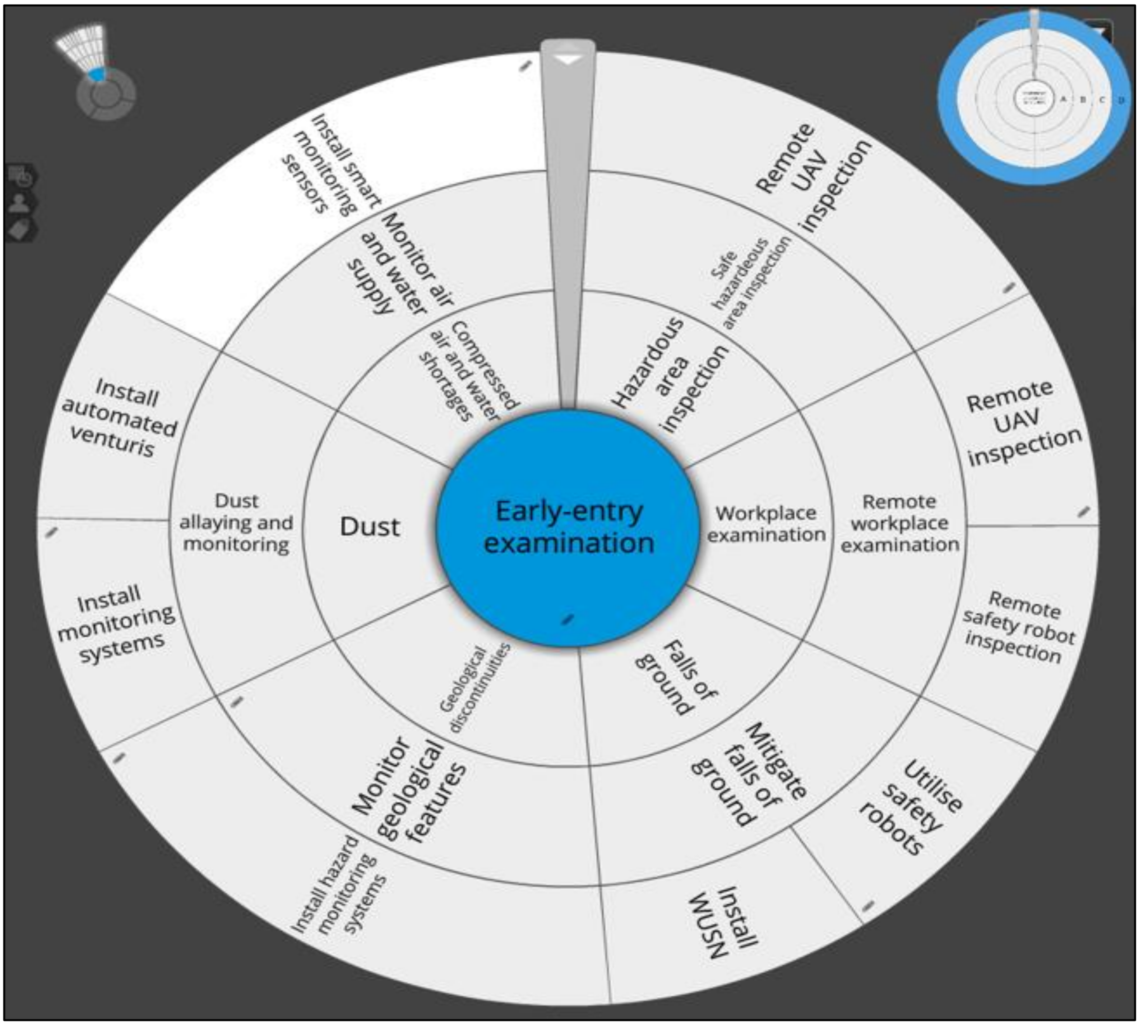


Figure 42: Digital Technology for the Early-entry Examination Phase

It has been previously stated in Table 4 that most falls of ground incidents are due to gravity therefore, the use of the safety robot will give sufficient warning of loose rocks to ensure the crew conducts proper barring. Falls of ground can also be mitigated by monitoring the seismic activity of the stope panel in real-time. This is while UAV's can be used to inspect inaccessible places such as orepasses. Unlike safety robots, UAV's are aeronautical and therefore, have better reach. Although stopes are characterised by geological features such as faults, dykes, brows, etc., the adoption of 4D geotechnical hazard assessing systems enables the monitoring of discontinuities in real-time. Hence, ensure the tracking and understanding of rock behaviour in response to mining activities.

Silicosis because of underground silica dust is referred to as a silent killer as it can go for many years undetected in the human body. However, once the symptoms begin to manifest, they are deadly. Therefore, the monitoring of dust levels through fixed environmental monitoring systems is essential. It is also important to adopt automated venturis that water down stopes during early-entry examination and when high dust levels are detected during the shift. While the shortage of compressed air and water has a detrimental effect on production and safety of employees, the installation of smart sensors throughout service pipes can provide early detection and location of shortages thus, can be repaired quicker.

Table 11 was used to summarise the required technology to modernise the early-entry examination stage of the mining cycle. Table 11 also uses the rating criteria outlined on Table 10 to estimate the current state of technology adoption at the conventional mine. The percentage state of technology adoption outlined on Table 11 was used as an input on Goalscape. This is illustrated in Appendix 3; the shaded section of the diagram represents how much of the technology has been adopted. Goalscape estimated this stage to be 16% modernised. This is because little or no technology has been adopted during this stage of the mining cycle. Most of the technology that should be implemented during this stage, as outlined in Figure 42, are still in the conceptual studies phase and yet to be implemented at the mine.

For example, although there are conventional measuring gauges at the level station to measure compressed air and water flow to an underground working level, other technologies such as UAV, safety robots, WUSN, smart sensors, 4D hazard monitoring systems and environmental detecting systems have not yet been installed. Table 11 also highlights the availability of compatible digital systems at DigiMine to modernise the early-entry examination of the mining cycle. The case study of the systems at DigiMine illustrate that the existing systems can automate the initial phase of the mining cycle. Although DigiMine does not have a safety robot prototype, the MHSC UAV can perform the same function of remotely inspecting dangerous working places.

Table 11: Early-entry Examination: State of Readiness at Conventional Gold Mine

Required technology	**Example of digital system**	**State of adoption at conventional mine**	**Examples of similar digital systems installed at DigiMine**
Remote workplace inspection	UAV	15%	MHSC UAV
	Safety robot	15%	×
Mitigate of falls of ground	Digital safety system	20%	Ramjack, Sibanye-Stillwater seismicity system, VibraTech Geosonics
Monitor geological features	4D hazard monitoring system	15%	Gold Fields MVS Scanner, VibraTech Geosonics
Monitor environmental conditions	Smart sensors	15%	Schauenburg MIMACS, VibraTech Geosonics, BBE Vuma-live
Monitor of air and water supply	Smart monitoring sensors	20%	Reactore

7.2.2 Supporting of Excavation Blueprint

Figure 43 shows the challenges associated with the installation of support at the conventional mine. The support standards enforced at the conventional mine have been outlined in Table 5. Adhering to support standards ensures that there is adequate protection from falls of ground and minimises closure of the hangingwall. Due to the depth at which gold mining occurs, deep-level mining operations tend to leave bigger support pillars behind. Hence, *Minerals Council South Africa (2019a)* reported that there is an estimated 160Mt high-grade gold ore left as support pillars in the Wits Basin. Hence, Figure 44 shows the functions the proposed technologies should have to address the challenges outlined in Figure 43. Adopting twenty-first century mining should enable the monitoring of support compliance and increase the current higher pillar extraction rate. Modern technology should also monitor the supply of compressed air and water because without it, neither temporal nor permanent support can be installed inside the stope.

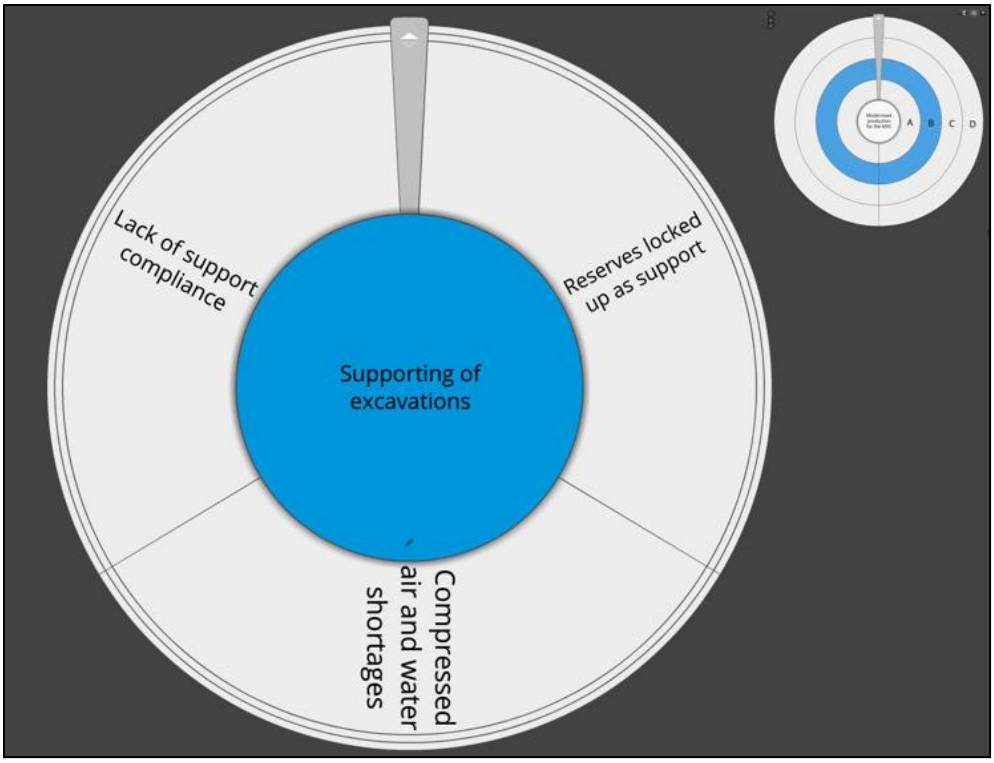


Figure 43: Challenges During Supporting of Excavations

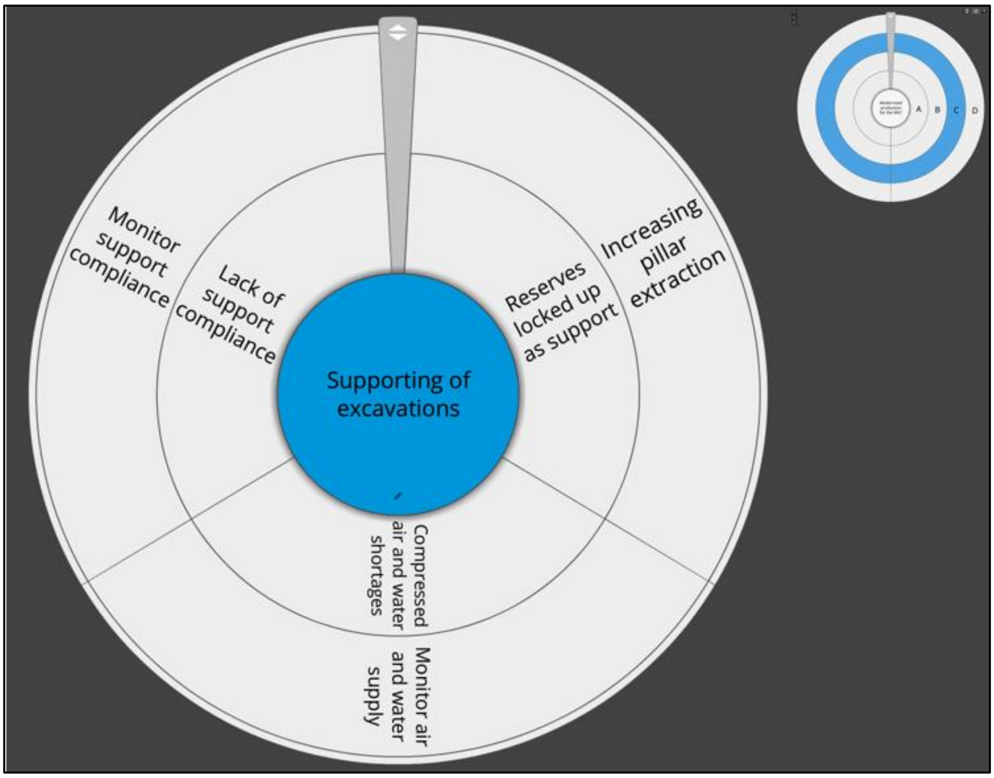


Figure 44: Output of Proposed Technology During Supporting of Excavations

Figure 45 highlights digital technologies that can be implemented during the supporting of excavations phase. The innovative technology that can be installed include 4D real-time reserves monitoring to increase pillar extraction. This is because reserves locked-up as pillars can be monitored in real-time, and algorithms can be used to offer the safe extraction thereof. Monitoring support compliance is essential to ensure support is installed according to mine standards. Currently, the safety and rock engineering department conduct visits to stope panels to determine support compliance however, these visits are not daily. Unfortunately, this results in miners becoming complacent and not making support installation a priority. Therefore, the use of UAV's would enforce support compliance with every shift.

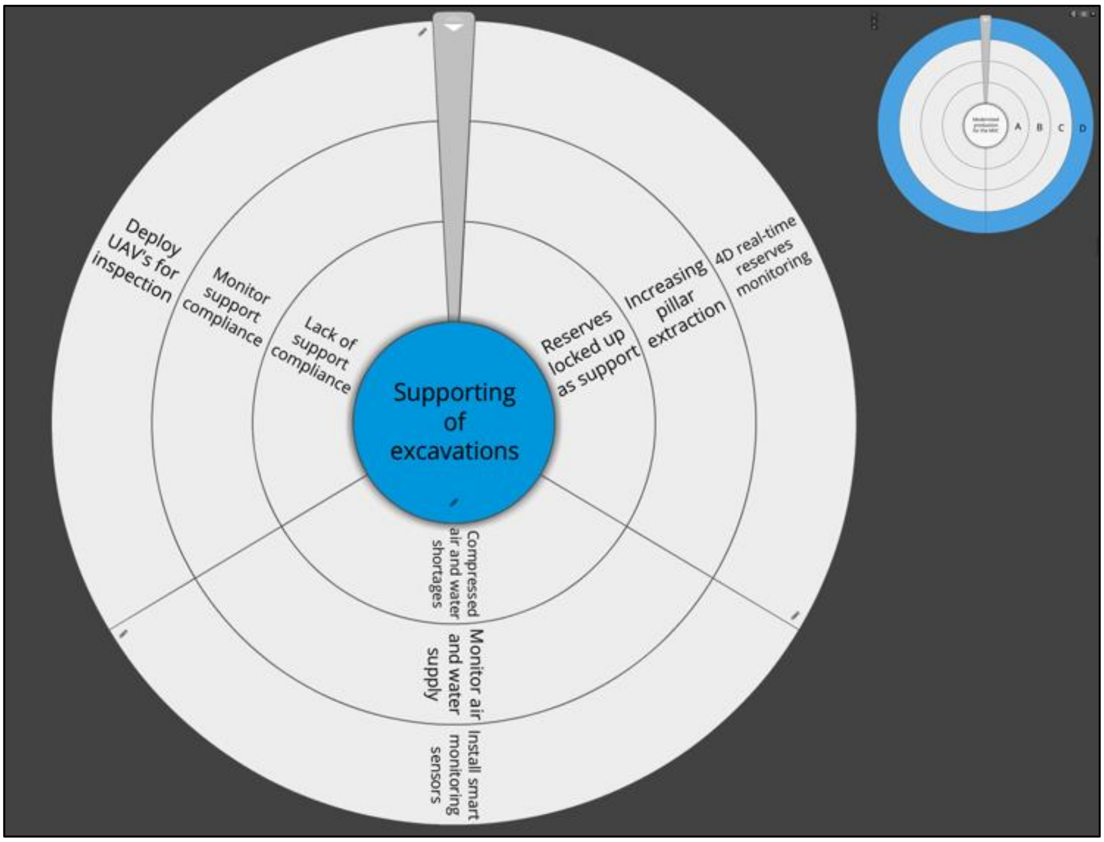


Figure 45: Digital Technology for the Supporting of Excavations Phase

Table 12 illustrates the state of readiness of adopting technology at the conventional mine where the case study took place by highlighting the percentage progress in modernising this stage of the mining cycle. Goalscape was also used to rate the overall percentage progress to modernise this stage. Appendix 4 illustrates that Goalscape has estimated the current state of modernisation during support installation at the conventional mine to be 20%. This is because the operation has adopted technologies similar to the ones outlined in Figure 45. For example, although the operation does not have 4D real-time reserves monitoring systems, the mine uses block modelling systems that give an estimate of the remaining reserves and grade. The use of 4D reserves monitoring systems would enable the monitoring of reserves in real-time and find alternative and safer extracting methods to mine complex reserves left in the form of stabilising pillars. Table 12 also shows systems available at DigiMine to automate the supporting of excavations stage of the mining cycle. These systems or similar, can be adopted at the conventional mine to fully automate this stage of the mining cycle.

Table 12: Supporting of Excavations: State of Readiness at Conventional Gold Mine

Required technology	**Example of digital system**	**State of adoption at conventional mine**	**Examples of similar digital systems installed at DigiMine**
Increase pillar extraction	4D reserves monitoring	25%	Gold Fields MVS Scanner
Monitor supply of air and water	Smart monitoring system	20%	Reactore
Monitor support compliance	UAV	15%	MHSC UAV

7.2.3 Marking and Drilling of Shotholes Blueprint

Figure 46 illustrates the challenges encountered while marking and drilling production holes. The fundamental challenge when marking a stope is adhering to the survey note issued by the survey department to follow the correct mining direction. If this is not done, the stope will ultimately mine off-reef. Mining off-reef means that waste is being blasted instead of the planned ore reserves. It can also mean that the reef is in the hangingwall or footwall hence, there will be dilution of reef. There are financial implications of mining off-reef because although the face is blasted, the operation will be unable to meet the targeted monthly gold output. In addition, RDO’s operate in close proximity to the face while drilling and this exposes them to face burst and high dust levels. Figure 46 also shows that NIHL is a challenge during marking and drilling the stope. NIHL is prominent in RDO’s due to noise emissions from the rock drilling machines.

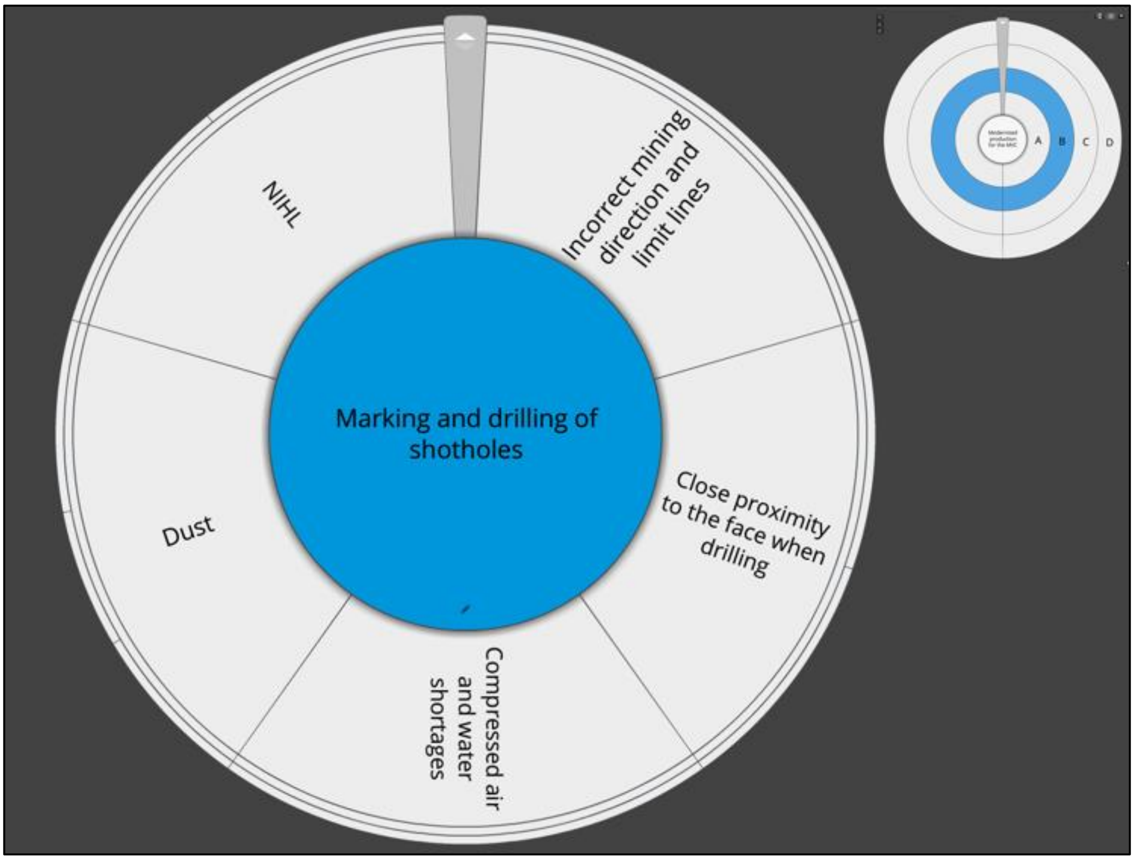


Figure 46: Challenges During Marking and Drilling of Shotholes

Figure 47 shows the output the proposed technology should have to address the challenges outlined in Figure 46. It is important to automate rock drill machines to distance RDO’s from immediate contact with the stope face. The implemented technology must improve the safety of miners by reducing occupational diseases such as silicosis and NIHL. The adopted technology must also increase productivity by monitoring the mining direction and limit lines with face advance to ensure crews continuously mine on-reef. Underground surveying plays a crucial role in mining and surveyors are responsible of installing survey pegs underground. These survey pegs are not only used to determine the mining direction but are also used to measure the square metres achieved with face advance after a certain period. Therefore, it is important that the installation thereof is correct.

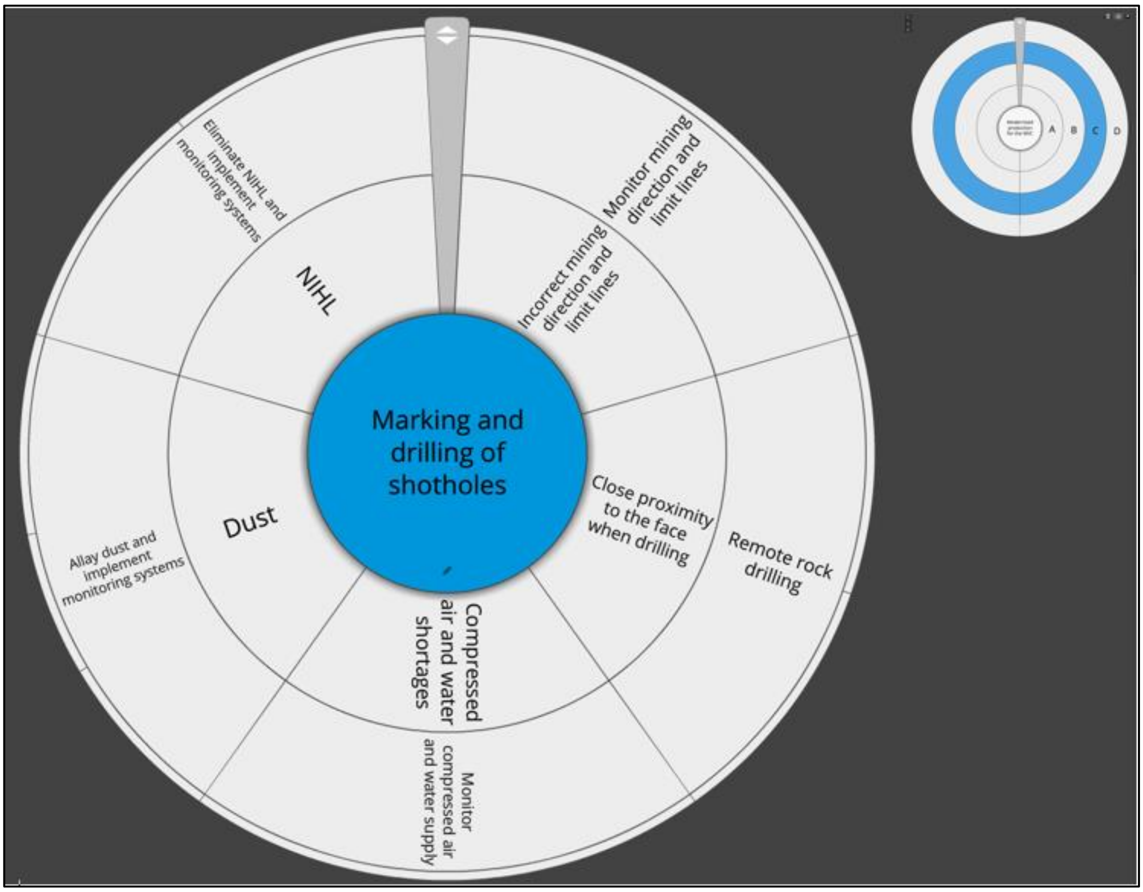


Figure 47: Output of Proposed Technology During Marking and Drilling of Shotholes

According to Hrabar (2019), UAV's can be used to conduct accurate underground surveying. UAV's can also be used to monitor the mining direction and the installation of survey pegs, Figure 48. Therefore, any deviation from the mining direction can be picked up by the UAV and rectified. The automation of the rock drill machine may be hard to implement due to the confinement of the stope which would hinder the implementation of large-scale equipment. There is also the option to implement hard rock cutting machines which would replace the conventional drilling and blasting methods. Although, the use of rock cutting machines in the gold mining industry is still within the conceptual phases, this method is currently in use at Twickenhan Platinum Mine.

Drilling can be made safer during this stage by implementing lower noise inducive drills. Fixed environmental monitoring systems at the stope can give warning to miners to wear ear PPE when high noise levels are detected from equipment underground. In addition, the digital twinning of rock drilling equipment can ensure that if there are any defects on the equipment, attention can be given to it before the damage is irreversable. Figure 48 also shows that installing environmental monitoring systems together with automated venturis can monitor dust levels and offer additional watering down during drilling to lower dust levels.

Figure 48: Digital Technology for the Marking and Drilling Phase

Goalscape was used to determine the overall progress into modernising this stage of the mining cycle. It was estimated that this phase has only advanced digitally by 18%, Appendix 5. This percentage adoption of technology adoption was derived from Table 13. Table 13 illustrates the state of readiness to adopt autonomous technology at the conventional mine during the marking and drilling stage of the mining cycle. Although the drilling of shotholes may be the hardest activity to automate in the mining cycle due to the confinement of narrow-reef stopes, the automation thereof would ensure RDO’s are distanced from immediate harm as a result of exposure to the stope face. In addition, the digital twinning of equipment can be used to monitor the performance of drilling machines to ensure shotholes are drilled in a manner which increases the face advance.

Currently, drilling machines used during this stage are powered by compressed air and water to reduce dust from the drilling process. Although employees are issued with PPE to reduce the impact of noise and dust on their health, there are no environmental systems to monitor dust and noise levels at the stope. Table 13 also shows the available systems at DigiMine that can be adopted to automate this stage of the mining cycle. Although remote rock drilling technology is yet to be adopted at DigiMine, other digital systems have been implemented to automate the marking and drilling stage of the mining cycle.

Table 13: Marking and Drilling of Shotholes: State of Readiness at Conventional Gold Mine

Required technology	**Example of digital system**	**State of adoption at conventional mine**	**Examples of similar digital systems installed at DigiMine**
Monitor mining direction and limit lines	UAV	15%	MHSC UAV, CUMT Hi-Target CORS station, Maptek Laser Scanning System
Remote rock drilling	Automated rock drills	15%	×
Monitor air and water supply	Smart monitoring systems	20%	Reactore
Monitor environmental conditions	Smart sensors	20%	Schauenburg MIMACS, VibraTech Geosonics, BBE Vuma-live

7.2.4 Charging and Blasting of Shotholes Blueprint

Underground blasting induces falls of ground by creating stress on the surrounding mass. Figure 15 illustrates that falls of ground has been responsible for majority of the fatality rates while Figure 16 shows that falls of ground is the second highest contributor to occupational injuries. Blasting activities release toxic gases such as carbon monoxide while unventilated areas tend to have methane accumulation. In addition, accessing deeper reserves has proven to be difficult for the conventional mining industry as these mining operations are currently operating several kilometres from surface. The average face advance after a blast at this conventional mine is between 0.7m and 0.8m when using a 1.2m drill steel. This decreases the measured square metres every month. Figure 49 further details challenges encountered during the charging and blasting phase of the mining cycle.

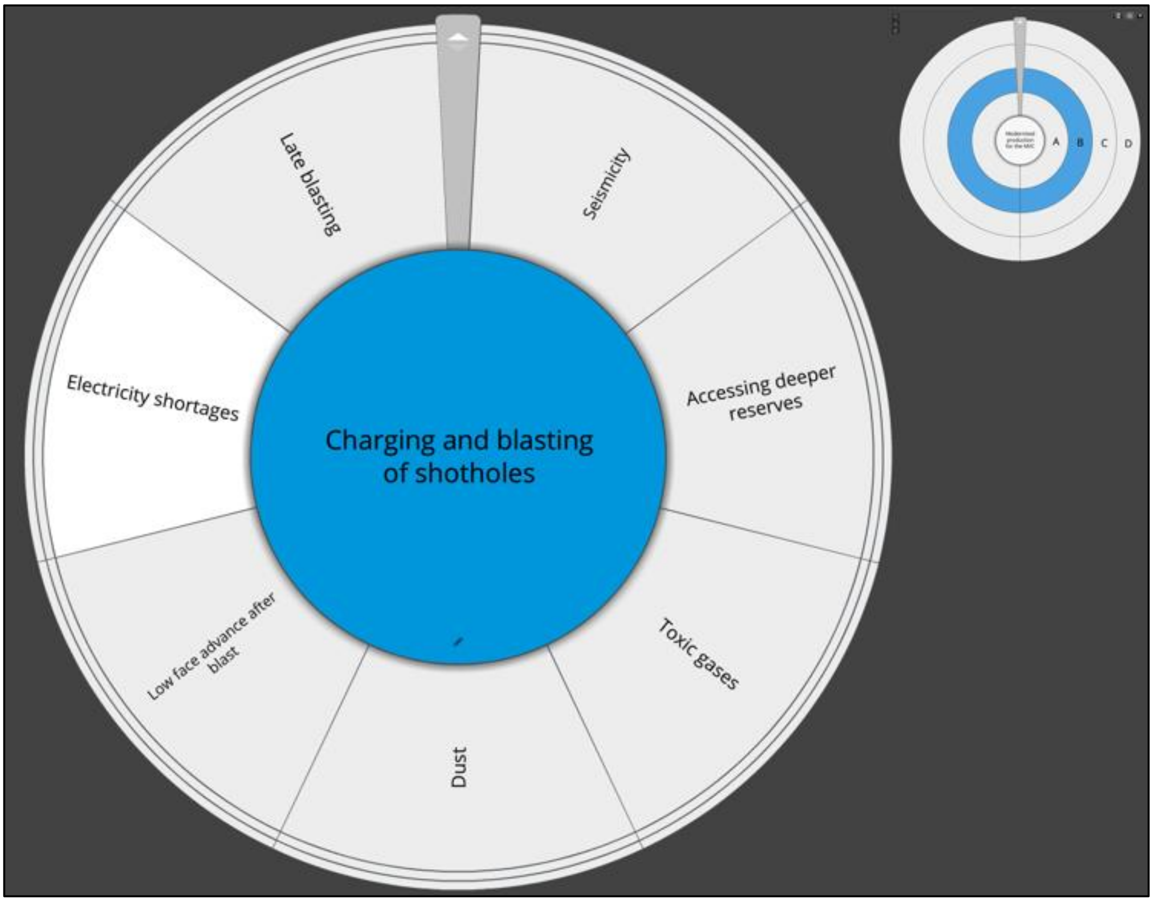


Figure 49: Challenges During Charging and Blasting of Shotholes

In order to reduce costs and increase efficiencies, the mining industry ought to manage electricity costs by implementing energy conservative systems. Goldcorp Éléonore mine has installed smart sensors which work with the geospatial tracking of personnel and machinery to switch lights on depending on the presence of people and machinery. This has resulted in the operation saving in energy costs. Energy requirements at Goldcorp Éléonore mine were also reduced by the installation of an intelligent ventilation system which adjusts the ventilation supply depending on the presence of personnel and machinery (Cisco, 2015). Figure 50 shows the functionalities the preventative measures should have to cater for the challenges shown in Figure 49.

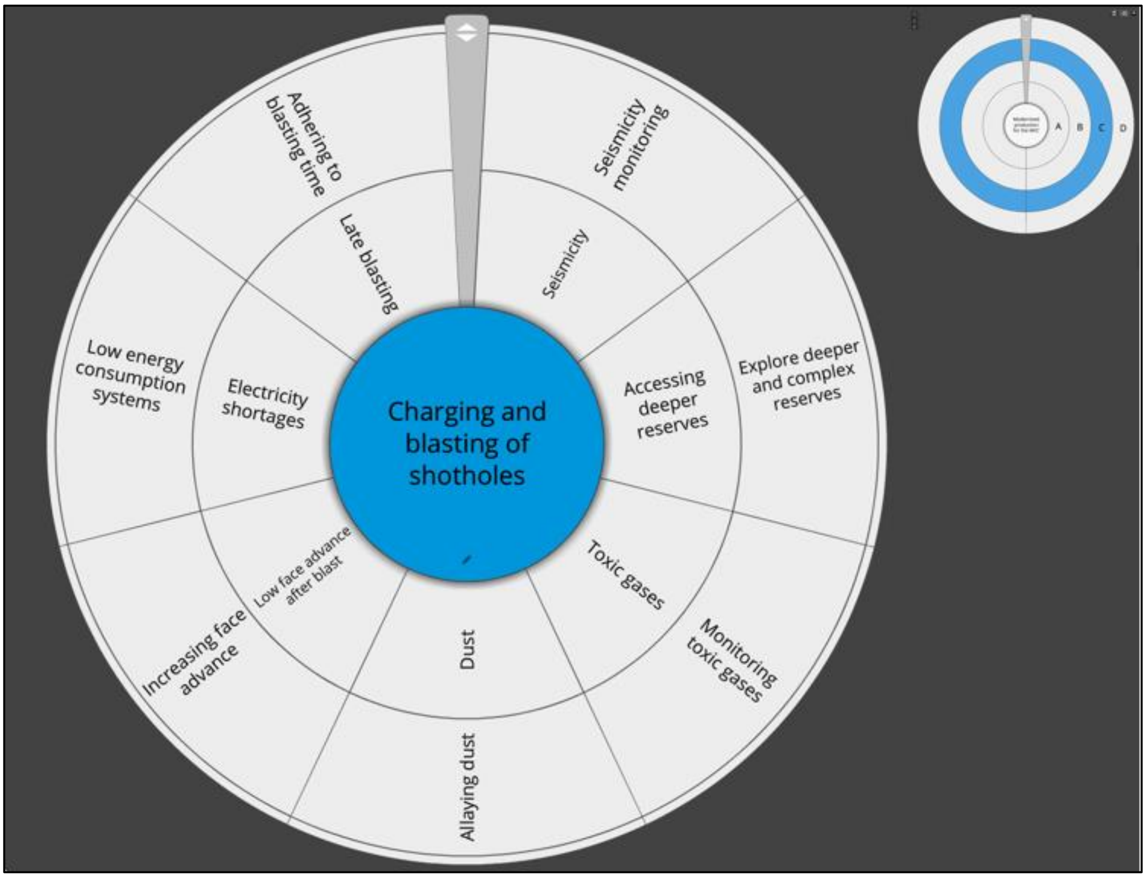


Figure 50: Output of Proposed Technology During Charging and Blasting of Shotholes

Modernising production has potential to not only increase production but to ensure that morning shift adheres to underground knock off times and therefore, enabling the operation to blast on time. Late blasting reduces the time which nightshift crews can be allowed to go underground as a re-entry period of three hours is mandatory. The geospatial tracking of personnel and real-time communication would enable the control room to contact and alert miners who are remaining underground when knock off time approaches. Figure 51 highlights different innovative technologies which can be implemented to address the challenges encountered when shotholes are charged and blasted.

The use of digitally twinned rock drilling machines would track the performance of the rock drill to ensure an optimum face advance is achieved after a blast. WUSN can monitor ground movement and seismicity in real-time and data from the WUSN can be used to warn employees of potential underground hazards ahead of time. A study of the use of WUSN at DigiMine proved that these sensor nodes can still communicate with the surface environment even after buried under debris (Zaman & Förster, 2018). Therefore, personnel who are trapped under falls of ground can be located if they are wearing PPE which has WUSN installed. The rescuing of such personnel would therefore be much quicker. Figure 51 also shows that fixed environmental monitoring systems and automated venturis can be used to automatically water down the stope after a blast has occurred.

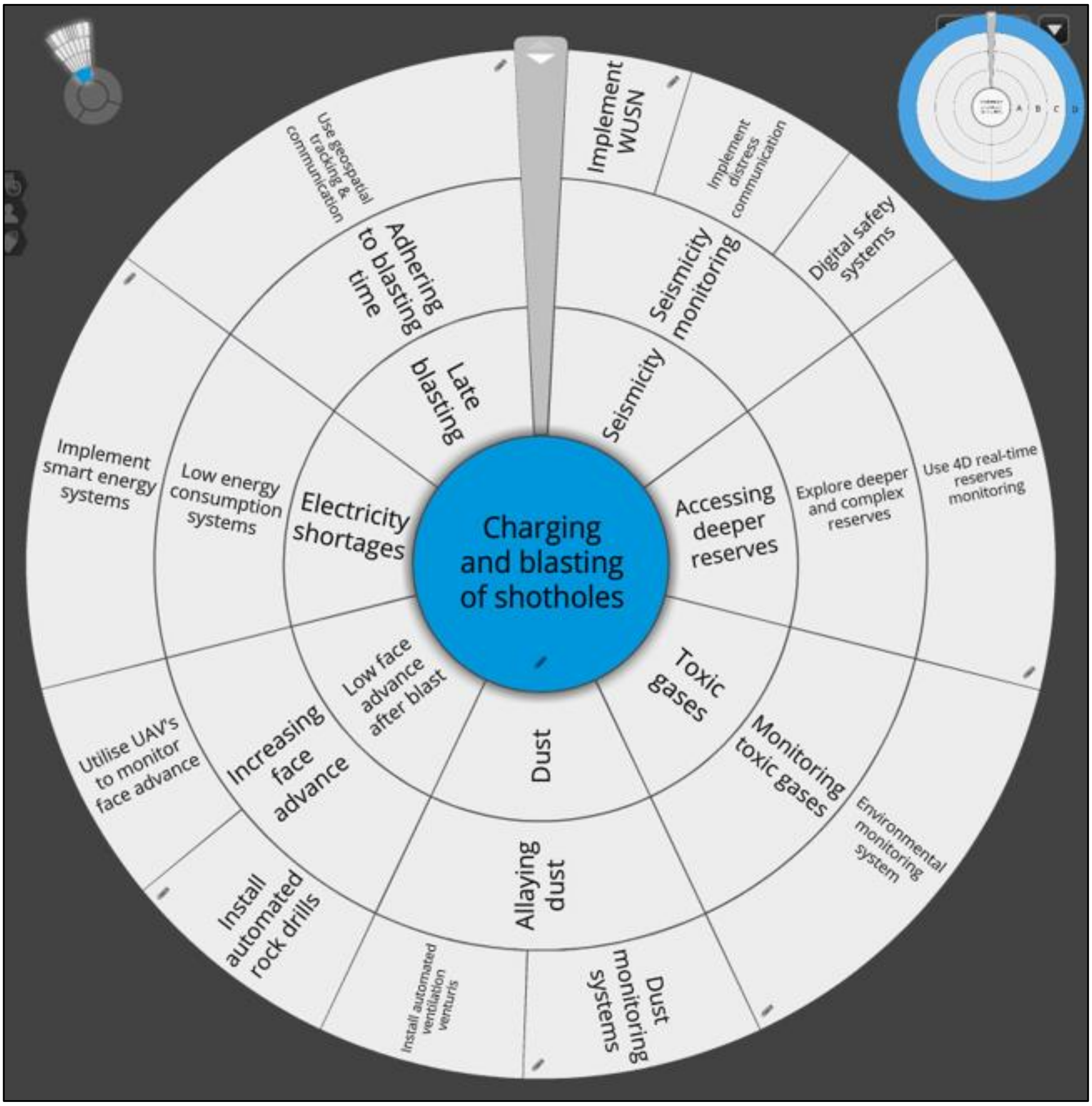


Figure 51: Digital Technology for the Charging and Blasting of Shotholes Phase

Table 14 illustrates the state of readiness to modernise the charging and blasting stage of the mining cycle. Table 14 also shows the current state of adoption of technology at the conventional mine during this stage of the mining cycle. Goalscape was used to estimate the overall progress to modernise this stage; Appendix 6 illustrates that the charging and blasting phase was estimated to be 18% modernised. This mainly due to the advanced seismic monitoring systems available at the operation. Although these systems cannot predict the exact time of the next event, it can predict the magnitude and the parameter of where the next event may be. Hence, miners are advised to check the seismic rating of their working place before proceeding underground.

Underground employees are issued with hand-held GDI’s to detect the presence of methane and carbon monoxide. However, late blasting is one of the most significant challenges during this stage of the mining cycle and there are yet to be any prominent solutions adopted to address it. In addition, the conventional block modelling systems used at the mine does not offer an operation the ability to monitor its reserves in real-time nor does it suggest alternative safer extracting methods to mine deeper and complex reserves. Table 14 also shows the available systems at DigiMine to automate this stage of the mining cycle; DigiMine is yet to implement automated drills.

Table 14: Charging and Blasting of Shotholes: State of Readiness at Conventional Gold Mine

Required technology	**Example of digital system**	**State of adoption at conventional mine**	**Examples of similar digital systems installed at DigiMine**
Seismicity monitoring	Digital safety systems	25%	Ramjack, Sibanye-Stillwater seismicity system, VibraTech Geosonics
Explore deeper and complex reserves	4D reserves monitoring system	25%	Gold Fields MVS Scanner
Monitor environmental conditions	Smart sensors	20%	Schauenburg MIMACS, VibraTech Geosonics, BBE Vuma-live
Increase face advance	Automated drills	15%	×
Low energy consumption system	Smart energy systems	15%	Visible light communications
Enforcing blasting on time	Geospatial tracking and communication	15%	WMI/Bremen Finding Missing Person technology, Visible light communications

7.2.5 Cleaning of Blasted Ore Blueprint

Figure 52 illustrates the challenges encountered during cleaning of blasted ore. According to *Mine Health and Safety Inspectorate (2019)*, scraper winches and rigging are the third highest contributors to occupational fatalities after falls of ground and RBE accidents. Stopes are cleaned by scraper winches and water jets thereafter; the broken ore is fed into an orepass. However, due to orepass size restrictions, orepasses can only accommodate a limited number of tonnes. If the orepass is full, crews will be unable to clean the panel as ore would have accumulated in the gullies. This has a significant impact on the MCF.

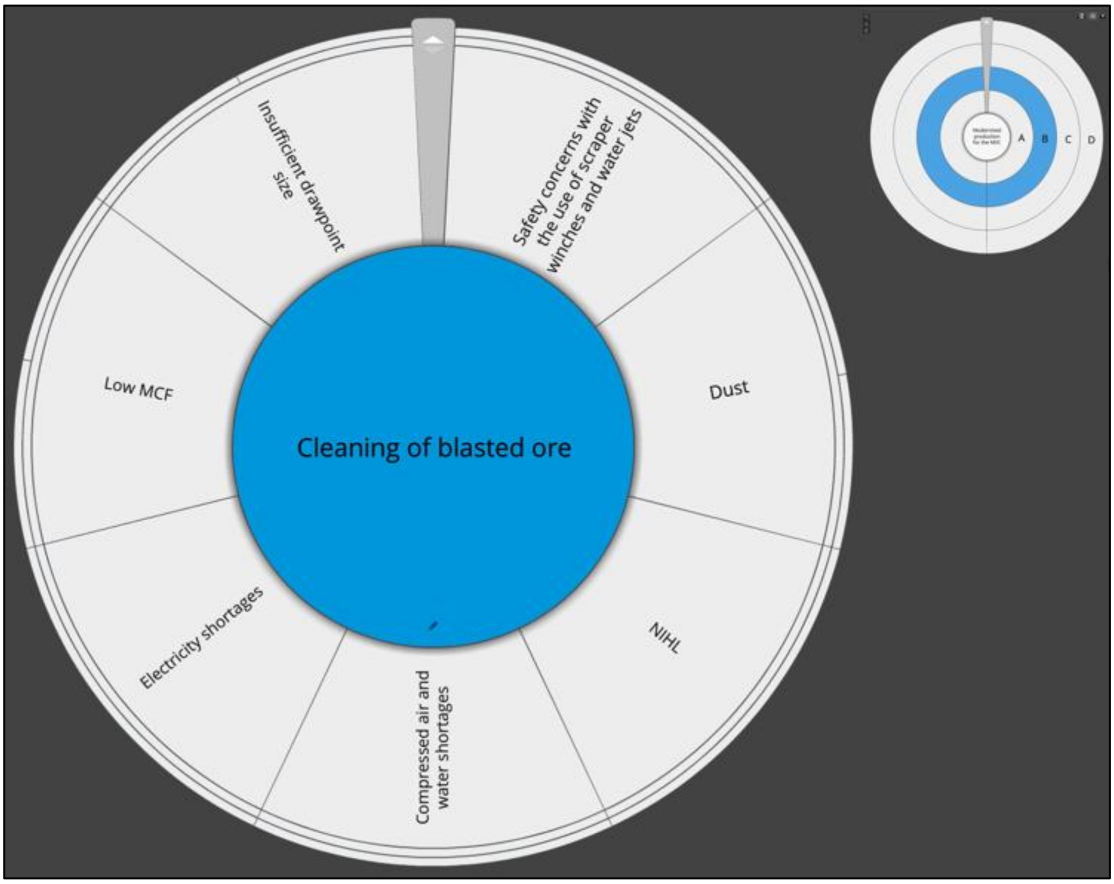


Figure 52: Challenges During Cleaning of Blasted Ore

The autonomous mine should address the safety concerns associated with the use of scraper winches and water jets by implementing remote cleaning. Automating the cleaning stage has an impact on increasing the cleaning efficiency of scraper winches and water jets. This has an impact on the operation's MCF as ore left behind reduces the gold recovery rate. Monitoring ore drawpoints is also crucial to increase the MCF as this has an effect on the ability for crews to clean panels. Figure 53 shows that is it important to have low-energy consuming systems to reduce the energy needs of the operation during cleaning. There is also a need to monitor the flow of compressed air and water to ensure the location of leakage is immediately detected.

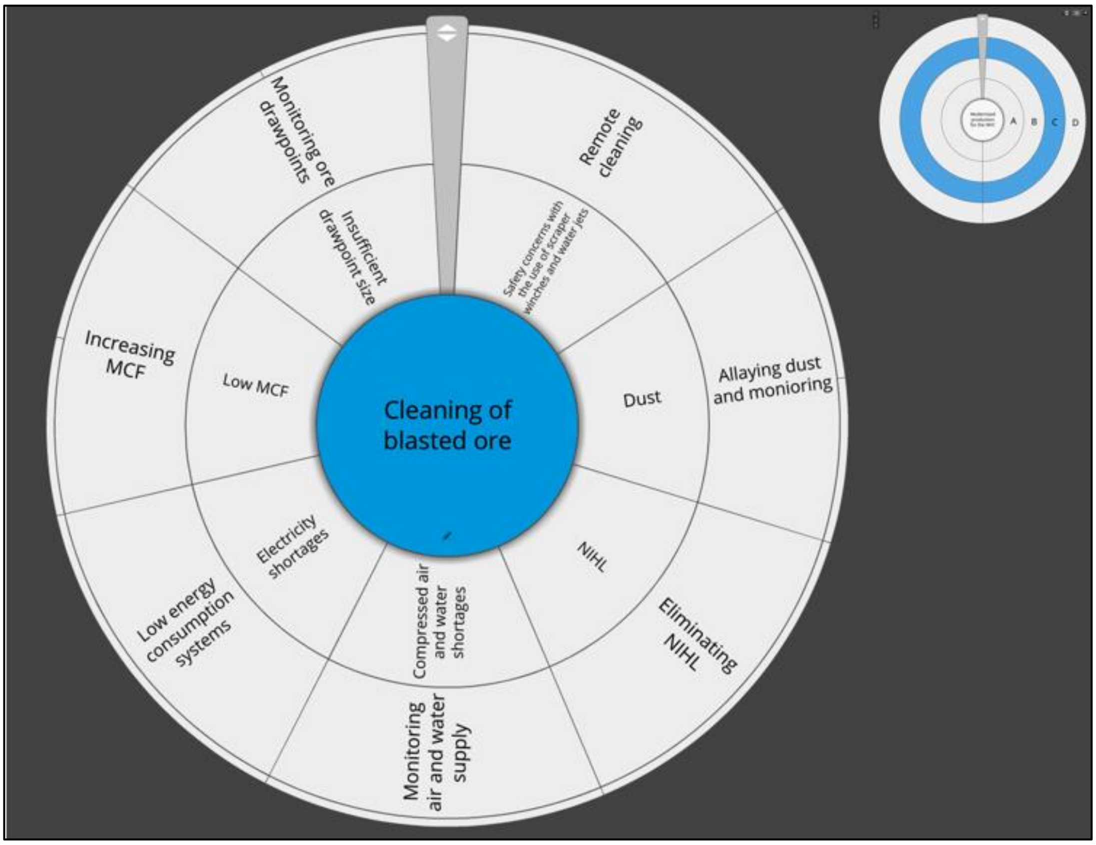


Figure 53: Output of Proposed Technology During Cleaning of Blasted Ore

The autonomous technology outlined on Figure 54 ensure that the stope is safely cleaned and the MCF is increased. The automation and installation of additional safety devices on cleaning equipment can improve safety and ensure the equipment detects the presence of humans close by and automatically come to stop in the proximity of humans. WUSN and UAV's can be used to detect the capacity of the orepass and report to the RBE crews to empty the orepass should it be full. This will ensure the orepass is never filled to capacity while RBE can be assigned to drawpoints which have confirmed ore to be transported. The implementation of environmental monitoring systems in the stope ensure that dust levels are detected, and automated venturis can water down the area to allay dust. In addition, the environmental monitoring systems will ensure that miners are alerted of high noise levels therefore, wear the appropriate ear protection.

Figure 54: Digital Technology for the Cleaning of Blasted Ore Phase

Table 15 illustrates the state of readiness to fully modernise the cleaning stage of the mining cycle. Table 15 further estimates the percentage adoption of modernisation during this stage of the mining cycle. Goalscape was also used to estimate the overall state of progress towards adopting technology. Goalscape estimated this phase to be 16% digitally advanced, Appendix 7. This is because the methods of cleaning the stope are conventional; Pickering (2007) reported that these cleaning methods were first adopted in the early twentieth century. In addition, there are increased operational costs at the mine as additional costs and resources have to be assigned to sweeping crews to reclean panels due to the current poor cleaning methods. This has resulted in a reduced MCF at the mine. There are currently no dust and noise monitoring systems implemented although miners are issued with PPE to reduce the impact of occupational dust and noise. Table 15 also shows the digital systems at DigiMine to automate the cleaning stage of the mining cycle. DigiMine is yet to implement automated cleaning equipment.

Table 15: Cleaning of Blasted Ore: State of Readiness at Conventional Gold Mine

Required technology	**Example of digital system**	**State of adoption at conventional mine**	**Examples of similar digital systems installed at DigiMine**
Remote cleaning	Automated scraper winches	15%	×
Monitor environmental conditions	Smart sensors	20%	Schauenburg MIMACS, VibraTech Geosonics, BBE Vuma-live
Monitor air and water supply	Smart monitoring systems	20%	Reactore
Low energy consumption system	Smart energy systems	15%	Visible light communications
Increasing MCF	Mine scheduling and data integration	15%	Adroit Scada system, Minetec Trax and Smarts, Reactore
Monitor ore drawpoints	UAV and smart sensors	15%	Adroit Scada system, Minetec Trax and Smarts, Reactore

7.2.6 Loading of Blasted Ore Blueprint

RBE are used for the transportation of workers, materials, and ore. Due to the size of underground haulages which are measured 3.5m by 3.5m at the conventional mine, there is only a single rail path for RBE to travel. This causes congestion as different RBE attempt to shunt to make way for each other. Workers and RBE travel in the same haulage which has resulted in the collision between RBE and workers. It is also common for RBE to collide with each other and other mining structures. Due to the long distances from the station to the working place, there is shorter effective shift length as it takes a long time to travel to the working places. Figure 55 illustrates other challenges encountered while loading blasted ore for transportation.

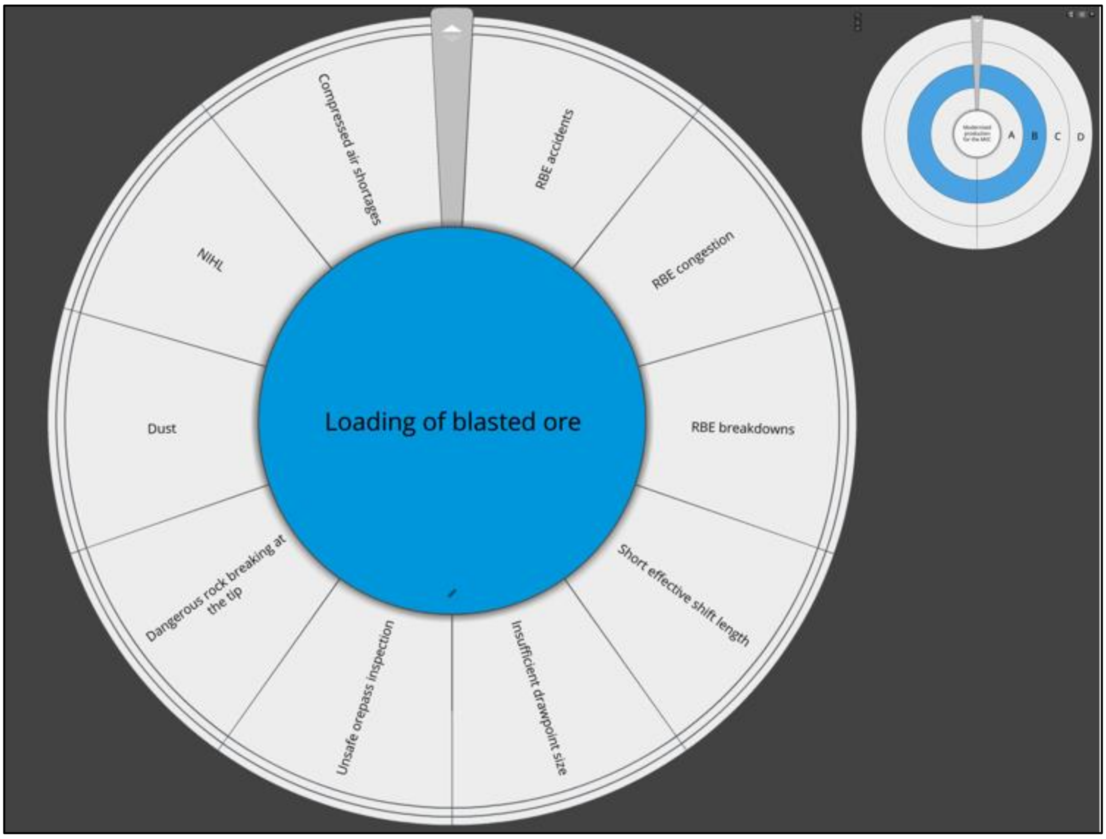


Figure 55: Challenges During Loading of Ore

Figure 56 illustrates the output the preventative measures should have to address the challenges mentioned in Figure 55. There should be remote inspection of orepasses in case there are hang-ups and to also detect whether the orepass is full or not. While ore is tipped onto the orepass, large rocks tend to accumulate on the orepass grizzly which requires the scraper winch driver to break. This can be a very hazardous activity and technology should be adopted to enable remote breaking at the orepass grizzly. Dust monitoring is important during this stage as ore flow from the orepass to the RBE hoppers generates a lot of dust.

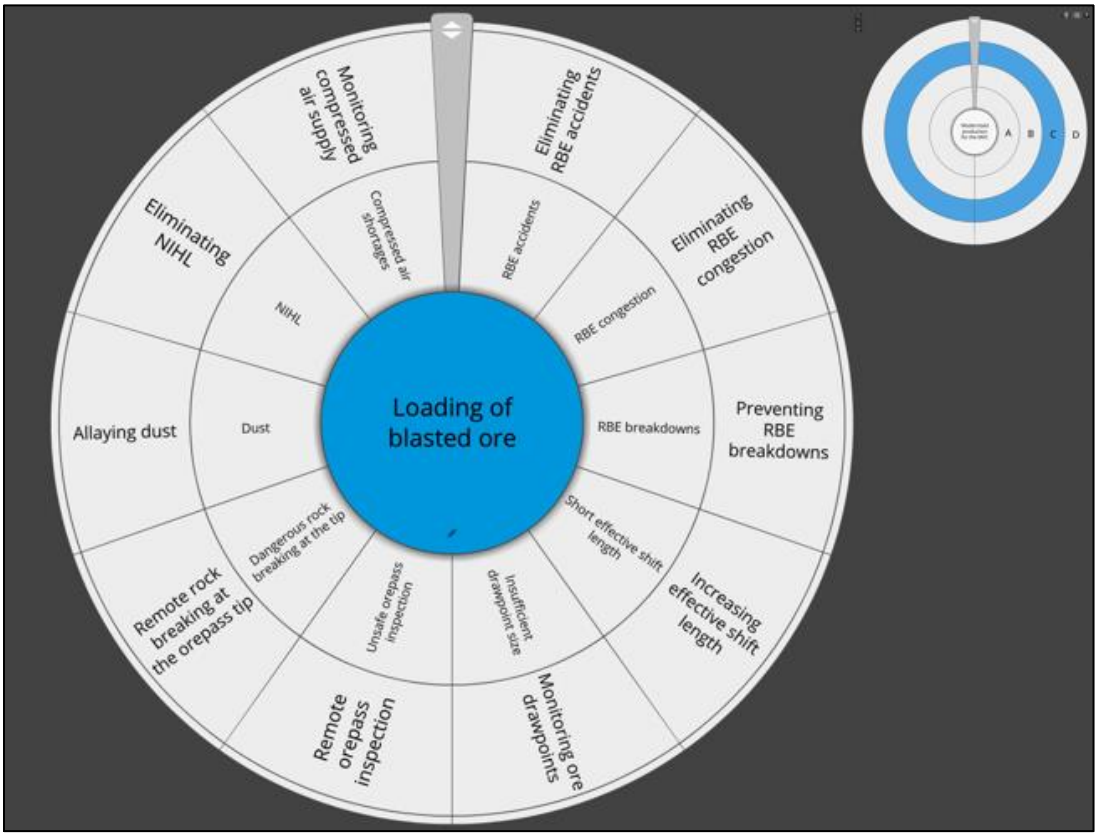


Figure 56: Output of Proposed Technology During Loading of Blasted Ore

Figure 57 shows the technology which can be implemented to cater for the challenges during this stage of the mining cycle. The digital mine is characterised by an autonomous hauling fleet. This fleet consists of anti-collision systems which automatically stops the vehicle once it comes in close proximity with other RBE, men or structures. Autonomous vehicles can be effectively scheduled to eliminate congestion during the transportation of men, materials, and ore. The use of an autonomous hauling fleet has the added benefit of increasing the effective shift length as hauling can run continuously with only maintenance breaks required. The digital twinning of RBE can track the performance of the equipment in real-time therefore, determine when the equipment needs repairs. South Deep mine has implemented a remote rock breaking system where an operator safely breaks rocks at the orepass grizzly using AR. This has ensured the health of employees are not compromised while breaking rocks at the tip.

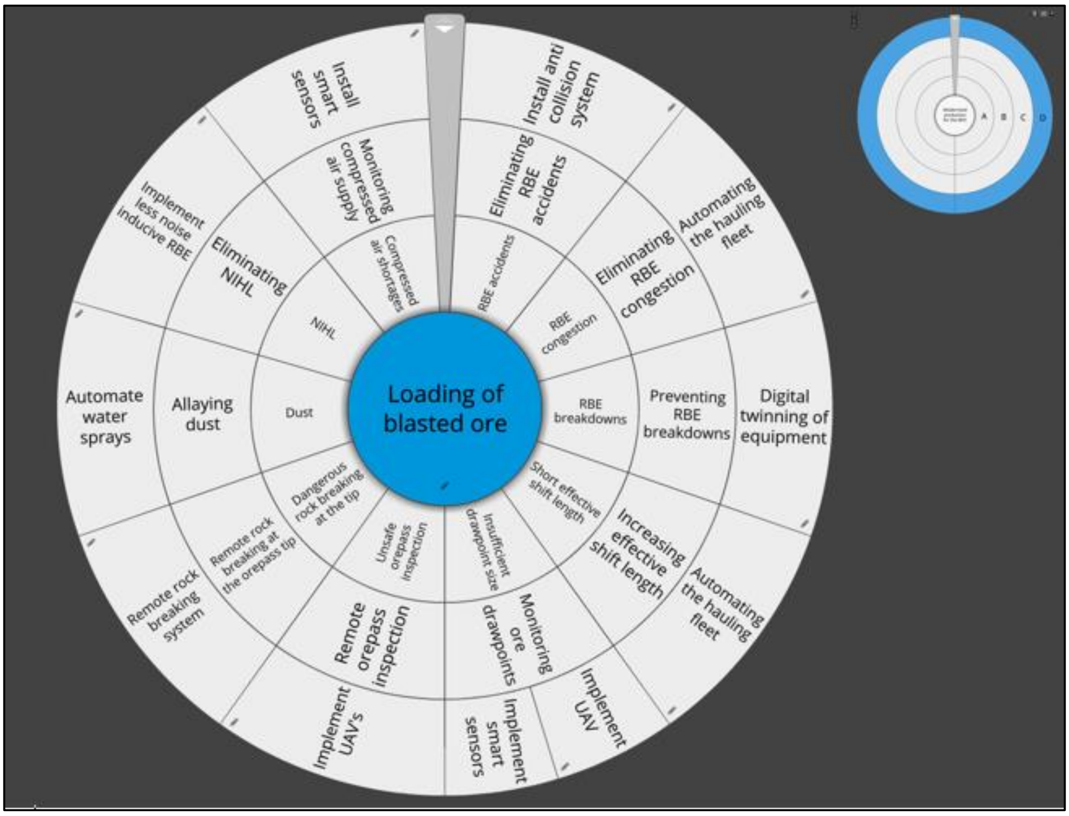


Figure 57: Digital Technology for the Loading of Blasted Ore Phase

Table 16 illustrates the state of readiness to modernise the loading stage of the mining cycle. Goalscape was also used to rate the progress of modernisation during this stage by using the percentage progress shown in Table 16. Appendix 8 shows the progress of modernising the stage of loading of blasted ore; Goalscape has estimated this stage to be approximately 17% modernised at the conventional mine. This is because conventional RBE is used and have resulted in accidents, breakdowns, and congestion. To automate the hauling fleet, there may be a need to replace the entire operation’s hauling fleet to accommodate automation. The conventional mine can adopt remote rock breaking systems which have been proven to be a safer rock breaking method at South Deep mine. Table 16 also shows the available systems at DigiMine to automate the loading of blasted ore stage of the mining cycle.

Table 16: Loading of Blasted Ore: State of Readiness at Conventional Gold Mine

Required technology	**Example of digital system**	**State of adoption at conventional mine**	**Examples of similar digital systems installed at DigiMine**
Eliminate RBE accidents	Anti-collision systems	15%	×
Eliminate RBE congestion	Fleet scheduling	15%	Minetec Trax and Smarts, Reactore
Eliminate RBE breakdowns	Digital twinning	15%	Reactore
Increase effective shift length	Monitoring fleet	15%	Minetec Trax and Smarts, Reactore
Monitor environmental conditions	Smart sensors	20%	Schauenburg MIMACS, VibraTech Geosonics, BBE Vuma-live
Monitor air and water supply	Smart monitoring systems	20%	Reactore
Remote rock breaking	Remote rock breaking system	15%	×
Monitor and inspect ore drawpoints	UAV and smart sensors	15%	Adroit Scada system, Minetec Trax and Smarts, Reactore

7.2.7 Underground Environmental Conditions Blueprint

Due to the depth of underground deep-level mining, remnant stoping panels and high temperatures are common. These environmental characteristics can compromise the health and efficiency of miners inside the stope. Deep-level environments are also characterised by low-grade mineralisation as the higher-grade reserves have been already mined out. In other cases, the high-grade reserves are located in stope panels several kilometres from the station which decreases the effective shift length spent underground as more time is spent travelling than doing actual work. Communication in conventional mines is through intercom telephones located at waiting places and refuge bays, and one can travel several kilometres before reaching a working telephone. Figure 58 illustrates the environmental characteristics of deep-level mining which pose a challenge to achieving a safe and productive shift.

Figure 58: Challenges Due to the Underground Environmental Conditions

Mature deep-level mines consist of decaying and old infrastructure as these mines have been operating for a very long time. Therefore, there is need to monitor these infrastructures and upgrade as deemed necessary to accommodate the adoption of technology. Illegal miners risk their lives by sometimes working in old panels where the support and ventilation is not up to standard. While working in active stope panels, illegal miners entangle mine workers in acts of bribery and theft. In some cases, when miners refuse to cooperate with illegal miners, their safety is threatened. The monitoring of the underground mining environment is therefore necessary to protect the mine's resources and infrastructure as well as the safety of employees from illegal mining activities. Figure 59 illustrates the outputs the preventative measures should have to eliminate or mitigate challenges as a result of the deep-level mining environment.

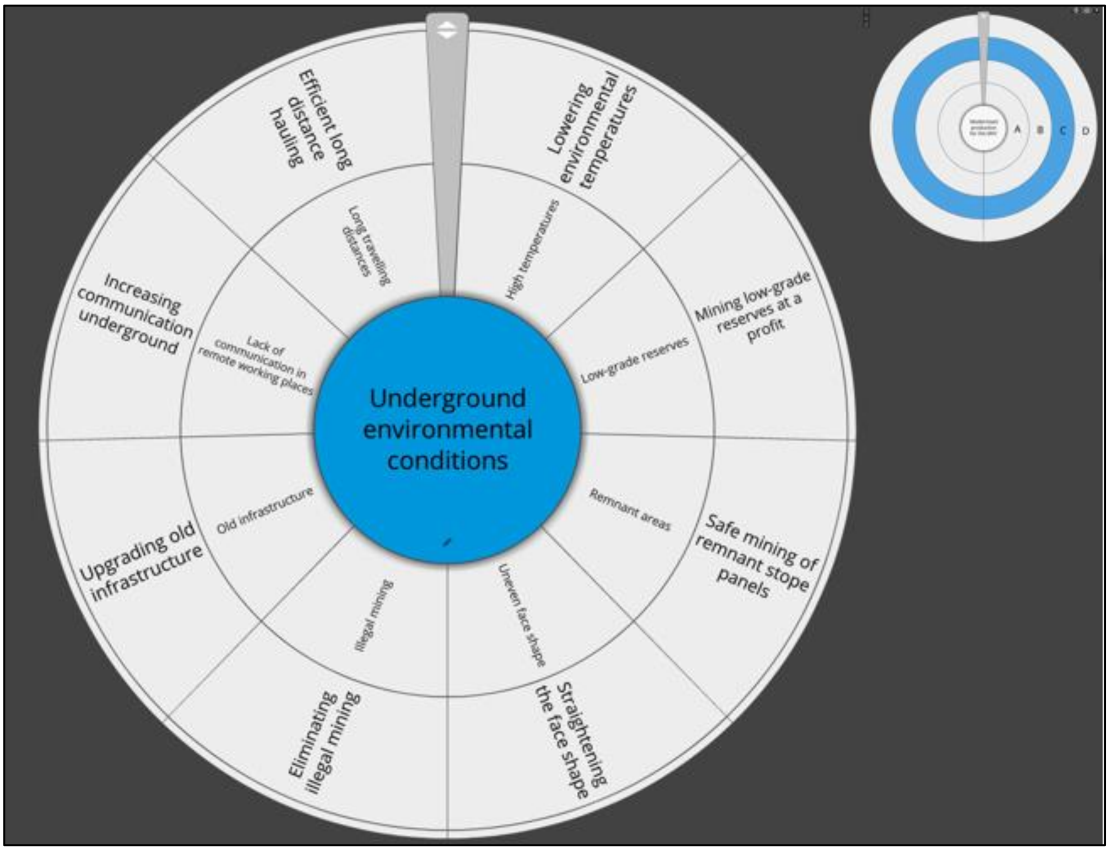


Figure 59: Output of Proposed Technology on the Underground Environment

Remnant areas are characterised by weaker zones on the face which tend to progress faster after a blast. This results in an uneven face shape. However, the use of UAV's can virtually alert miners of the face shape and use algorithms to determine how the face should be marked in order to straighten the face shape. The implementation of technology in the deep-level mining environment will result in the mining environment having fixed environmental monitoring systems which monitor temperature and adjust the ventilation fans to minister ventilation as required. This has the added benefit of lowering the energy costs as a result of lower cooling requirements.

The geospatial tracking of personnel and surveillance can assist in the combating of illegal miners. This is because illegal miners gain insight information about the operation through employees underground. Employees also assist illegal miners with food, contraband, and access to equipment to carry out their illegal activities. Without the help from employees, illegal miners would starve, have no access to the mine's infrastructure to work and no insight on which panels have high grade. Moreover, the installation of a wireless communication network underground will enable employees to communicate with each other and with the surface environment without the need to look for a telephone. This means that every underground employee would have to be issued with a communication device. Figure 60 illustrates the various technologies which can be implemented to modernise this stage of the mining cycle.

Figure 60: Digital Technology for the Underground Environment

Table 17 illustrates the state of readiness at the conventional mine to modernise this stage of the mining cycle. Appendix 9 shows the state of modernisation of the conventional mining environment. This was derived from the percentage progress of modernisation illustrated in Table 17 and inputting this data onto Goalscape. Hence, the underground environment has been approximated to be 17% digitally advanced. The underground deep-level mining environment is characterised by high temperatures, low-grade reserves, remnant areas, old infrastructures and long travelling distances to the working place, Figure 58. These underground working places are also remote from each other. These challenges make the underground environment unsafe and also make it difficult to implement new technology onsite. However, the presence of illegal miners threatens the adoption of digital technology. This is because better surveillance can eliminate illegal mining by monitoring employees, equipment and the stoping environment. Therefore, contingency plans should be in place to mitigate the retaliation from illegal miners towards the digitalisation of the industry. Table 17 also illustrates the available digital systems at DigiMine to automate the underground mining environment. DigiMine is yet to install an AHS for underground transportation purposes.

Table 17: Underground Environmental Conditions: State of Readiness at Conventional Gold Mine

Required technology	**Example of digital system**	**State of adoption at conventional mine**	**Examples of similar digital systems installed at DigiMine**
Lower environmental conditions	Ventilation-on-demand systems	15%	Schauenburg MIMACS, VibraTech Geosonics, BBE Vuma-live
Mine lower grade reserves	4D reserves monitoring	20%	Gold Fields MVS Scanner
Safe mining of remnant areas	4D geotechnical reserves monitoring	20%	Gold Fields MVS Scanner, VibraTech Geosonics
Straighten the face shape	UAV	15%	MHSC UAV, DetNet blast controller
Eliminate illegal miners	Underground surveillance	20%	EOH and IBM Camera System, IBM Smart Mine Access Control
Monitor aging infrastructure	Survey and inspection robots	15%	MHSC UAV, CUMT Hi-Target CORS station, Maptek Laser Scanning System
Increase communication	Wireless underground communication network	15%	Visible Light Communications
Efficient long-distance hauling	Automated hauling fleet	15%	×

7.2.8 Labour's Blueprint

Labour plays a vital role in any mining operation. The gold mining industry is dominated by an illiterate workforce. This is because the gold mining industry has thrived on cheap and unskilled labour. The use of a workforce of this nature was influenced by the need to pay underground workers low wages. The culture and behaviour of mine employees has rarely changed from how it was decades ago with the primary language of communication being Fanakalo. Workers also tend to have a familiarity complex, and disregard safety standards. Figure 61 outlines other challenges experienced because of and presence of mining labour.

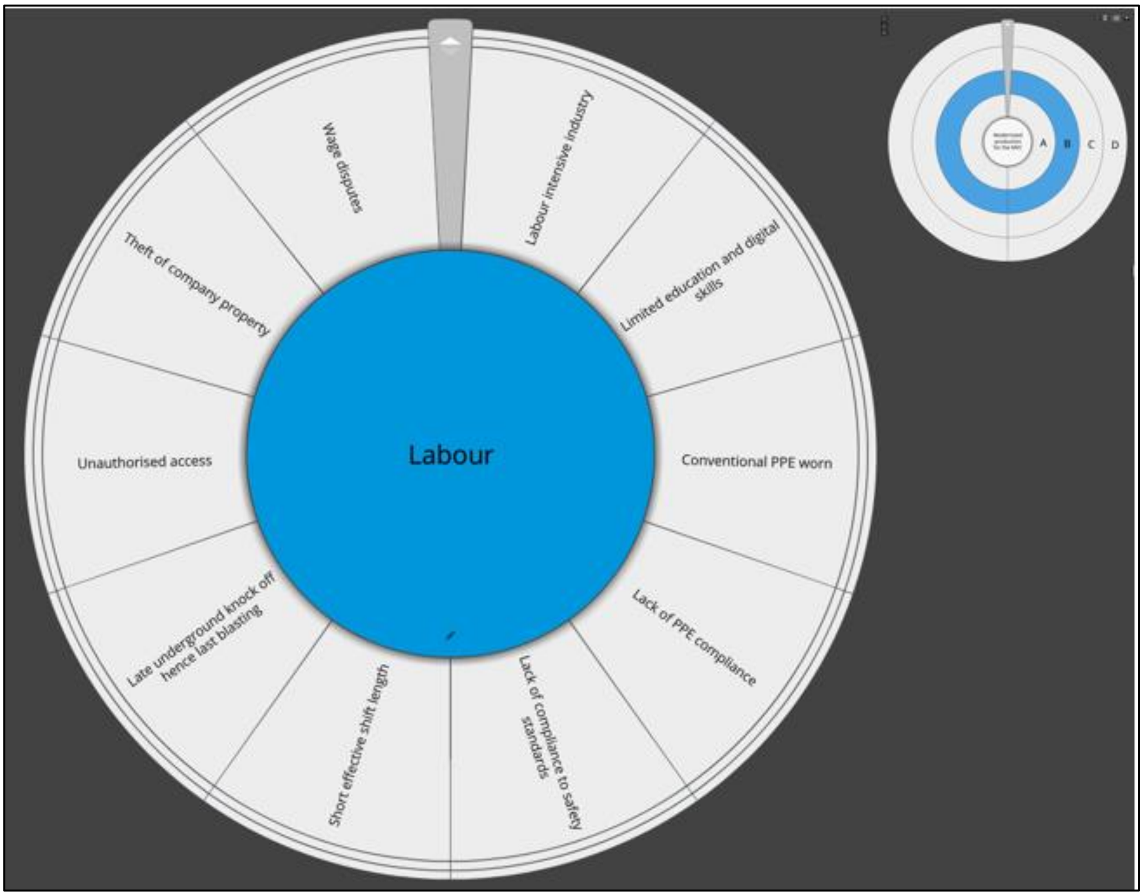


Figure 61: Challenges Experienced by Labour

Figure 62 shows the characteristics the implemented technology must have to address the challenges encountered by the underground stoping labour. It is priority to distance workers from harm and to facilitate the skills shortage in the industry. The PPE worn by employees is still conventional in nature consisting of a hardhat, overalls, headlamp, arm, and knee guards, GDI, self-rescuer and safety boots. There is need to upgrade the PPE to enable geospatial tracking, distress communication and environmental monitoring to improve the health and safety of employees underground.

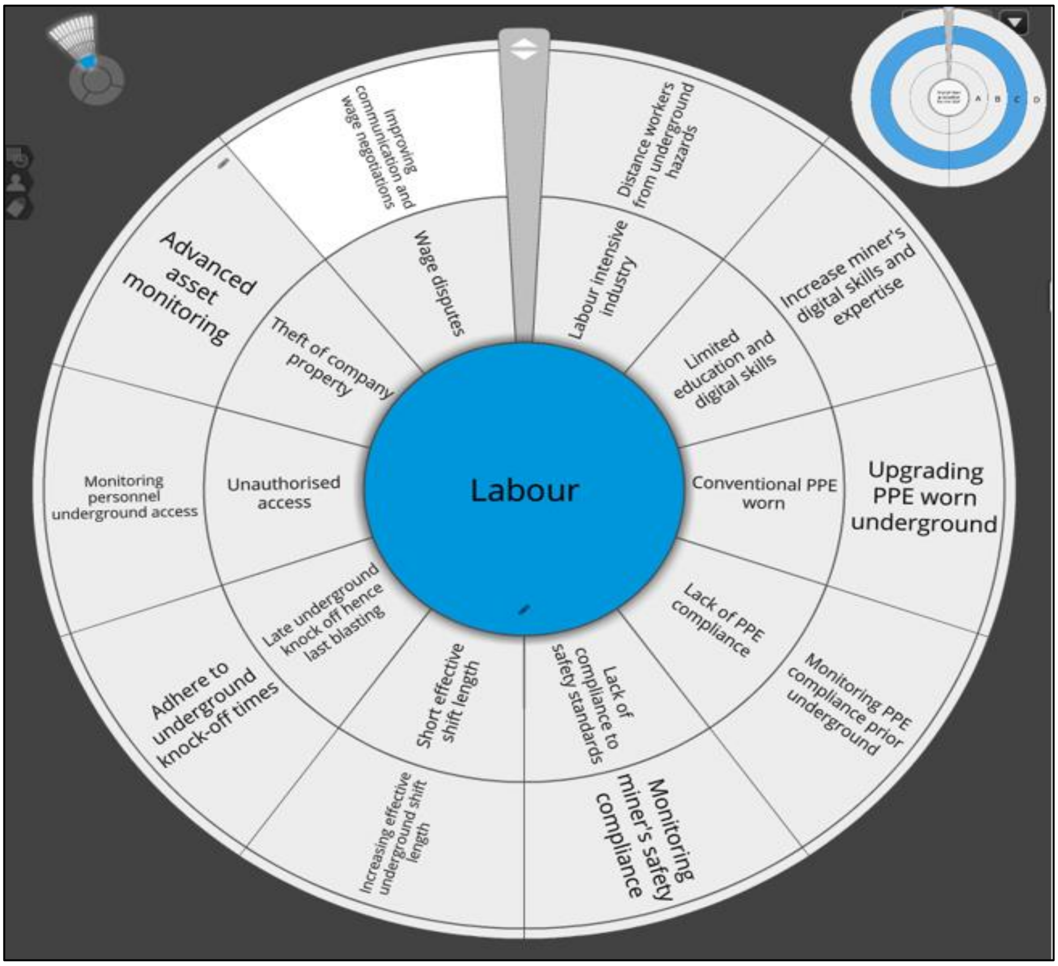


Figure 62: Output of Proposed Technology Concerning Labour

The adoption of technology aims not only to change the workplace but the workforce as well. The labour-intensive industry will be transitioned through modernisation to become versatile and safer. There can be real-time monitoring of employees from anywhere underground which will make rescuing operations much quicker in the case of an emergency. The PPE compliance of miners can be checked before they proceed underground while their compliance to safety standards can be tracked throughout the mine through underground surveillance. This will increase employee’s awareness and compliance to safety rules.

Late blasting is as a result of a delay in the work conducted throughout the mining cycle such as drilling and cleaning. The delayed supply of material also influences late blasting as miners will install support later than usual. When work is delayed, it results in employees hastily conducting work and more often neglecting safety standards. Therefore, automating production and introducing digital technology will increase the speed at which each shift underground can complete their tasks. Figure 63 highlights other digital technologies which can be adopted in order to reduce risks and increase productivity of mine employees.

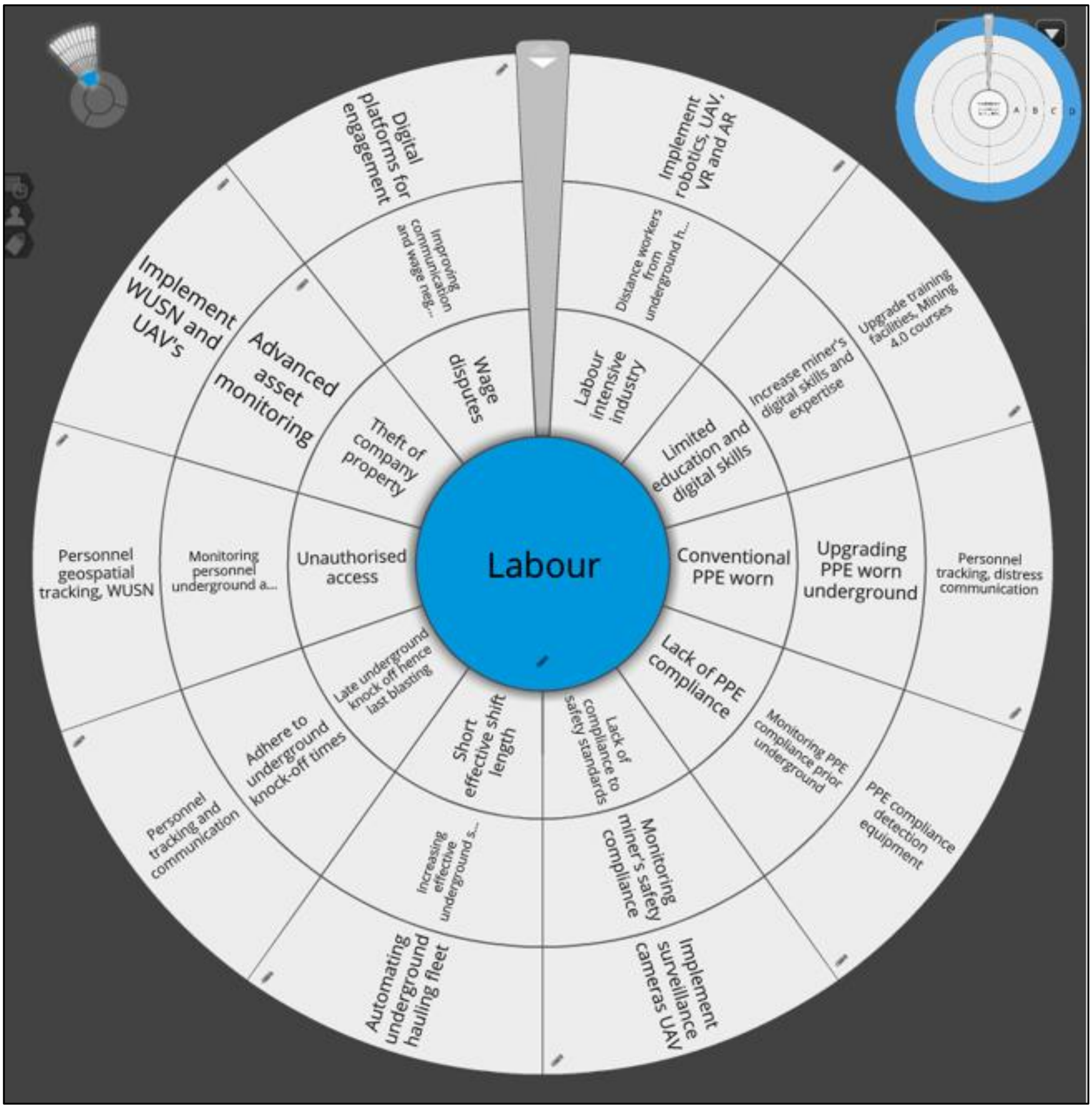


Figure 63: Digital Technology to Cater for the Mining Labour

Table 18 illustrates the state of readiness to modernise this stage of the mining cycle. Appendix 10 shows how digitally advanced the mining labour is at this operation. Goalscape estimated the mining labour to be 19% digitally advanced. This was derived from using the percentage progress of modernisation highlighted in Table 18. Table 18 shows that this conventional mine has fast-tracked digital innovation by adopting a digital application which employees can use to engage with management to raise their concerns and obtain feedback. The conventional mining industry is dominated by a workforce which is less skilled on the use of technology, therefore, the industry should decide whether to train the existing workforce or obtain new employees who are familiar with technology. The latter may be met with strong opposition from current employees and labour unions. While Mining 4.0 will increase the monitoring of employees and their compliance to safety standards through geospatial tracking, it should be considered that this form of technology may be met with strong opposition.

Table 18: Labour: State of Readiness at Conventional Gold Mine

Required technology	**Example of digital system**	**State of adoption at conventional mine**	**Examples of similar digital systems installed at DigiMine**
Distance workers from harm	UAV	15%	MHSC UAV
Increase digital skills	Mining 4.0 training	20%	DigiMine seminars, Tshimologong/Braamfontein Incubator
Upgrade PPE	Advanced distress communication feature	15%	Schauenburg MIMACS, WMI/Bremen Finding Missing Person technology
Monitor PPE compliance	PPE compliance detection equipment	15%	Schauenburg
Monitor safety compliance	Underground surveillance	15%	EOH and IBM Camera System, MHSC UAV
Increase effective underground shift	Automated hauling fleet	15%	×
Enforcing blasting on time	Geospatial tracking and communication	15%	WMI/Bremen Finding Missing Person technology, Visible light communications
Preventing unauthorised access	Underground surveillance	15%	EOH and IBM Camera System, IBM Smart Mine Access Control
Preventing company theft	Underground and surface surveillance	15%	EOH and IBM Camera System, IBM Smart Mine Access Control, BeiDou
Managing wage disputes	Communication and engaging platforms	50%	Digger, Let’s Talk app

7.2.9 Reporting and Communication Blueprint

Figure 64 illustrates the challenges encountered when reporting and communicating at the conventional mine. As the operation is conventional in nature, communication is very limited. Mine employees are not awarded a platform to engage with management when conducting the weekly safety and production meetings and this creates obscurity between workers and management regarding the operation. Although refuge bays are reported daily by miners to ensure they have the life-sustaining requirements should an emergency occur, sometimes refuge bays are not called in. Therefore, the level of safety compliance of the refuge bay is unknown. There is also a lack of clear communication between morning shift and night shift. Although the miner for each shift is required to give a report or instructions for the following shift, at times these instructions can be vague and not well understood. Different mining departments also fail to be transparent with one another leading to further misunderstandings.

Figure 64: Challenges while Reporting and Communicating

The phase of reporting and communicating can be enhanced by introducing digital technology to enhance communication between mine employees and management, promoting transparency between different mining shifts and mining departments. Increasing means of communication underground will ensure breakdowns of equipment can be reported quicker and therefore, repaired faster. Figure 65 highlights other outputs digital systems should have in order to address the challenges encountered while reporting and communicating at the conventional mine.

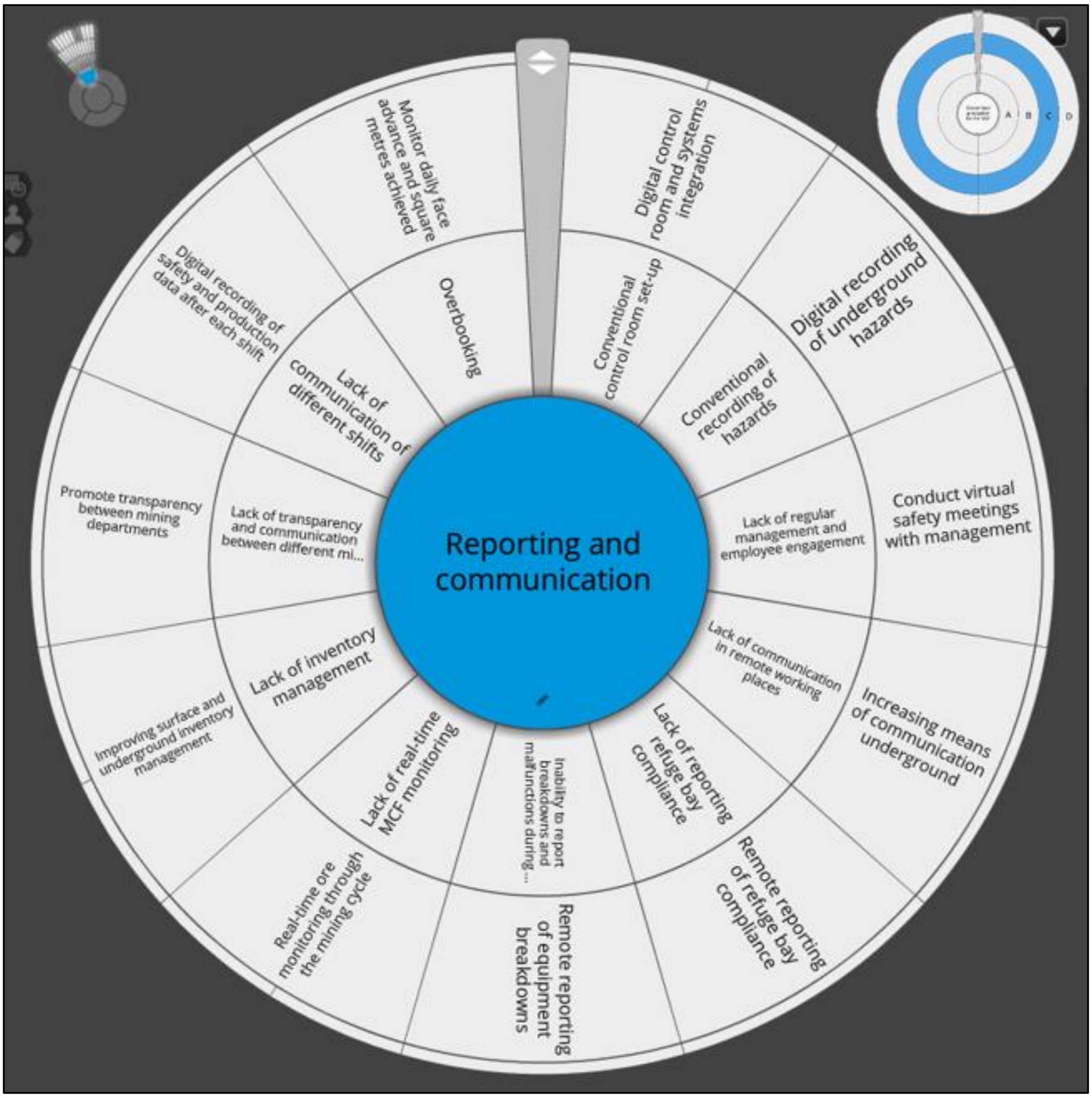


Figure 65: Output of Proposed Technology During Reporting and Communication

It is important for any mine to enhance its communication methods as this allows for those on surface to keep track of what is happening underground. Reporting and communication also make it easier for the workforce to understand the safety hazards at the working place before proceeding with work. The issuing of communication devices to underground workers will ensure employees are able to efficiently communicate with the control room and with each other. Figure 66 shows digital technology that can be implemented to improve the current state of reporting and communication at the operation.

Figure 66: Digital Technology for Reporting and Communication

Table 19 shows the percentage adoption of modernisation at the operation and the state of readiness to automate. These percentages were used as an input on Goalscape and the software estimated this phase to be 19% modernised. Appendix 11 shows how digitally advanced the stage of reporting and communicating at the conventional mine. This stage of the mining cycle is still far from complete automation because communication is only through telephones available at the waiting place and refuge bays. There are many shortcomings of reporting and communicating in this mine as highlighted in Figure 64.

The implementation of digital technologies that have been outlined in Figure 66, will result in transparency between the different mining departments. Communication will also be enhanced between mining employees underground and the different working shifts. Inventory can be tracked to ensure the operation well manages its resources and less waste is produced. The control room can also be transformed to constantly give feedback of the systems underground as a videowall at the control room will report in real-time the performance of the installed systems. The mining operation thus becomes a continuous flow of information. Table 19 also highlights digital systems at DigiMine to fill the automation gap while reporting and communicating in conventional mines.

Table 19: Reporting and Communication: State of Readiness at Conventional Gold Mine

Required technology	**Example of digital system**	**State of adoption at conventional mine**	**Examples of similar digital systems installed at DigiMine**
Digital control room	Integrated control room	20%	DigiMine Control room, YoungBlood Mine IoT, IBM Video Wall, Future Systems
Digital recording of hazards	Electronic data capturing	25%	Adroit Scada System, YoungBlood Mine IoT, Future Systems
Conduct virtual meetings	Live streaming underground meetings	20%	Adroit Scada System
Effective communication underground	Wireless underground communication systems	15%	Visible Light Communications
Remote reporting of refuge bays	UAV	15%	MHSC UAV
Remote reporting of equipment breakdowns	Digital twinning	15%	Reactore
Real-time ore monitoring	Smart sensors and UAV	15%	MHSC UAV
Inventory management	Underground surveillance and UAV	15%	EOH and IBM Camera System, IBM Smart Mine Access Control, BeiDou
Promote transparency	Shared database for information sharing	25%	Adroit Scada System, YoungBlood Mine IoT
Overbooking	UAV	15%	MHSC UAV

7.3 Summary and Conclusion

Figure 67 illustrates the various stages of the mining cycle which are included in the blueprint for modernised production. Other factors have been included in the blueprint which do not fall under the mining cycle but have significant influence on the production phase of the MVC. Appendix 12 summarises the challenges encountered in each stage of the mining cycle while Appendix 13 is a summary of the different outputs the proposed technologies to be implemented must have to mitigate the effects from the mentioned challenges. Appendix 14 is a summary of the entire production blueprint including the challenges, output of proposed technology and selected digital technology as shown from Figure 40 to Figure 66.

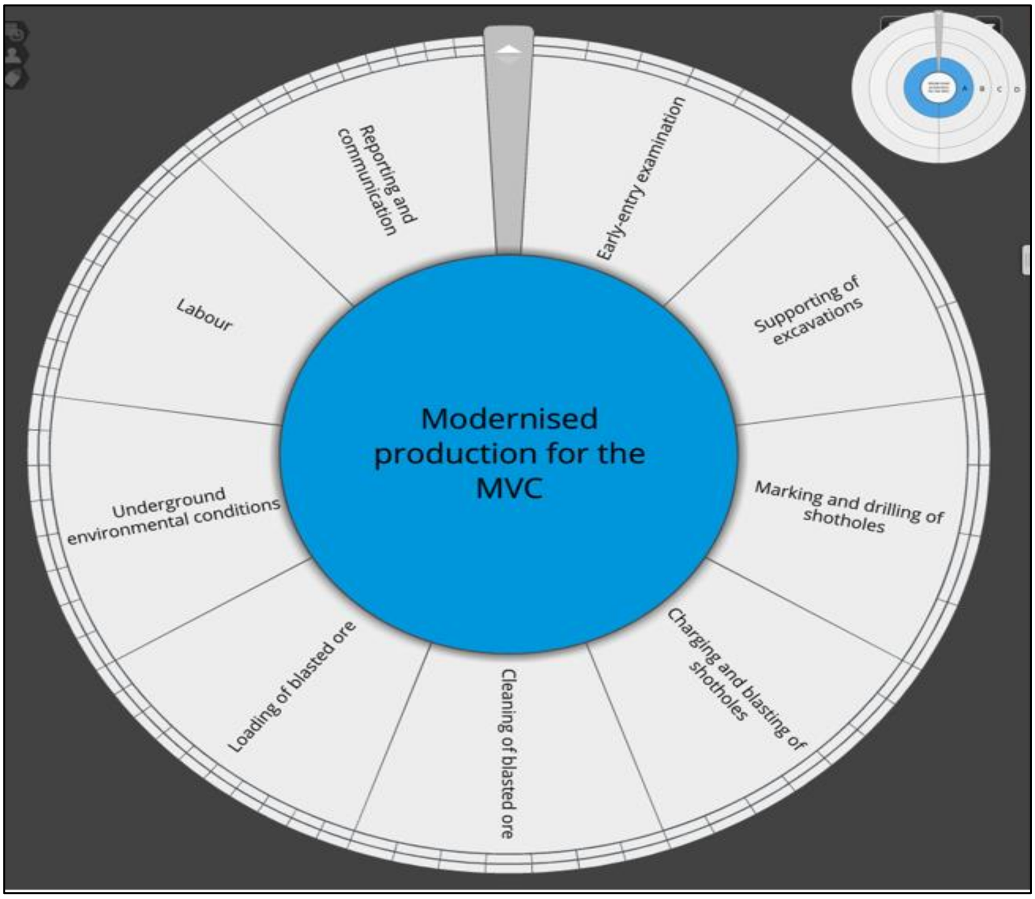


Figure 67: Stages of the mining cycle

Using Table 10 as a guide, it was found that the adoption of digital technology and automation was still relatively low at the conventional mine with most technology still in the conceptual phase of adoption. This is illustrated in Appendix 15. Using Goalscape, the conventional mine was estimated to be 18% modernised when considering all the activities that occur during the mining cycle of a working stope (Appendix 15). Therefore, it is evident that more work still needs to be done in this conventional deep-level mining operation to automate production.

What is noticeable that there are many studies that have been conducted on the implementation of innovation in the deep-level environment. Although the implementation of most of the technology highlighted above are still relatively low, the industry is actively progressing towards the implementation thereof.

Figure 68 is a master blueprint of DigiMine systems to enable smart mining. The blueprint in Figure 68 is a summary of the systems at DigiMine that can be integrated to produce an autonomous operation. Although DigiMine is yet to acquire autonomous drilling, cleaning and hauling systems as well as remote AR rock breaking systems, DigiMine is always looking forward to new partnership with vendors. DigiMine has collaborated with several vendors to have a digital mining laboratory therefore, it can be expected that in the next few years DigiMine will have more partners to have a fully autonomous digital mining laboratory consisting of drilling, cleaning, and hauling equipment and systems.

In conclusion, Goalscape was used to determine the progress of modernisation at the conventional mine where the case study was conducted. The scale of modernisation in each stage of the mining cycle was estimated by developing a progress rating criterion. This enabled the overall estimation of modernisation for the entire mining cycle at the operation. The vital finding from this chapter is that this conventional mine has only modernised 18% of the production in the mining cycle. This is because most of the technology is yet to be adopted and still in the conceptualisation phase. Although studies have been conducted on the adoption of innovative technology in the deep-level conventional mining industry, the results obtained from Goalscape illustrate how far behind this conventional gold mine is with modernisation.

The Goalscape blueprint illustrated in this chapter highlights digital technologies that can be implemented to eliminate or mitigate the challenges encountered in each phase of the mining cycle of a working stope. The adoption of this blueprint will result in the conversion of conventional mines into autonomous twenty-first century mines which have improved safety and production. The next chapter is the case study of DigiMine and discusses the lessons drawn from the adoption of digital systems at DigiMine. Chapter 8 also details the implementation plan highlighting the skills and competence required for a twenty-first century mine.

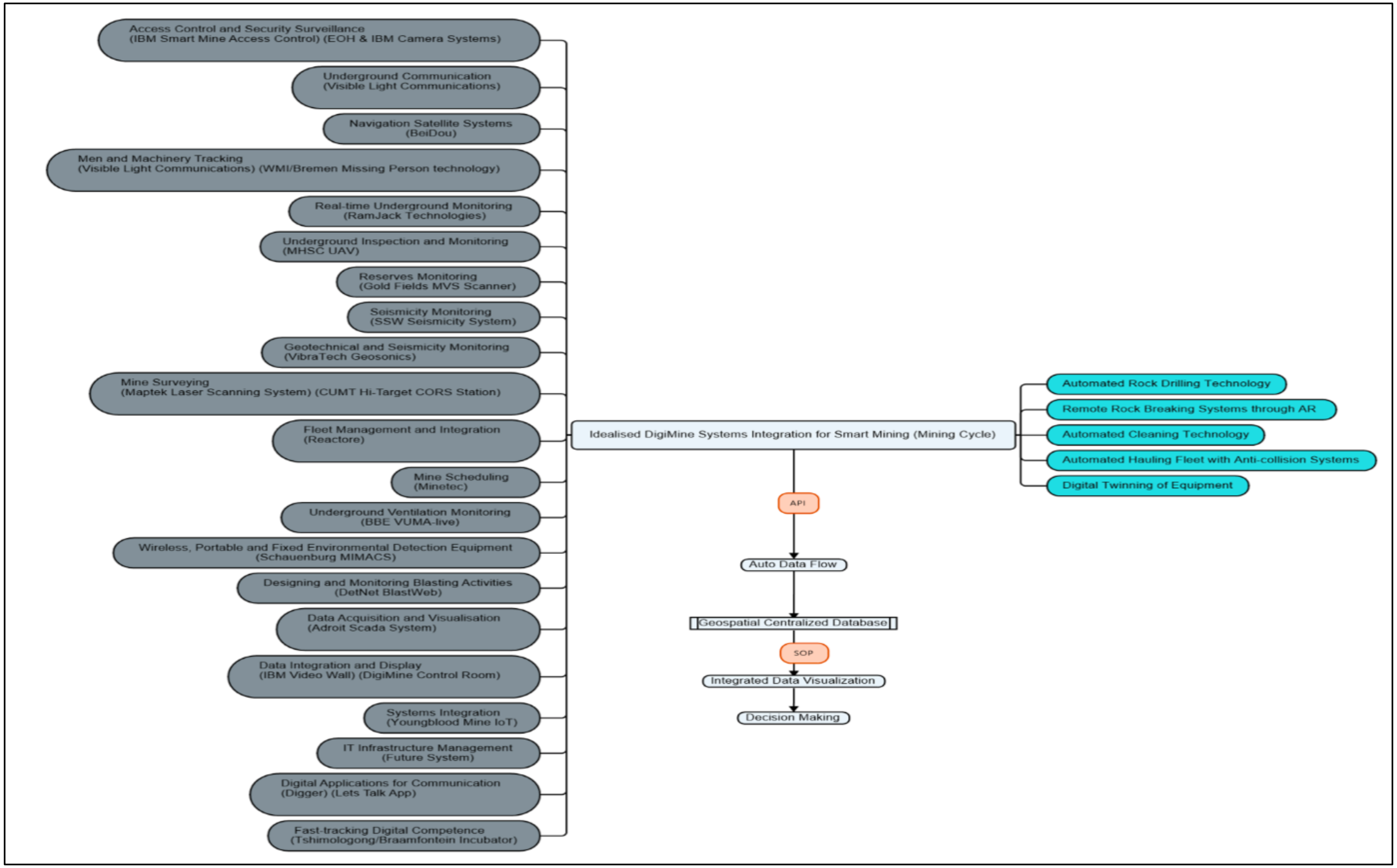


Figure 68: Master Blueprint of DigiMine Systems to Enable Smart Mining

8 Implementation Plan and DigiMine Lessons

A conceptual mine modernisation blueprint for the activities within the mining cycle of a conventional mine was discussed in Chapter 7. The blueprint illustrated how the challenges encountered in the mining cycle can be mitigated using digital technology. This chapter details the implementation plan that can be used to adopt the mine modernisation production blueprint highlighted in Chapter 7. The chapter also compares the skills and competence of current employees to that required for a modernised mine. The implementation plan illustrated in this chapter focuses on the preparation of the work environment for mine modernisation. Lastly, the chapter seeks to draw lessons from the use of digital systems at DigiMine to anticipate the requirements of installing digital innovation in the conventional mining industry.

8.1 Implementation Plan

Malsam (2019) defined an implementation plan as a tool to identify and map out the necessary steps to achieve a certain goal within a given time frame. Prior the implementation of technology in the conventional mining industry, an implementation plan must be drafted. This is because the roles and responsibilities in such an operation must be known. Figure 69 illustrates an implementation plan that can used when adopting the mine modernisation production blueprint discussed in Chapter 7. Adopting an implementation plan has the following benefits:

- Goals are well-defined and understood;
- Required resources are known ahead of time;
- Schedules are set, and progress is regularly monitored;
- Required teams and their respective responsibilities are known;
- There is increased communication amongst involved teams;
- Challenges are anticipated well over time and contingency plans are available; and
- There is increased investor confidence through better risk management and visible progress rating.

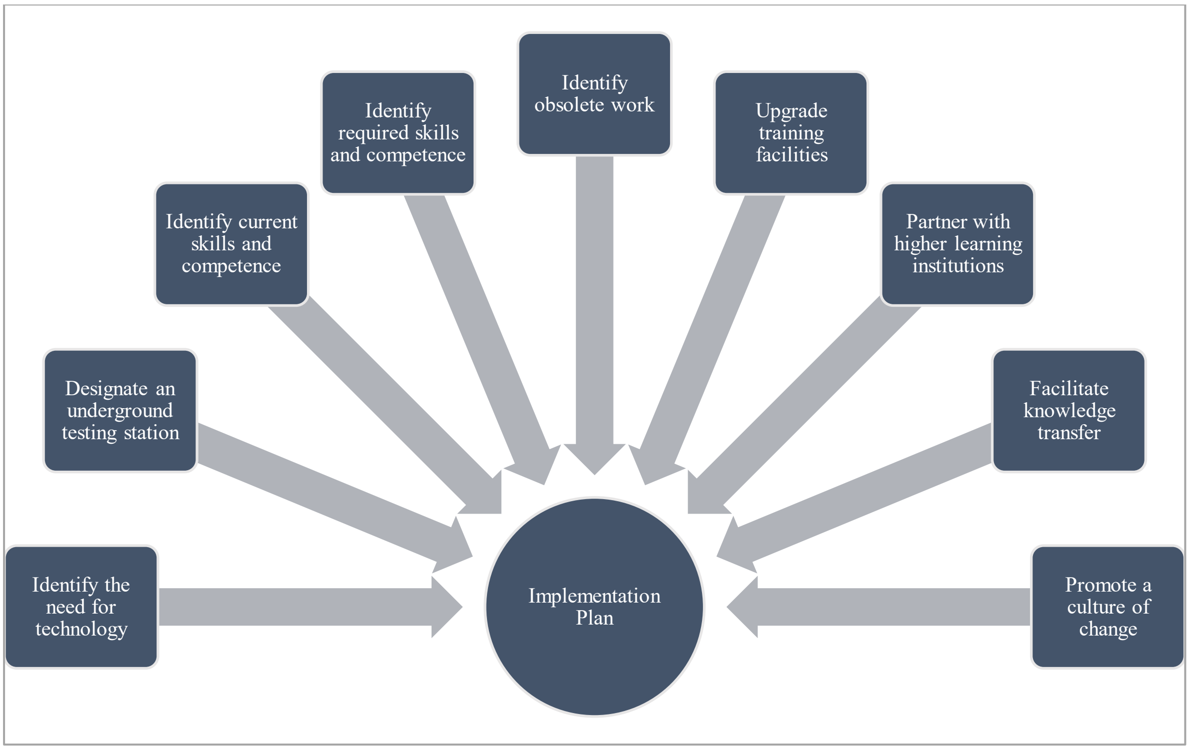


Figure 69: Implementation Plan

8.1.1 Identify the Need for New Technology

Different mining entities adopt technology for different reasons. Therefore, it is important for an entity to understand its need to implement technology. Hereinafter, the mining operation seeking to adopt digital technology will be referred to as the commissioning entity. Once the needs of the commissioning entity are known and the required technology has been identified, the commissioning entity can begin to look for suitable vendors. The vendors will supply the commissioning entity with the required technology as well as the necessary after-sale support. However, to determine the functionality of different systems in the humid, dark and deep-level underground environment, it is important to test the systems on the actual mining environment.

8.1.2 Designate An Underground Testing Station

Testing and implementing digital technology on an operating mining entity has potential to disrupt production when conducted on working stoping panels. Therefore, it should be considered to initially test digital systems on an underground mining level which is not actively busy. The entire level can be designated for the testing and implementation of new technology. This testing level can be referred to as the “digital level” of the mine, and this level will be entirely powered by digital technology and automation. The digital level can have its own digital control room located either on surface or in a safe underground area. It is known that change introduced too quickly on any environment can cause too much shock to the system and induce failure. Therefore, establishing a digital level ensures that technology can be gradually introduced to the operation thus giving sufficient time to have the workplace and workforce adapt. Once the testing of technology at the digital level is successful and the technologies are well understood, the digital systems can then be rolled over to the rest of mine. The following benefits can be expected when adopting a digital level in a conventional mine:

- Integrate new technology with the mining cycle;
- Allows for the testing of technology without disrupting the mine's production;
- Gives enough time to test and understand the technology;
- Prepares the work environment for the implementation of technology;
- The digital level can be used to test and showcase the latest digital technology available on the market;
- Fast-tracks the adoption of high-level technology in the deep-level mining environment;
- Allows for the anticipation of risks and threats;
- Prepares the workforce and gives adequate time to train the current workforce on the use of digital systems;
- Promotes digital skills and competence through advance training;
- Enables the operation to identify and grow existing talent through exposure and training in digital technology;
- Enables research students to test their innovation on a practical environment;
- Increases investor confidence towards the funding of digital innovation in the deep-level environment; and
- The gradual introduction of technology ensures that once full-scale implementation occurs, the entity is already familiar with the use of digital systems.

An adjustment must be made on the environment and the various digital systems to enable compatibility. This means that the current conventional infrastructure must be upgraded at the digital level to ensure the desired output of the installed technologies are achieved. Once there is understanding of what it takes to convert a conventional mine to an autonomous operation, the various digital technologies can then be gradually phased out to other parts of the mine. Although the digital level is a testing level for new technology, there must be blasting activities taking place within the stopes of this level. This is because blasting activities will make it possible to determine the effect the installed technologies have on safety, profitability, and life of mine. However, the above approach of adopting a digital level has the following limitations:

- There will be high investment required as a result of additional costs to run the digital level;
- An independent team of mining departments will have to be selected and assigned to the digital level;
- Miscommunication between the production teams in other parts of the mine and the digital level crew can lead to frustration of the project; and
- The digital level crew will have to follow the schedule of the mine so as to not interrupt the mine’s existing schedule.

8.1.3 Identify Current Skills and Competence in A Conventional Mine

According to Muir (2015), the conventional gold mining industry is dominated by a workforce that is less technology-skilled than any other mining sector. This is due to the industry having implemented fewer technologies in their operations in the past. Macfarlane (2001) appropriately suggests that South African mines are not learning organisations. Previously, the entry-level into the mines was basic primary education, and today the minimum entry to the mining industry is a Grade 12 certificate. Although this is the case, a majority of the workforce in the conventional mining industry is the aged workforce who did not matriculate, and struggle to read and write in English. This is the fundamental reason the primary language of communication in the conventional mines is still Fanakalo. The mining industry has initiated skills development of the aged workforce in the form of Adult Education and Training (AET) which was previously known as Adult Basic Education and Training (ABET).

Appendix 16 highlights the roles and responsibilities of the current workforce at the conventional mine while Appendix 17 shows the qualifications possessed by this workforce. Appendix 16 and Appendix 17 thus give an idea of the skills gap in the conventional mining industry. The miner is the most qualified member in the crew as it is mandatory for him/her to have a Grade 12 certificate. This is because a Grade 12 certificate is required when applying for a blasting certificate for metalliferous mines and for effective communication to higher levels of management. The blasting certificate issued to miners is an external examination and is accredited by the DMR. Appendix 17 shows that the rest of the stoping crew has obtained certification internally through training programmes offered by the operation’s training centre. Underground workers who have been issued with operating licenses attend refresher courses annually to have their license renewed. Due to the dangerous nature of work underground, only those with valid operating licenses are allowed to conduct certain tasks.

Figure 70 illustrates the hierarchy of supervision at the conventional mine. The line of communication is from executives and goes through several channels until it reaches the crew underground. Mine overseers and shift bosses monitor the health and safety of employees while ensuring production targets are achieved. The shift boss is the supervisor with more direct contact with the underground crew and the workplace as compared to the mine overseer and other high-level management. The shift boss is therefore, the link between underground crews and management.

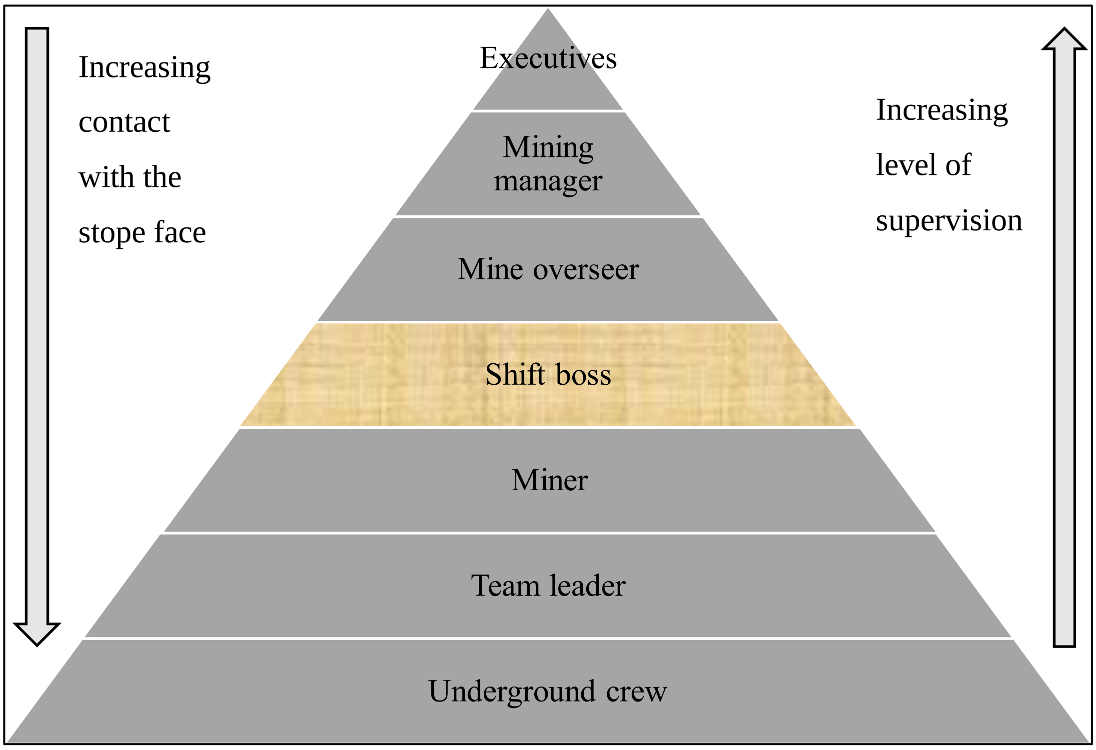


Figure 70: Hierarchy of Employees in a Conventional Mine

Table 20 illustrates the current education requirements for underground supervisors. As can be seen from Table 20, it is not mandatory for supervisors to have any higher learning qualification, they only need to possess the required certification issued internally by the mine’s training centre and by the DMR. For an individual to reach shift boss supervisory level, they need to have obtained necessary underground experience as a miner and the certification shown in Table 20. Mine overseers and managers are usually university graduates and the mining industry obtains mining engineering graduates from three leading universities namely; Wits University, University of Pretoria and the University of Johannesburg. These institutions offer a mining engineering qualification in the form of a Bachelor of Science, Bachelor of

Engineering and Bachelor of Technology respectively. Once completed with studies, mining engineering graduates undergo an extensive graduate programme which consist of training and exposure to the underground environment and various mining departments. Mining operations have uniquely designed their graduate programmes to cater for the needs of their operation. Ultimately, the role of graduate programmes is to produce future supervisors with underground experience and engineering knowledge.

Table 20: Supervisor's Certification in a Conventional Mine

Role	**Required certificate**	**Issuing body**	**Pre-requisite certification**
Shift boss	Shift boss certificate	Internal	Blasting certificate
Mine Overseer	Mine overseer's certificate	DMR	Blasting certificate, shift boss certificate
Mining Manager	Mine manager's certificate of competency	DMR	Blasting certificate, shift boss certificate and/or mine overseer's certificate, diploma/ bachelor's degree in mining engineering

8.1.4 Identify Required Skills and Competence for A Modern Mine

Adopting the *Conceptual Mine Modernisation Blueprint for the* Mining Cycle illustrated in Chapter 7.2 will require increasing the level of competence of underground stoping crews, Appendix 18. This competence is mandatory for employees to have to be able to navigate in a modern autonomous mine. While Appendix 18 shows the competence underground stoping crews should possess by work designation, every employee at the autonomous mine should be able to:

- Read and analyse data from smart monitoring systems and smart sensors;
- Understand digital and technology systems;
- Understand how smart energy systems work;
- Use wireless communication network and distress communication features;

- Use digital platforms to engage management;
- Share production and safety data electronically;
- Use the operation’s shared database to find information; and
- Use advanced training facilities and attend Mining 4.0 courses.

As supervisors are the line of communication between management and workers, it is fundamental that they are competent in the use of digital technology. There is also a need to reskill the different mining departments to fulfil their duties in the autonomous mine. Frontline supervisors such as shift bosses should be competent in the following:

- Remote monitoring of the health and safety of employees;
- Remote monitoring of the underground environment;
- Accessing underground surveillance;
- Assessing and interpreting trends of electronically logged workplace hazards;
- Understanding the use and functionalities of various digital systems;
- Interpreting integrated feed displayed on the video wall;
- Interpreting data from digitally twinned equipment;
- Managing inventory and assets; and
- Communicating with vendors and suppliers.

While the skills required for a modernised mine are entirely dependent on the nature of work conducted at the mine, the basic skills have been outlined in Table 21. Work underground in a modern mine can be conducted remotely through VR, AR and robotics as shown in Figure 71. As the nature of work will transition to require less physical strength, there will no longer be a need, for example, for a scraper winch driver to break large rocks at the tip as cleaning can be done remotely. Therefore, more roles can be open for women and those who are not physically considered strong. The skills highlighted in Table 21 ensure the operator shown in Figure 71 is able to manipulate and control the equipment they are remotely responsible for.

Although the equipment used at the mine will have built in safety features, employees are ultimately responsible for controlling the movement of autonomous vehicles. Therefore, these operators should have high attentive skills and a quick response time. The physical strenuous work may be eliminated by automation however, employees must be able to work under high pressure and apply immerse reasoning when making decisions. Operators need to have good judgement and good decision-making skills. As the digital technology will be supplied by various vendors, the workforce at the modern mine should have good communication and social skills to ensure that the relationship with respective vendors is maintained. In addition, the modern mine consists of a workforce that is keen on learning and introducing new ideas to the workplace to result in a versatile work environment.

Table 21: Twenty-first Century Skills Required for a Modern Mine

Critical thinking	Data analysis	Resilience and stress tolerance
Complex problem solving	Communication skills	Perpetual skills
Cognitive skills	Interpersonal skills	Kinaesthetic skills
Creativity	Fine abilities to operate joystick functions	Agility
Programming and software skills	Emotional intelligence	Coordination

Figure 71: Machine Operator Controlling Equipment Remotely (Swart, 2019)

8.1.5 Identify Obsolete Work as A Result of Mine Modernisation

Chapter 6.2.8 highlighted the number of people within the stoping crew at the conventional mine. This was compared with the number of personnel that can be expected to be required in a modern mine in Table 22. Table 22 shows that the adoption of digital and 21st century technology will require less people to conduct work activities and may result in an estimated

45% reduction. This is because the rock drilling process can be modernised and there will be no need to have as many rock drillers to drill the face. Using advanced rock drilling equipment, a rock driller can drill the entire stope face length alone. Seemingly, the cleaning phase of the mining cycle can be automated. Therefore, there will be no need to have many scraper operators as one person can remotely clean the stope face, strike gully and centre gully simultaneously.

Table 22: Stoping Crew in a Conventional vs Modern Mine

Conventional mine stoping crew	**Number of personnel**	**Modern mine stoping crew**	**Estimated number required**
Miner	1	Miner 4.0	1
Team leader	1	Team leader	1
RDO	6	Remote RDO	1
Scraper winch drivers	6	Remote scraper operator	1
Stoping labourers	4	Stoping labourers	4
Construction crew	4	Construction crew	4
Total: 22		Total: 12	

Table 22 shows that the conventional miner is replaced by a more advanced and digitally skilled miner referred to as a Miner 4.0. Miner 4.0, becomes a new addition to the crew and remotely oversees the work conducted during the shift such as monitoring face advance, ground conditions and mining reserves. The team leader remains an essential part of the crew yet takes on the role of a “conventional miner”. This is because unlike the Miner 4.0, team leaders will monitor the work conducted by employees left at the stope. These employees include stoping labourers and the construction crew who install support and extend essential services closer to the stope face respectively. As this work is not modernised, the number of employees in this line of work is likely to remain the same.

Shift bosses’ roles will be to monitor the health and safety of employees and oversee the Miner 4.0. The functions of the shift boss will overlap with that of the Miner 4.0 as he/she will have more supervisory roles. Therefore, an operation may not need as many shift bosses as required today. As a result of the Miner 4.0 having more roles and responsibilities to remotely monitor working places underground, an operation may need more digital miners. This is because the traditional way of having a miner with several panels may be unsuitable as the Miner 4.0 should be attentive and focused on a particular working stope to ensure safety compliance and productivity.

The conceptual mine modernisation blueprint for the production phase of the MVC has resulted in some work becoming obsolete, Table 22. In addition, there will be a significant reduction in the number of people required to work in close proximity to the stope face. Table 22 shows that the modern mine can result in over a 45% reduction in the number of underground stope employees. It can also be expected that the decline in employment as a result of modernisation will not necessarily reduce labour costs as the skilled workforce at a modern mine may come at higher wages. This theory was also put forth by Johansson, et al. (2010) who stated that although automated mines have fewer workers due to removal of redundant work, there are higher individual wage costs due to the workforce's increased skills and competence. The adoption of the digital level at the conventional mine will thus enable a commissioning entity to prove or disprove this statement by measuring and comparing the input and outputs from this section of the mine. This will also offer the industry time to determine what to do with those whose work has now become obsolete.

8.1.6 Upgrade the Existing Training Facilities

Although the skills required for a modern mine are not common in the conventional mining industry, developing a digital level at the conventional mine will ensure the operation has adequate time to skill its current workforce on the use of digital technology before rolling out the technology to the rest of the mine. Therefore, a commissioning mining entity should upgrade its current training facilities to become twenty-first century training facilities. There has to be a change in the skills and competence offered in these training centres to facilitate the competency required in an autonomous mine. Mining companies can work closely with the MQA which administers and develops learning programmes for the mining industry.

The MQA is also responsible for addressing skills shortages in the mining industry by introducing development training and exposure (Minerals Council South Africa, 2019d). Collaboration in the mining industry would ensure that shift tasks are assigned to the already employed low-skilled workers rather than to replace existing workers. This means that some of the current workforce can be used without the need to employ an entirely new workforce. In addition, the partnership between the MQA and mining operations would ensure the industry retains the mining engineering graduates in the industry. Thus, the mining industry will have sufficient competent personnel for safe production for autonomous mining.

8.1.7 Partner with Higher Learning Institutions

Further Education and Training (FET) colleges offer artisan skills and training. Although these colleges are yet to offer Industry 4.0 and Mining 4.0 learning, they can be a great way for the mining industry to improve the competence of artisans. In the foreword to *Universities of the Future (2019),* Maria Clavert reported that university are currently preparing students for jobs that do not yet exist, to use technologies which have yet to be inverted to solve problems which are not yet known. Hence, Clavert further reported that higher institutions need to work closely with the industry, governmental agencies, and student organisations in order to cater for the emerging competency needs of the industry. Therefore, as there are many changes occurring on the mining environment and nature of work, universities are challenged to transition to become University 4.0 institutions that offer an advanced Mining 4.0 syllabus. Moreover, the current primary and high school curriculum must be adjusted to include 4IR for undergraduates to already have a background on digital technology when they enter university.

8.1.8 Facilitate Knowledge Transfer

As the conventional mining industry has a workforce that is less educated as illustrated in Appendix 17, a majority of these workers have aged. Although these workers may be too old to endure the extensive training that is required to be competent to operate in an autonomous mine, they possess decades of mining experience. This is while mining engineering graduates will have digital experience yet lack underground mining experience. Therefore, there is a need to transfer knowledge from the older to the younger generation to ensure employees possess sufficient knowledge and expertise.

8.1.9 Promote A Culture of Change

Although advanced training facilities can be established, a culture of change is required in the conventional mining industry. According to Macfarlane (2001), there has been instances where technology has failed due to managerial reluctance; Steward (2013) awards this reluctance from managers as a result of conservatism. Therefore, if the attitude of reluctance is from those higher up in the hierarchy of management as shown in Figure 70, it can be expected that the manager’s subordinates will likely not be accommodating to the change. Hence, Vogt and Hattingh (2016) stress that the failure to successfully implement technology in any system is dependent on the people than the technology itself. It is because of these reasons that it is much easier to mechanise a new mine than an existing one as the new employees should not share the same managerial systems and values of an existing mine (Macfarlane, 2001). This observation by Macfarlane is fundamentally important for modernising deep-level gold mines in South Africa.

Considerations for the Implementation Plan

Figure 72 illustrates the various factors the implementation plan should entail. In each stage of the implementation plan it is important to define the goals and allocate timeframes when such goals should be achieved. This will ensure that the progress into achieving the milestones is tracked; this should be done regularly. In addition, there should be a metric of success which is used to compare the progress within the various stages of the implementation plan. It is also important to determine the required resources for the milestone such as budget, personnel, etc. Thereafter, teams must be designated towards these goals. Team leaders should also be assigned who will identify roles and assign responsibilities. Most importantly, risk assessment should be conducted to identify areas of threat and resistance in each phase of implementation. This ensures that contingency plans are in place to reduce the effects of threats.

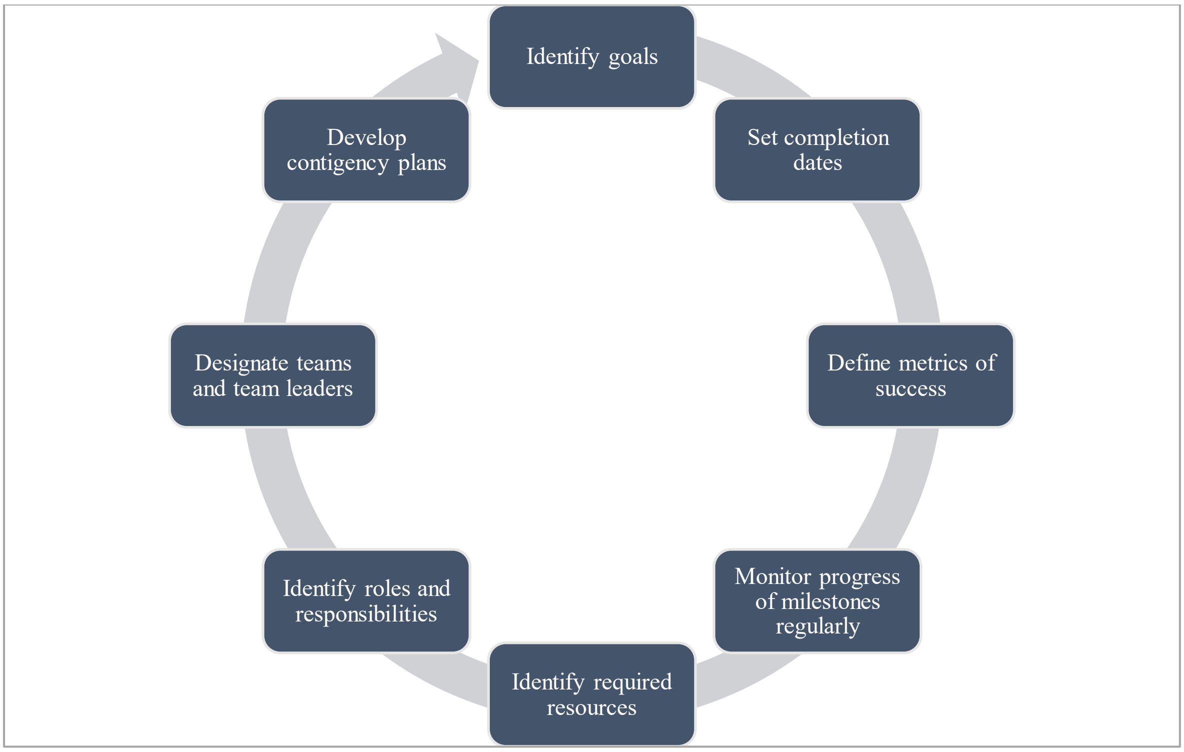


Figure 72: Considerations for the Implementation Plan

8.2 The Digital Mining Laboratory

The Wits Mining Institute (WMI) is hosted at Wits University, Johannesburg. WMI comprises of several research institutions such as the Sibanye-Stillwater Digital Mining Laboratory (DigiMine), Centre for Sustainability in Mining and Industry (CSMI) and Centre for Mechanised Mining Systems (CMMS) (Potgieter, 2019). WMI aims to introduce twenty-first century mining to the current African mining environment. Although the African continent is rich in minerals, the adoption of innovative technology in the mining industry is still relatively low. Hence, WMI aims to fast-track the adoption of Mining 4.0 and future of work. WMI conducts twenty-first century research on sustainable mining therefore, growing talent in the different mining fields (Cawood, 2019c).

DigiMine is equipped with the latest digital mining innovation to evaluate the benefits of using technology in the mining environment to restore safety, competition, and profit in operations. DigiMine consists of several students conducting research on digital systems and their application in the real mining environment. The case study of DigiMine broadens insight on how technologies available at DigiMine can be incorporated into existing deep-level narrow reef mines. DigiMine has installed a wide variety of digital systems and the case study thereof enable the conventional mining industry to draw lessons from the installation of digital technology, this will be discussed in Chapter 8.3. Table 23 illustrates the digital themes at DigiMine to enable the mine of the future.

Table 23: DigiMine Themes to Enable the Digital Mine of the Future (Cawood, 2019c)

Theme	**Purpose**
Theme One	Wireless Communications Systems: Reliable and multi-purpose underground communication systems
Theme Two	Surveying, Mapping and Navigation: Real-time mapping of underground working places
Theme Three	Health, Safety and Security: Real-time intelligent risk management
Theme Four	Integration for Smart Mining: Enabling systems integration

8.2.1 The DigiMine Mock Mine

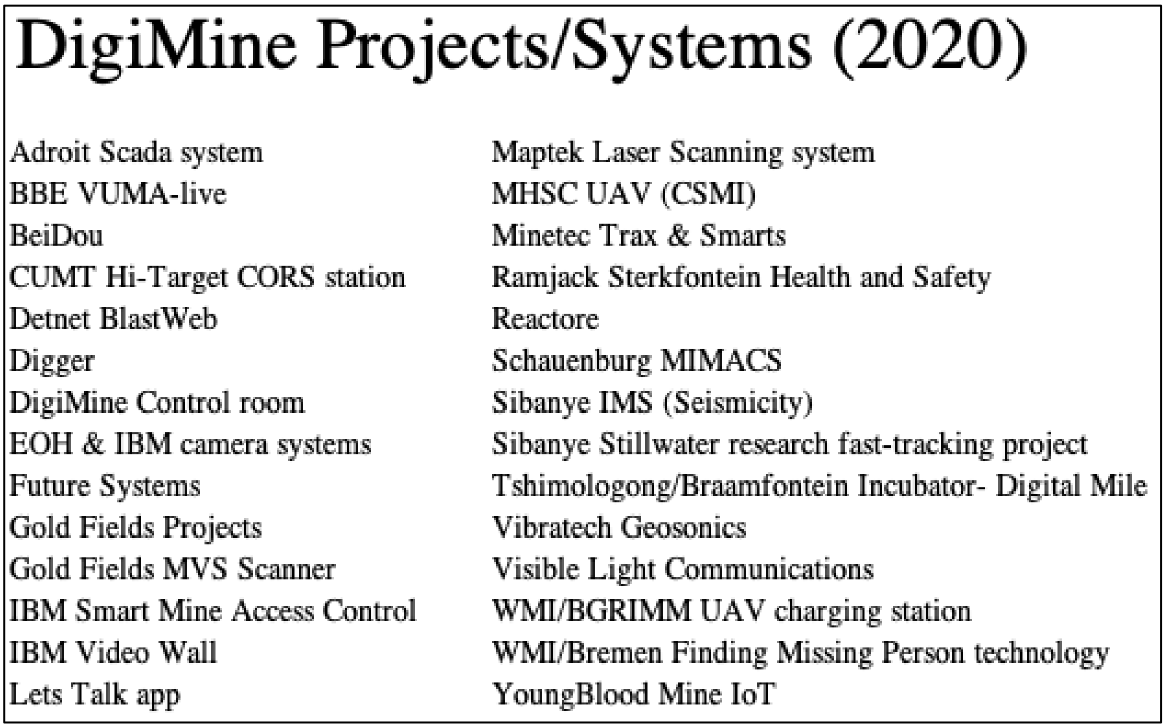
DigiMine consists of a mock mine situated on the basement of the Chamber of Mines building, Wits University. The mock mine was constructed in 2012/2013 and simulates the real underground environment (Birch, 2018). This mock mine is not only used by postgraduates for research, but undergraduates have access to it as well for better understanding of the real underground environment. Birch (2018) revealed that the roof of the Chamber of Mines building represents ‘surface’ and the stairwells to the mock mine represent the ‘shaft’. The mock mine consists of a lamproom, crosscut, development end and a support-installed stope, Figure 73 and Figure 74. This mock mine offers an idea of the actual underground environment for people who have never been underground and provides an ideal mining environment to install and test underground mining systems.

Figure 73: DigiMine Lamproom (Javaid, 2018)

Figure 74: Crosscut, Development End and a Stope (Javaid, 2018)

8.2.2 Systems Installed at DigiMine

DigiMine has collaborated with different system vendors; the systems listed in Figure 75 have been installed at DigiMine to address the different themes outlined in Table 23. DigiMine has integrated different systems to result in an ecosystem of vendors. Based on contractual agreement, the vendors install and test their systems at DigiMine and both parties have access to the generated data generated from the systems. DigiMine uses the data for research purposes while vendors also have remote access to the processed data from DigiMine (Fan, 2019).



DigiMine Projects/Systems (2020)

Adroit Scada system
BBE VUMA-live
BeiDou
CUMT Hi-Target CORS station
Detnet BlastWeb
Digger
DigiMine Control room
EOH & IBM camera systems
Future Systems
Gold Fields Projects
Gold Fields MVS Scanner
IBM Smart Mine Access Control
IBM Video Wall
Lets Talk app
Maptek Laser Scanning system
MHSC UAV (CSMI)
Minetec Trax & Smarts
Ramjack Sterkfontein Health and Safety
Reactore
Schauenburg MIMACS
Sibanye IMS (Seismicity)
Sibanye Stillwater research fast-tracking project
Tshimologong/Braamfontein Incubator- Digital Mile
Vibratech Geosonics
Visible Light Communications
WMI/BGRIMM UAV charging station
WMI/Bremen Finding Missing Person technology
YoungBlood Mine IoT

Figure 75: DigiMine Projects and Systems in 2020 (DigiMine, 2020a)

In addition, DigiMine comprises of a control room which integrates and monitors the performance of the different installed systems, Figure 76. The control room consists of a videowall which displays the performance of the systems in real-time. According to Fan (2019), this highly efficient control room is the operations centre, and is capable to reacting faster than the traditional control room set-up. This is because the systems are monitored in real-time therefore, any discrepancies can be detected earlier.

Figure 77 illustrates the flow of data from the installed systems at the mock mine to the videowall display in the control room. The control room consists of different computers which are supplied by the vendor to process data from the mock mine to the videowall. The data obtained from the mock mine is gathered and processed by different systems and then stored on the WMI servers (Fan, 2019). The computers are also connected to a spatial database and a central server-computer for the storage of data (Javaid, 2018). Javaid (2018) further reported that the central server is connected to the videowall in the control room through the videowall processor. The videowall displays alerts of the various installed systems therefore, the responsible person for the system can attend to it.

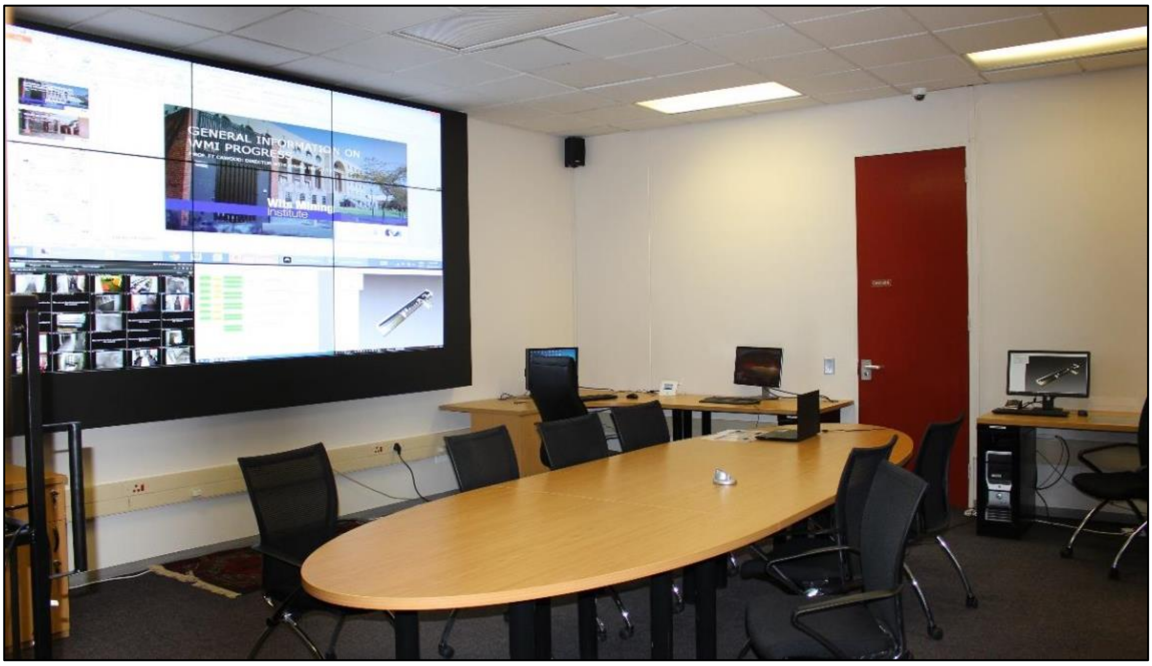


Figure 76: DigiMine Control Room (Javaid, 2018)

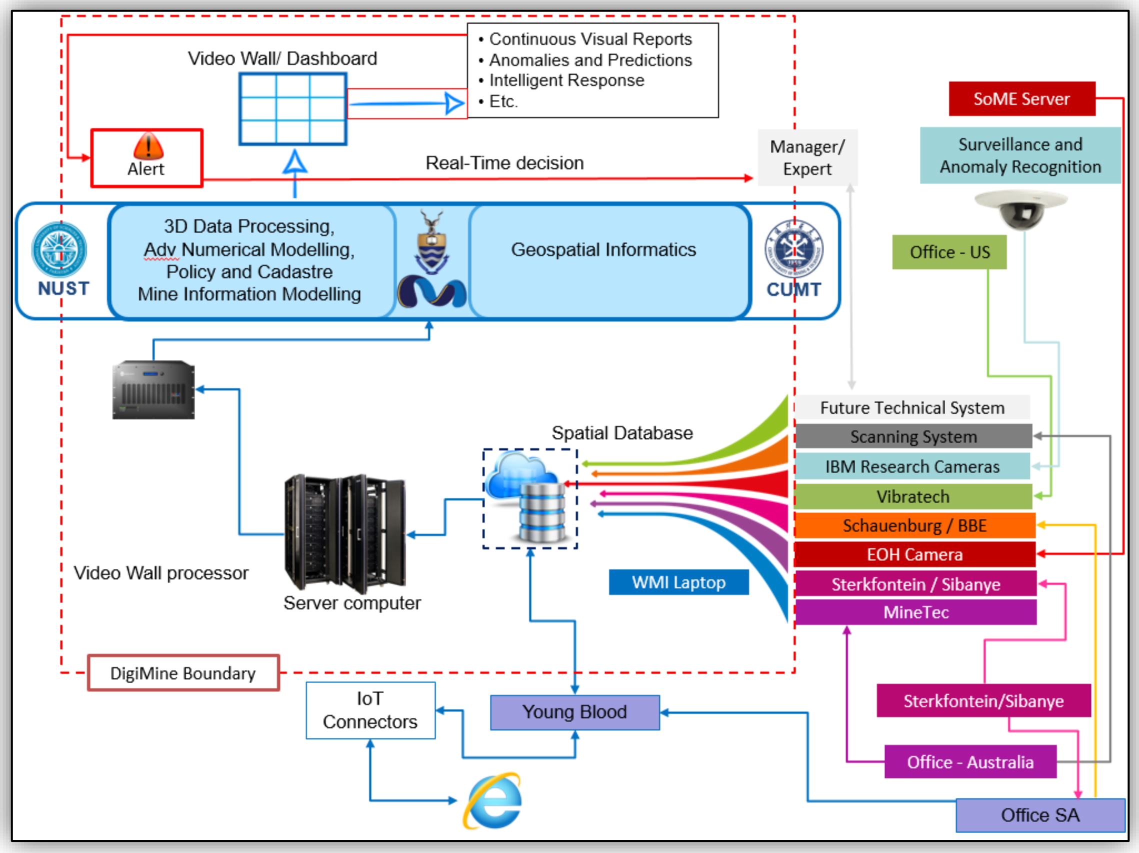


Figure 77: Architecture of Systems Installed at DigiMine (DigiMine, 2020b)

The responsible person for any system is referred to as a ‘system champion’. A system champion oversees the performance and functionality of the system they have been assigned to. A system champion for each system has to be appointed to ensure the functionality of the system is monitored. At DigiMine, system champions are allocated to various digital systems based on their area of research and field of experience. The system champion is also in communication with the vendor in case of any malfunction of the system and if the system requires upgrading. DigiMine has also established a system document technique which assists with the transfer of knowledge in case the current system champion is unable to carry on with their duties. The new system champion obtains the necessary knowledge about the system through the system document which is updated regularly.

8.3 DigiMine Lessons

The DigiMine lessons illustrated in this section highlight the lessons drawn from the installation and use of digital systems at DigiMine by expanding the research of Fan Xiang. Fan (2019), who designed a blueprint for the adoption of new technology, focuses on the lessons gained from the installation and use of digital systems at DigiMine. The blueprint architecture created by Fan (2019) requires the completion of a list of activities in each stage of technology adoption: pre-installation, during installation and post-installation. This ensures that the performance of adoption in each stage is properly monitored.

The use of this blueprint also allows for an entity to predict problems way before they occur as the blueprint ensures that most common glitches are included in the considerations. Mining operations can use the experience gained from DigiMine to prepare themselves for digital transformation as the lessons gained from DigiMine can form part of the considerations the deep-level mining industry can take into account pre-installation, during installation and post-installation of digital systems. Fan (2019) described the following three ways to acquire new digital technology in the mining industry:

- Supplier: An organisation or individual that supplies new digital technology with the capability of local technical support, however, does not provide new-technology-related services such as customised design of devices or components;
- Original equipment manufacturer (OEM): An original equipment manufacturer who normally excludes branding, marketing, and full services for their products; and
- Vendor: An organisation or individual that offers new digital technology and required services as a package. The package usually includes pre-sale installation and post-installation support services therefore, this tend to be the most suitable way to obtain new technology.

8.3.1 Pre-Installation Phase

According to Fan (2019), the pre-installation phase has the objective to understand the background of the entity which wants to adopt new technology, and to identify suitable and innovative digital solutions to install. Fan (2019) identified that the pre-installation phase has two subphases, Figure 78. The following section discusses activities to be completed by the mining operation which is about to adopt technology during the pre-installation phase.

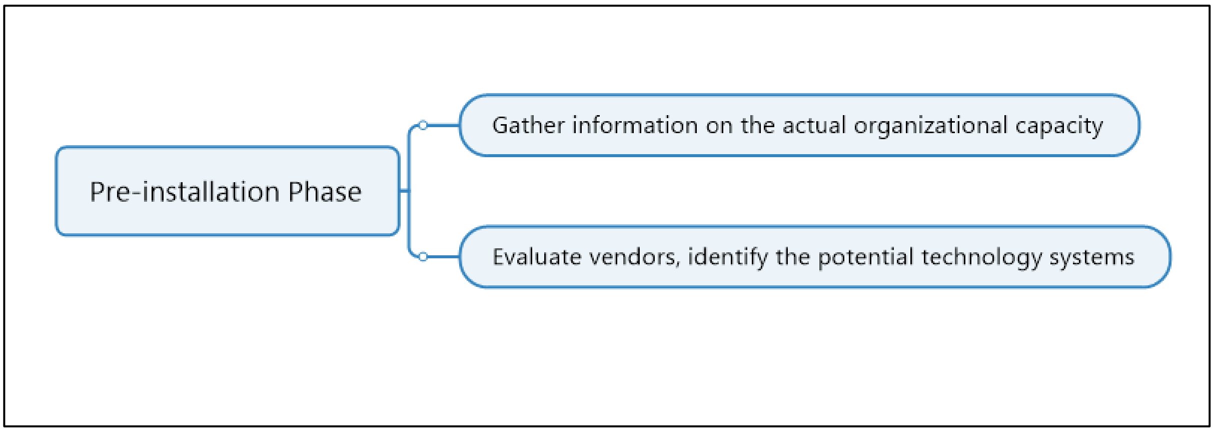


Figure 78: Pre-installation Phase (Fan, 2019)

Gather Information on the Actual Organisational Capacity

While gathering information on the commissioning entity's capacity during the pre-installation phase, the following must be observed as illustrated in Figure 79. Different mining entities will adopt technology for different reasons. It is, therefore, important for an operation to individually select technology based on the shortfalls and needs of the entity. The commissioning entity's capacity should be clearly defined during this phase. In addition, the technology to be implemented should align with the vision and beliefs of the company (Fan, 2019). According to Fan (2019), this section is critical as it provides understanding of the existing infrastructure within the entity. This enables the entity to have a clear picture of the necessary upgrades which must be made to accommodate the new technology.

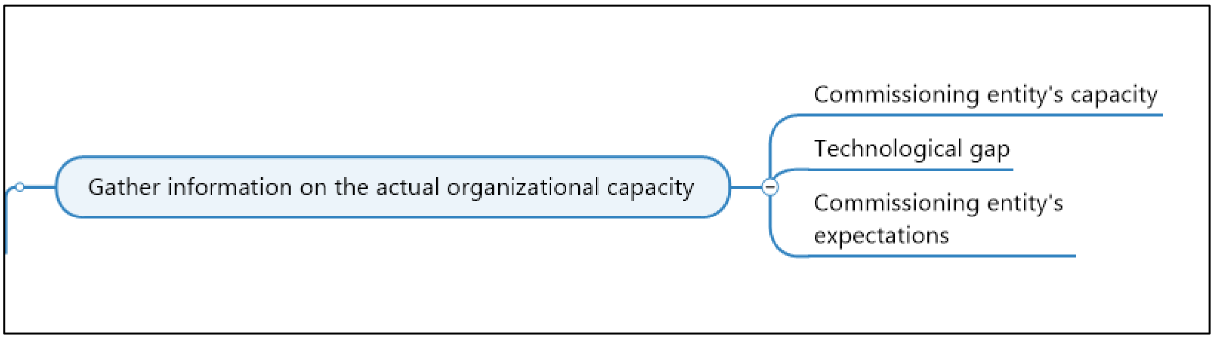


Figure 79: Tasks to be Completed while Collecting Data at the Commissioning Entity (Fan, 2019)

Moreover, prior the installation of digital systems in an entity, it is important to know the current stage of digitalisation within the entity, thereafter, develop an approach to address the shortfalls of the entity. The rate of progress in adopting digital technology must be monitored to ensure deadlines are met. It can also be useful to learn from similar organisations which adopted technology. This will ensure the entity can draw lessons from the implementation of technology. While managing the commissioning entity's expectations, it is important to have a clear budget and an understanding of what can be achieved within the budget. There should be an extra budget allocated for the upgrading of systems and an achievable timeframe for the installation of technology. In addition, it is important to understand the impact technology will have on the overall operation hence, the expectation of the operation should be regularly compared with the progress of digitalisation.

Evaluate Vendors, Identify Potential Technology Systems

The pre-installation phase also involves the evaluation of vendors to identify potential technology systems, Figure 80. The commissioning entity must find suitable technologies to cater for the challenges encountered at the operation. Thereafter, the commissioning entity must find vendors who can supply the operation with the technology. Gathering information on the vendor's capacity and technology system functionality enables the commissioning entity to have better understanding on the features the technology will comprise of and its ability to cater for the challenges in the entity. This stage also involves assessing and selection of appropriate vendors and technology systems. It was found important to have quotations from various vendors and select the best and most suitable vendor for the operation.

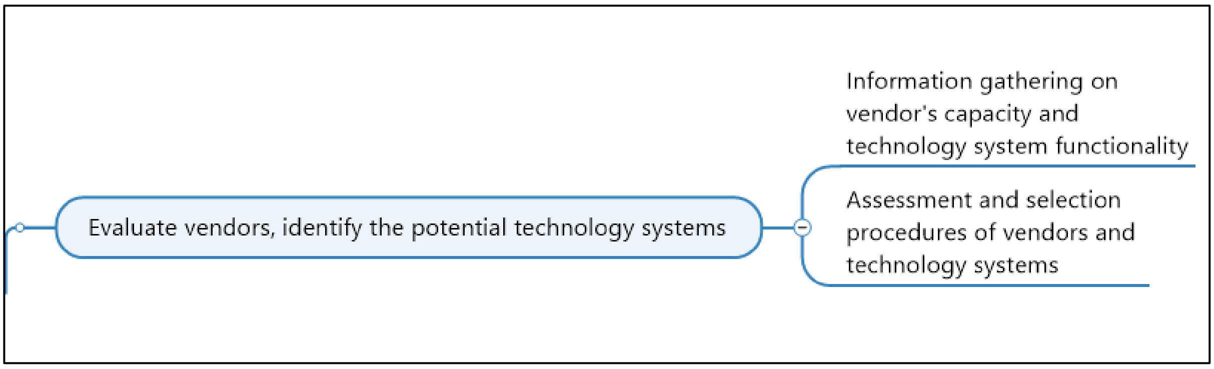


Figure 80: Evaluation of Vendors and Digital Technology Identification (Fan, 2019)

8.3.2 Installation Phase

The installation phase should provide the commissioning entity guidelines on the adoption of new technology. During this stage, the commissioning entity should implement and test the compatibility of the systems in the operation. According to Fan (2019), it is crucial to initially draft legal documents prior the adoption. The installation phase consists of three subphases as illustrated in Figure 81.

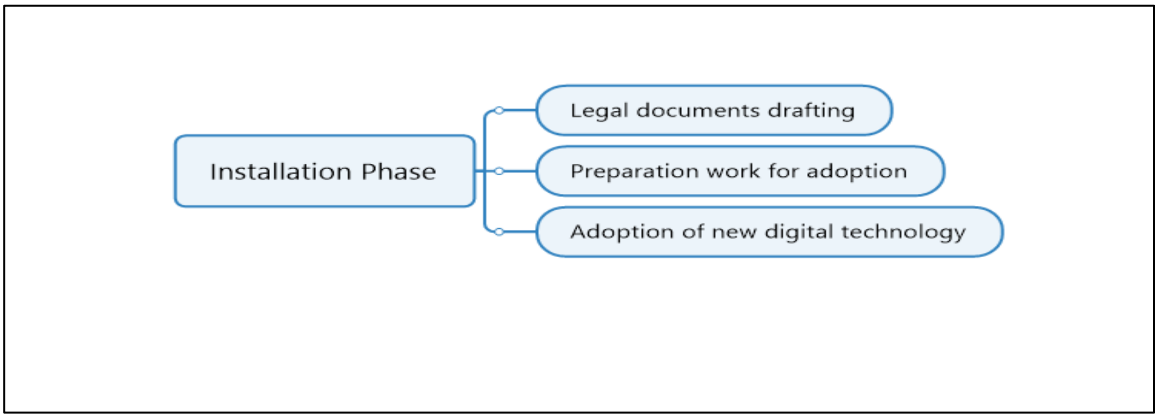


Figure 81: Installation Phase (Fan, 2019)

Legal Documents Drafting

The legal drafting of documents, Figure 82, consist of drafting of the agreement as well as contracts. The agreement should include a detailed implementation plan and estimated costs. The contract should also contain what is required for systems integration and there should also be an exit strategy which indicates under what circumstances can the commissioning entity or vendor terminate their contract.

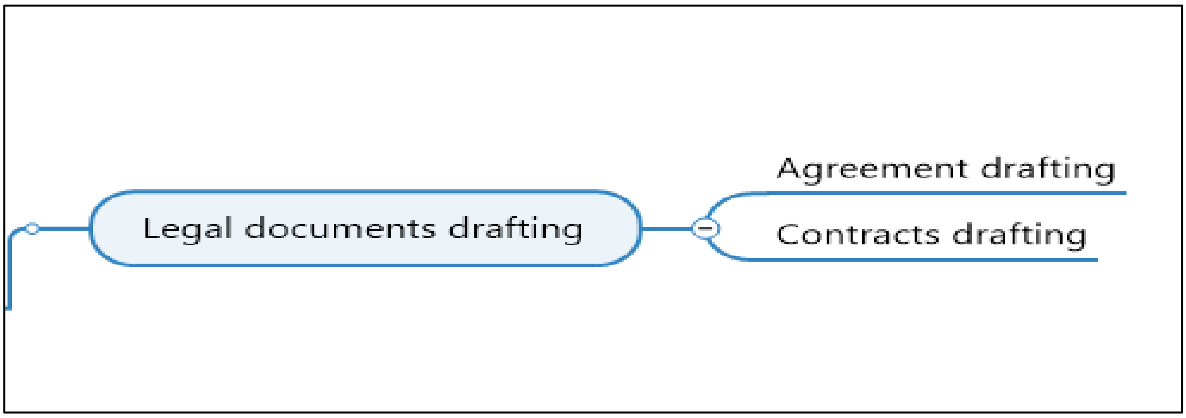


Figure 82: Legal Drafting of Documents (Fan, 2019)

Preparation Work for Adoption

While preparing for the adoption of new technology, Fan (2019) revealed that the lessons gained from this subphase includes the tasks highlighted in Figure 83. The commissioning entity should obtain the necessary information from the vendor detailing the documents required to run the system. The vendor should also provide information regarding the requirements to upgrade the system in the future.

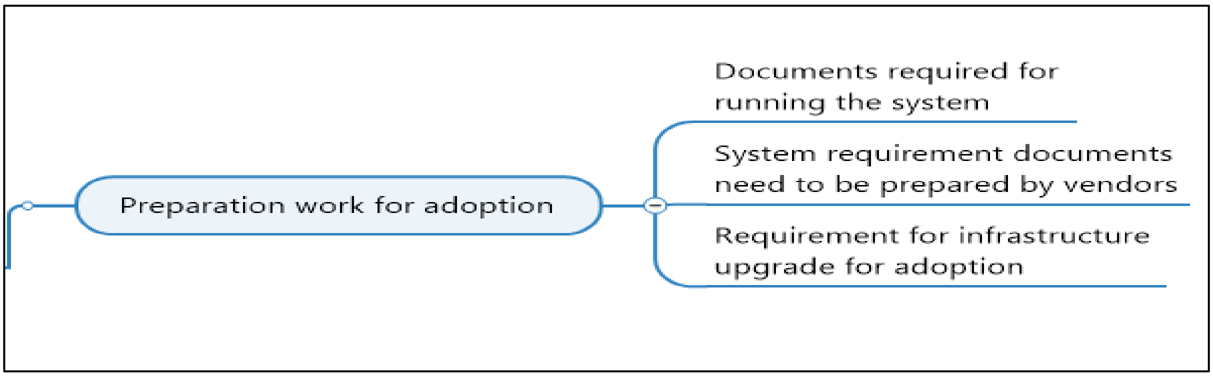


Figure 83: Preparation Work for Adoption (Fan, 2019)

Adoption of New Digital Technology

Fan (2019) reported that adoption can be completed once the above-mentioned stages and those highlighted Figure 84 have been completed. Fan (2019) advised that it is important for a person with project management skills to be the head of supervision during the life of the project. There should also be principles drawn to manage the use of resources during this stage. In addition, there should be a budget control criterion in the contractual agreement between the commissioning entity and the vendor as well as a planned budget for the life of the project. Lastly, there must be an established means of communication between the commissioning entity and the vendor for the term of the contract.

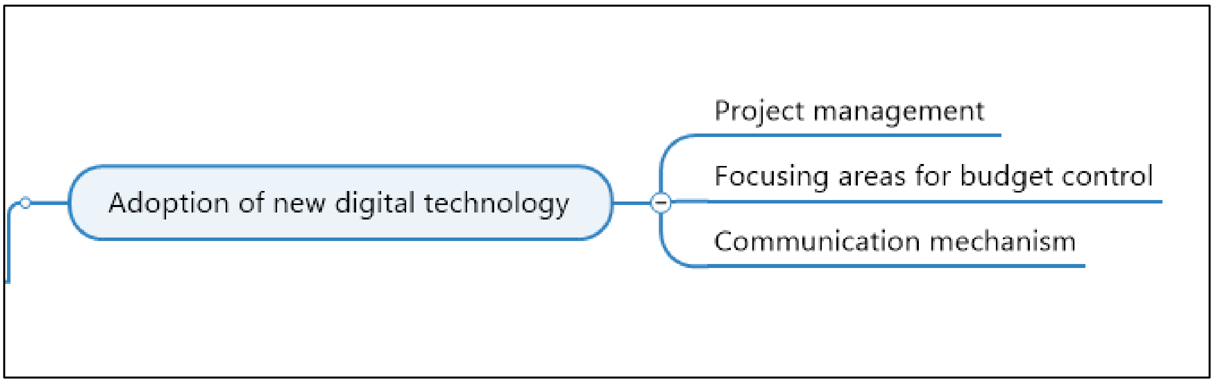


Figure 84: Adoption of New Digital Technology (Fan, 2019)

8.3.3 Post-Installation Phase

The post-installation phase aims to maintain the functionality of the system after installation. The subphases within the post-installation phase have been highlighted in Figure 85. The activities that need to be conducted include the calibration, testing and integration of the system. After-sale services are also essential during the post-installation phase. These activities are conducted to ensure the system performs at its maximum and the desired outputs are achieved.

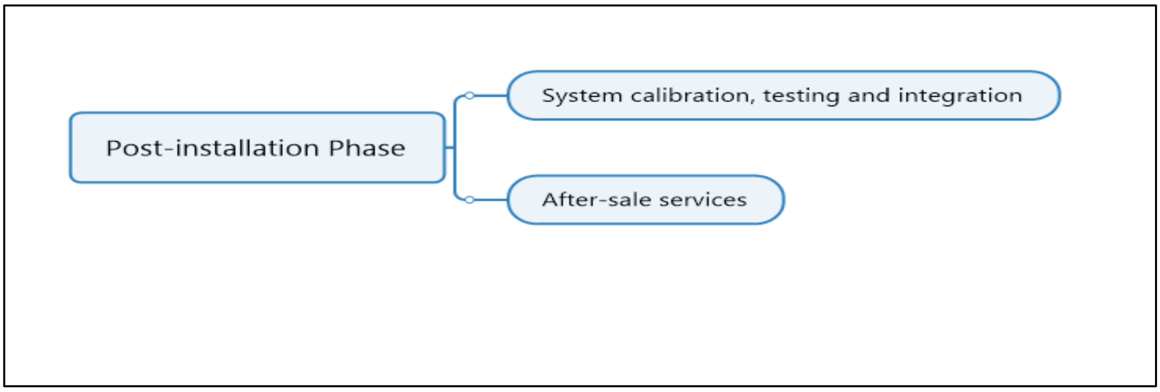


Figure 85: Post-installation Phase (Fan, 2019)

System Calibration, Testing and Integration

Figure 86 highlights the tasks to be completed on the system during this stage. System calibration and testing are conducted to ensure there is accurate data from the installed system and there are no malfunctions occurring on the system. Once this has been established then the system can be integrated. It is essential to then perform quality checks to ensure the system is compatible with the other installed systems.

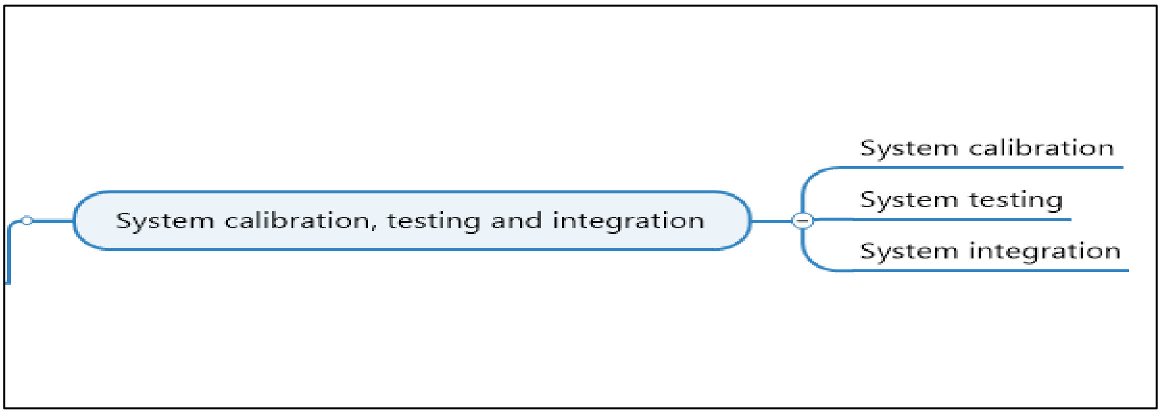


Figure 86: System Calibration, Testing and Integration (Fan, 2019)

After-Sale Services

Lastly, Fan (2019) reported the lessons acquired from the installation of digital systems at DigiMine include the need for after-sale support, Figure 87. The support from the vendor should ensure system maintenance and assistance in the case of system malfunctioning. In addition, there should be regular hardware upgrade and software updates support from the vendor. Figure 87 also outlines the exit strategy. The exit strategy is implemented when either the commissioning entity or the vendor fail to meet each other's expectations. The exit strategy can also be implemented if the problems the commissioning entity was aiming to solve are not addressed by the new technology. This blueprint thus offers a commissioning entity the necessary information to look out for from the pre-installation phase up until post-installation.

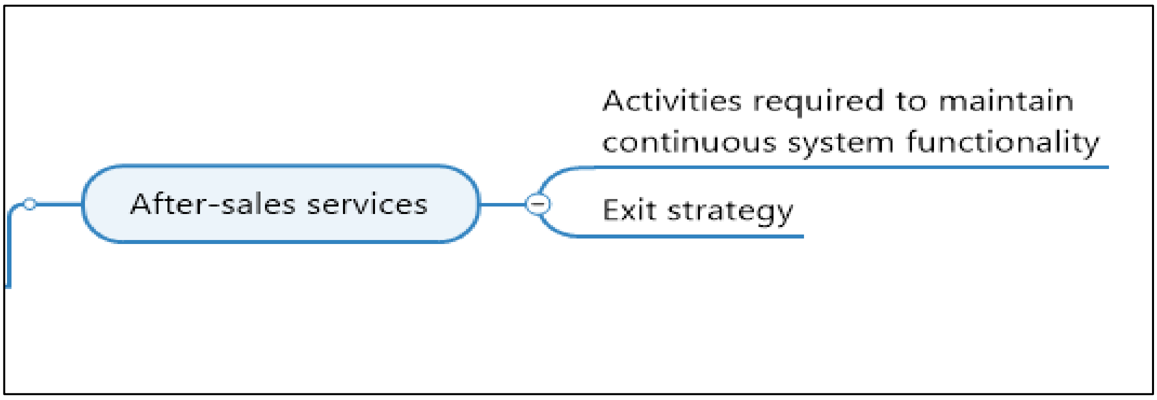


Figure 87: After-sales Services (Fan, 2019)

8.4 Summary and Conclusion

The implementation plan discussed in this chapter focuses on how a 21st century mine can be introduced in the conventional deep-level gold mining industry. The implementation plan also details the required skills and competence when introducing new technology in an entity. In addition, the importance of gradually introducing technology in a commissioning entity by developing a digital level has been highlighted. This is because the digital level allows the mining operation to have sufficient time to adjust to the use of digital technology. The gradual introduction of technology from the digital level to other working places at the mine has the following advantages:

- Gives enough time for people and the environment to adjust to the technology;
- The suitable systems for the operation will be known;
- There will be better knowledge on different digital technologies;
- There will be sufficient time to adequately train the workforce on the digital systems;
- The lessons gained from the digital mine can be transferred to the rest of the mine; and
- There will be sufficient skills and knowledge to phase out the technology to other parts of the mine.

The chapter also draws lessons from the implementation of technology at DigiMine by expanding the blueprint created by Xiang Fan to introduce new technology in a commissioning entity. The implementation plan consists of three stages; pre-installation phase, installation phase and post-installation phase. Each adoption phase has been further divided into subphases and series of tasks which need to be completed in order to manage the complexities associated with the adoption of new technology. This ensures mining operations complete the technology adoption phase by phase.

In conclusion, the conventional mining industry must not only envision the mine of the future but the industry must work towards creating such an operation. This is called mine modernisation This can be made possible by continually promoting change and the adopting new technology. The most important finding from this chapter is that there is a lot of work which must be completed prior the adoption of technology as the pre-installation phase sets the scene for the successful installation of technology. An implementation plan must also be drafted prior the installation of technology. Moreover, to manage employee reluctance, it is important to include workers from the very beginning stages of digital transformation. This is because the successful implementation of technology in any environment is dependent on the acceptance thereof by the workforce. The next chapter is a summary detailing the conclusion and recommendations based on the findings from the research study.

9 Conclusion and Recommendations

The four industrial revolutions have ultimately shaped the way we live today. The complexities and efficiencies of the industrial revolutions have increased over time and improved quality of life. Today, we live in a connected world where systems are interlinked, and the world has become a connected village. As a result, the nature of work itself has changed. This is because what would have required hundreds of manpower before the first industrial revolution, required less during the second revolution and far less in the third industrial revolution. At the present moment, 4IR has ushered automation where machines are becoming man.

This research highlighted the impact 4IR has on employment, businesses, and mining in particular. The study found that the adoption of 4IR will have a significant impact on the way we live, communicate and work. The 4IR has enabled the digitalisation of production, not only in the manufacturing industry, but in the mining industry as well. Hence, Industry 4.0 has given rise to Mining 4.0. It is predicted that mine modernisation, through the adoption of the 4IR, will improve the current state of mines by increasing safety and profitability. Mine modernisation transitions the mine of today to a mine of the future through digital technology and automation.

Digital mines have a positive impact on safety and efficiency by enabling real-time monitoring of the underground environment and therefore, restore safety in mining operations. A 21st century mine also has the potential to increase the life of mine by mining complex and lower grade reserves. These digital mines are characterised by IoT, cyber-physical systems, big data, AR, VR, ML and AI. The digital mine is also characterised by:

- Real-time data capturing and feedback;
- Real-time environment and asset monitoring;
- Wearable sensors;
- A digitally connected workforce;
- Drones for inspection;
- Autonomous mining and hauling; and
- Digital twinning.

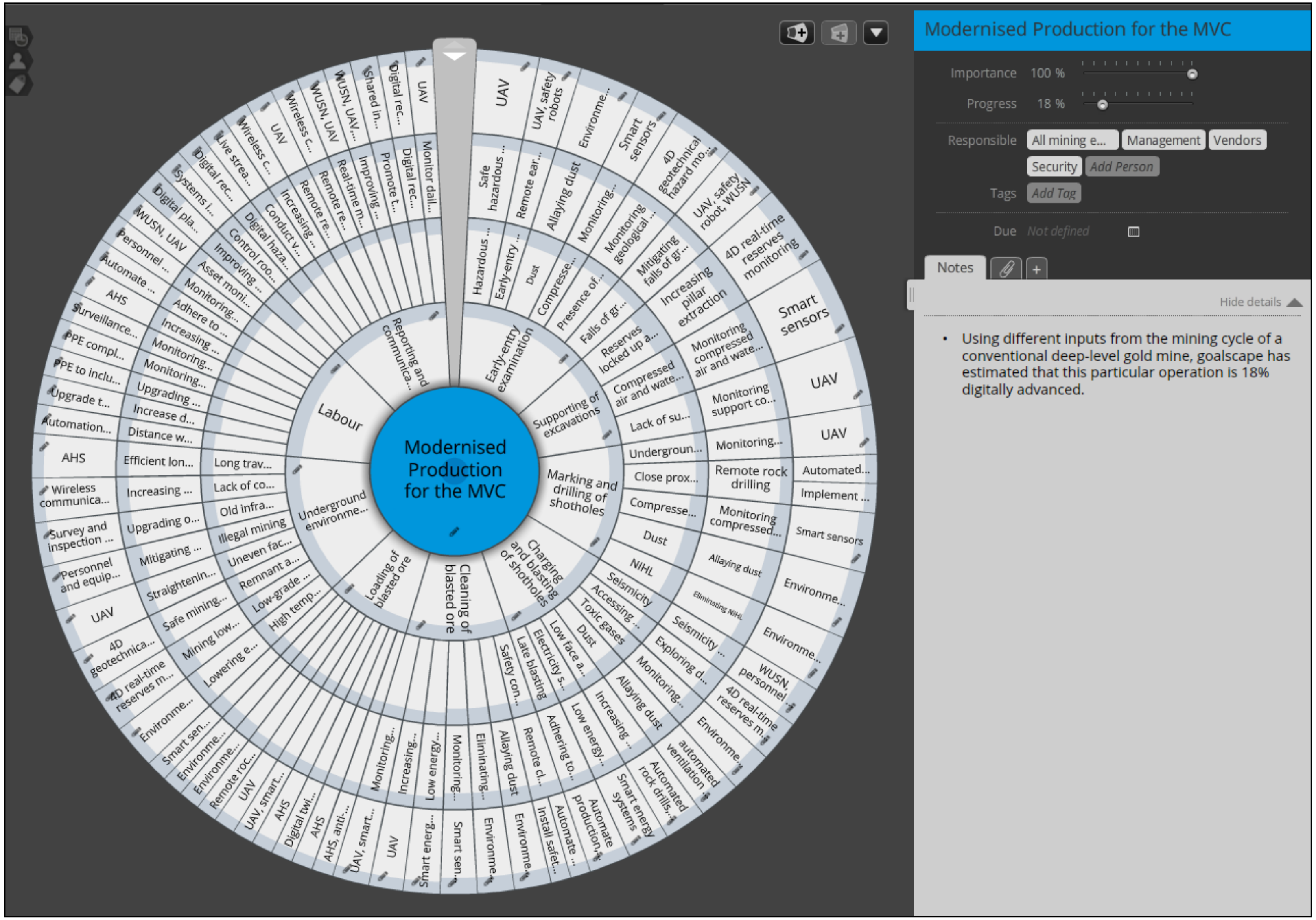
However, the South African mining industry is said to be still in the second industrial revolution because not much effort has gone to digitally transforming the industry. The conventional gold mining industry has rarely adopted any new technology; there were very few mines which attempted to mechanise operations. Although the lack of technology adoption in the conventional mining industry was because of the complex geology and blueprint of the mines, the most significant factor has been worker resistance. This is because resistance from workers has the potential to disrupt and induce failure of the project. Therefore, it has been recognised that employees should be involved throughout the various stages of technology adoption to ensure transparency and communication.

There are several operational challenges facing the deep-level mining industry including mining at depth, mining low-grade reserves, unauthorised access, and labour disputes. This study also provided the deep-level mining industry digital technology to increase safety and efficiencies. However, this study also found that there are many challenges presented by modernising the conventional deep-level mining industry. These challenges include the absence of ICT infrastructure, lack of skills and expertise as well as the general reluctance to invest in new technology.

The research outcomes were achieved through the case studies of a conventional deep-level gold mine, DigiMine and other digital mines around the world. The research encountered the following limitations:

- The study relied on safety and production reports from the MHSC and the DMR. The lack of updated reports from these public domains meant that only data from previous years could be analysed. This is because some information was not yet available for public consumption; and
- There were limitations to what could be reported from the conventional mine as some information was considered confidential.

To understand what it takes to modernise a working mining stope at the conventional mine, the author sought to understand the activities and challenges that occur during the mining cycle. Therefore, the author designed a production blueprint illustrating the different activities and challenges encountered in all the phases of the mining cycle. This allowed the author to determine how the phases of the mining cycle can be modernised. Using Goalscape, the percentage mine modernisation at the conventional mine was estimated to be 18% (Figure 88). This is because the mine still uses conventional methods of mining. The most advanced technology used in the operation is the use of a digital application, which employees use to communicate with management.



Modernised Production for the MVC

Importance 100 %

Progress 18 %

Responsible: All mining e... | Management | Vendors | Security | Add Person

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Notes

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- Using different inputs from the mining cycle of a conventional deep-level gold mine, goalscape has estimated that this particular operation is 18% digitally advanced.

Figure 88: The Conceptual Mine Modernisation Blueprint for a Conventional Mine

DigiMine is a twenty-first century mining laboratory consisting of a mock mine and control room consisting of various installed systems. These systems have been integrated to ensure the output of one system becomes the input of other systems. These systems thus communicate with each other as well as the simulated environment. The case study of DigiMine offers commissioning entities lessons gained from the installation of digital systems at the mock mine. These lessons were based on the experienced gained during pre-installation, installation, and post-installation phase of digital systems adoption at DigiMine. It was found that the pre-installation phase was the most crucial phase as it sets the scene for successful technology adoption. From the case study of DigiMine, a master production blueprint for mine modernisation during the mining cycle was created, Figure 89. However, there are some systems which are yet to be adopted at DigiMine such as:

- Autonomous drilling systems;
- Autonomous cleaning systems;
- Autonomous hauling systems; and
- Remote rock breaking.

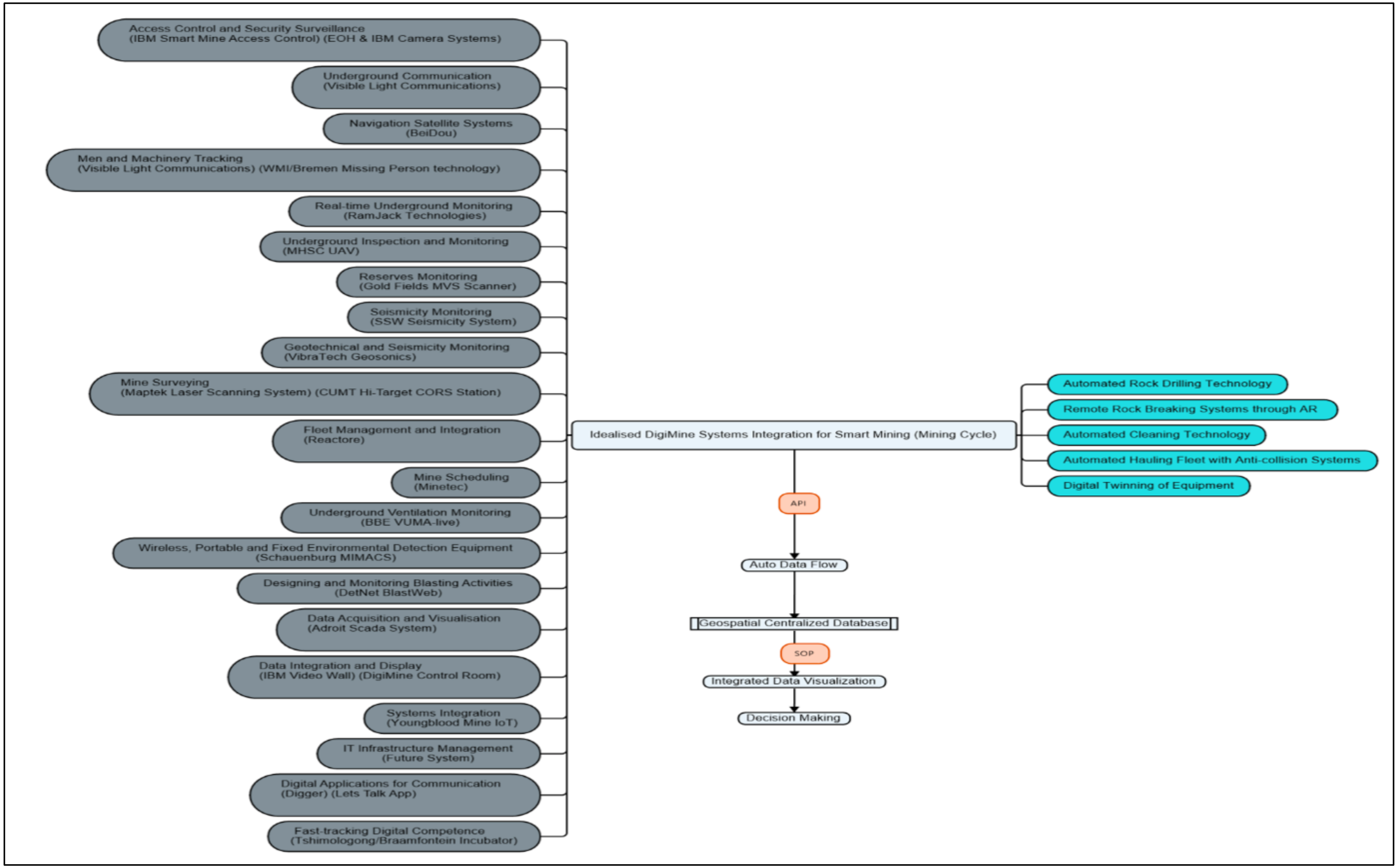

Figure 89: Idealised Master Blueprint to Enable Smart Mining at DigiMine

It is expected that once the 4IR has been adopted in various industries, it will have an impact of the future of work as well as gender neutrality in the workplace. This is because Mining 4.0 will bring light on the impact 4IR will have on women and the future of work. Although the nature of work in a digital mine requires less manpower and physical strength is no longer mandatory in the line of work, the workforce needs to develop digital skills and soft skills. Therefore, mine workers are inclined to develop themselves to strive in this new revolution. This is because the future of work in a digital mine involves a Miner 4.0 who is a digital miner capable of remotely conducting work.

This research study also included an implementation plan (Figure 90), detailing how the conventional mining industry can transition toward better use of technology. The implementation plan highlighted the need to identify suitable technology and vendors. Instead of introducing technology to the entire mining operation, the research study revealed that having a digital level at the conventional mine may be the most suitable option. This is because the digital level allows for gradual introduction of technology without causing too much shock to the system. This strategy also enables the operation to have sufficient time to train the existing workforce and prepare the environment. The implementation plan also highlighted the immense skills and competence gap between the conventional mine and the modernised mine. It is therefore, crucial to adequately train and equip the workforce with digital skills.

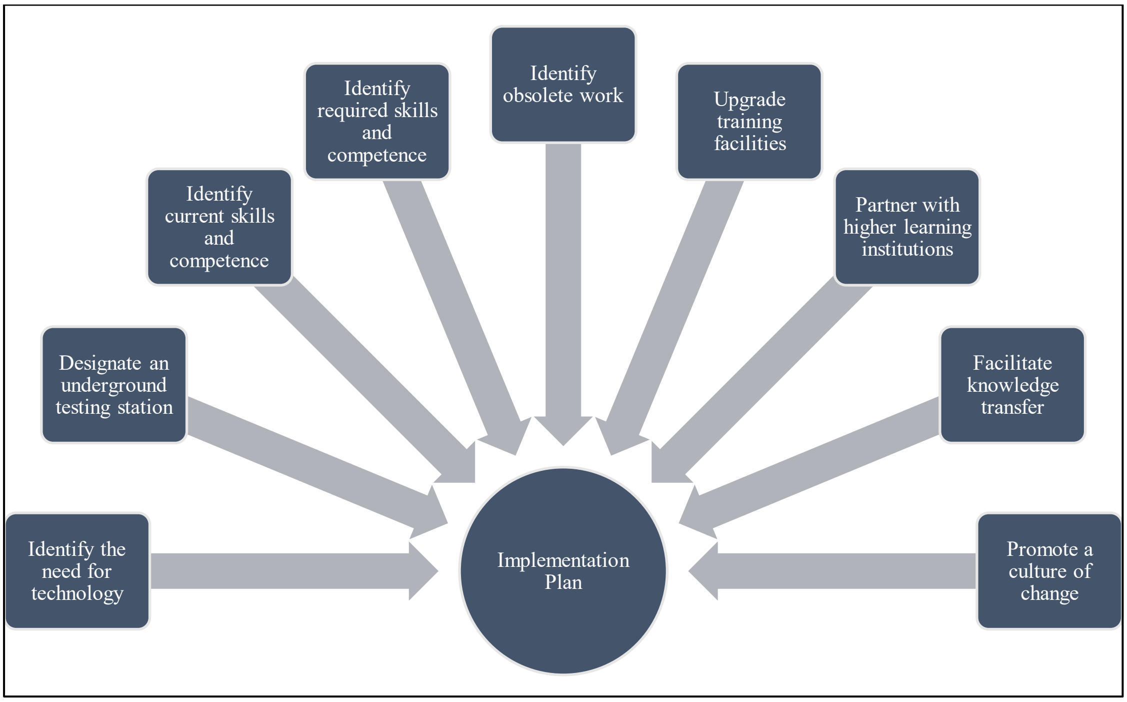

Figure 90: Implementation Plan to Introduce New Technology in the Conventional Mining Industry

The adoption of digital systems and autonomous technology ensure that safety is a priority; hence, mines which have adopted these technologies report fewer injuries and fatalities. Therefore, it can be expected that there will be a decrease in the number of fatalities and injuries reported in the conventional deep-level mining industry as a result of adopting Mining 4.0. For example, the use of UAV’s enables inspection of underground working areas which would be dangerous for humans to inspect.

The digital workforce may demand higher wages therefore, an operation may not be able to leverage on the decline of employees to decrease labour costs. However, Mining 4.0 offers potential to monitor reserves in real-time and mine complex deep reserves. In addition, lower grade reserves can be mined at a profit as the cost of mining will substantially decrease over time. This is because Mining 4.0 ensures higher efficiencies and therefore, a cost cut on consumables. This in turn increases an operation’s profitability thus, decreasing the operating costs of the mine. The mining of these lower grade and deeper ore reserves therefore, increase the life of mine. Hence, employment will be preserved as the industry continues to mine these remaining reserves.

9.1 Recommendations and Further Research

- There should be better estimation of the state of modernisation within a commissioning entity by looking in detail at the various activities and challenges during the mining cycle;
- The mine modernisation production blueprint should be updated regularly;
- Should a conventional mine opt to have a digital level within the operation, there should be adequate support from the management and production crew to the digital crew;
- A commissioning entity should have contingency plans in the case of technology failure;
- There should be detailed research looking into the modernisation of each stage of the mining cycle to ensure strategic planning and implementation; and
- At the speed at which the industrial revolutions are occurring, it can be predicted that it will not be long until there is the rise of the Fifth Industrial Revolution. Therefore, there should be further studies on the application of 4IR in the conventional deep-level mining industry.

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11 Appendices

Appendix 1: Digital Technology to Cater for the Challenges in the Mining Cycle

Mining Cycle	Challenge	Example of Digital Technologies	Remarks
Early-entry examination	• Early-entry inspection	• Safety robots • Hovermap drone	• CSIR no longer conducting active research on safety robots
	• Hazardous area inspection	• Hovermap drone	• System is adequate
	• Dust	• Environmental monitoring system	• System can be fixed or lampfitted • Used in conjunction with dust masks
	• Falls of ground	• Safety robots • Hovermap drone	• CSIR no longer conducting active research on safety robots

	- Geological discontinuities	- 4D geotechnical hazard assessing	- System forecasts hazards but does not mitigate
Supporting of excavations	- Reserves locked up as support	- 4D real-time reserve monitoring	- Enhances pillar recovery rate
	- Lack of support compliance	- Hovermap drone	- System is adequate
Marking and drilling of the face	- Underground surveying: mining direction and limit lines	- Hovermap drone	- System is adequate
	- Dust	- Environmental monitoring system	- System can be fixed or lampfitted - Used in conjunction with dust masks
	- NIHL	- Environmental monitoring system	- System can be fixed or lampfitted - System used in conjunction with earplugs

Charging and blasting of shotholes	• Accessing deeper reserves	• 4D real-time reserve monitoring	• System is able to suggest appropriate mining method
	• Low face advance after blast	• Hovermap drone	• Drone can only measure face advance after the blast, drilling process needs to be automated
	• Seismicity	• WUSN • Personnel geospatial tracking and distress communication	• WUSN must be extended with face advance
	• Toxic gases	• Environmental monitoring systems	• System can be fixed or lampfitted • System is used in conjunction with self-contained rescue device
	• Dust	• Environmental monitoring system	• System can be fixed or lampfitted

		• System is used in conjunction with dust masks
	• Electricity shortages	• Smart electricity	• Smart electricity offers reduction in electricity usage and costs however, there are energy back-ups required in case of load shedding
	• Dust	• Environmental monitoring system	• System can be fixed or lampfitted • System is used in conjunction with dust masks
Cleaning of blasted ore	• NIHL	• Environmental monitoring system	• System can be fixed or lampfitted

			- System is used in conjunction with earplugs
	- RBE accidents	- AHS - Anti-collison systems	- Current RBE may need to be replaced
Loading of blasted ore	- Dust	- Environmental monitoring system	- System can be fixed or lampfitted - System is used in conjunction with dust masks
	- NIHL	- Environmental monitoring system	- System can be fixed or lampfitted - System is used in conjunction with earplugs
Other Challenges			
Underground environmental conditions	- High temperatures	- Ventilation on demand system - Environmental monitoring system	- Monitoring system can be fixed or lampfitted

	• Low-grade reserves	• 4D real-time reserve monitoring	• Digital technologies can reduce operating costs and cut-off grade
	• Illegal mining	• Personnel and machinery geospatial tracking	• Additional security surveillance is required
	• Old infrastructure	• Surveying and inspection robots	• Robots can be used for rail inspection
	• Remote working places	• Wireless network connection • Issue miners with communication devices	• Employees would require communication devices
	• Long travelling distances	• AHS	• May need to change current RBE fleet

Labour	• Labour intensive industry	• Automation • Robotics • Drone control via VR and AR	• Size of the stope may hinder the implementation of some technology i.e mechanisation
	• Unauthorised access	• WUSN • Personnel geospatial tracking	• Additional surveillance cameras are required
	• Theft of company property	• Asset monitoring via drones • WUSN • Personnel geospatial tracking	• Additional surveillance cameras are required
	• Wage disputes	• Transparency through digital applications	• Wage negotiations still should be held regularly

Appendix 2: Conventional Gold Mine Case Study: Challenges and Digital Solutions

Mining Cycle	**Challenge**	**Example of Digital Technologies**	**Remarks**
Early-entry examination	• Early-entry inspection	• UAV • Safety robot	• System can be operated remotely via VR and AR
	• Hazardous area inspection	• UAV	• System can be remotely controlled
	• Dust	• Environmental monitoring systems • Automated ventilation venturis	• Venturi waters down area based on dust levels recorded by the fixed environmental monitoring systems
	• Compressed air shortages	• Smart sensors to detect leakages in pipes	• System is able to determine location of leakage along the length of pipes sooner
	• Water shortages	• Smart sensors to detect leakages in pipes	• System is able to determine location of

			leakage along the length of pipes sooner
	• Falls of ground	• UAV • Safety robot • WUSN	• UAV and safety robot can be operated remotely via VR and AR • WUSN can still communicate even when buried under debris
	• Geological discontinuities	• 4D geotechnical hazard assessing	• System is updated in real-time
Supporting of excavations	• Reserves locked up as support	• 4D real-time reserves monitoring	• Algorithms can be used to offer safer extraction methods
	• Compressed air shortages	• Smart sensors to detect leakages in pipes	• System is able to determine location of leakage along the length of pipes sooner

	- Water shortages	- Smart sensors to detect leakages in pipes	- System is able to determine location of leakage along the length of pipes sooner
	- Lack of support compliance	- UAV	- System remotely operated using VR
Marking and drilling of the face	- Underground surveying: mining direction and limit lines	- UAV	- System is able to ensure survey notes highlighting limit lines are complied with - System offers assistance in marking the stope face through AR
	- Compressed air shortages	- Smart sensors to detect leakages in pipes	- System is able to determine location of leakage along the length of pipes sooner

	• Water shortages	• Smart sensors to detect leakages in pipes	• System is able to determine location of leakage along the length of pipes sooner
	• Dust	• Environmental monitoring systems • Dust allaying drills	• Venturis to offer additional watering down
	• NIHL	• Environmental monitoring systems • Less noise-inducive drills	• Additional warning can be issued to miners to wear ear plugs when noise levels exceed mine standards
Charging and blasting of shotholes	• Accessing deeper reserves	• 4D real-time reserves monitoring	• Algorithms can offer mining methods to safely mine deeper reserves
	• Low face advance after blast	• Automated rock drills • UAV	• Narrow-reef stope restrictions- automated

			drills may be unsuitable - UAV can accurately measure face advance
	- Seismicity	- WUSN - Personnel geospatial tracking and distress communication	- WUSN will have to be installed with face progression
	- Toxic gases	- Environmental monitoring system	- System can be fixed or lamp-fitted
	- Dust	- Automated ventilation venturis	- Venturis can automatically water down area after a blast
	- Electricity shortages	- Implement smart energy systems	- Electricity back-ups in the form of generators required
	- Late blasting	- Automate production - Personne geospatial tracking and real-time communication	- Communication devices should offer warning signals when

			knock off time approaches
Cleaning of blasted ore	- NIHL	- Environmental monitoring system	- Warning can be issued to miners to wear ear plugs when noise levels exceed mine standards
	- Dust	- Environmental monitoring system - Automated water sprays	- Water sprays can be activated based on dust levels recorded by the fixed environmental monitoring systems
	- Compressed air shortages	- Smart sensors to detect leakages in pipes	- System is able to determine location of leakage along the length of pipes sooner
	- Water shortages	- Smart sensors to detect leakages in pipes	- System is able to determine location of

			leakage along the length of pipes sooner
	• Electricity shortages	• Implement smart energy systems	• Electricity back-ups in the form of generators required
	• Insufficient drawpoint size	• UAV • Smart sensors	• Systems can measure orepass capacity and RBE can be requested if orepass is full
	• Low MCF	• UAV	• UAV can be used to monitor sweepings after cleaning
	• Safety concerns with the use of scraper winches and water jets	• WUSN	• Cleaning equipment can be programmed to halt upon detecting close proximity of humans
Loading of blasted ore	• RBE accidents: Collision with other RBE, workers	• AHS • Anti-collision systems	• May have to replace current RBE fleet to

	and structures such as ventilation doors		accommodate automation
	• RBE breakdowns	• Digital twinning	• Maintenance of RBE can be done ahead of breakdowns
	• RBE congestion	• AHS	• Algorithms can be used to allocate RBE for transporting men, materials and ore
	• Short effective shift length due to long travelling distances	• AHS	• Able to schedule the transportation of men, materials and ore
	• Insufficient drawpoint size	• UAV • Smart sensors	• Can measure orepass capacity and RBE can be requested if orepass is full
	• Orepass inspection	• UAV	• Remotely conducted through VR

	• Rock breaking at the tip	• Remote rock breaking system	• Technology uses VR and currently used at South Deep gold mine
	• Dust	• Environmental monitoring system • Automated water sprays	• Water sprays can be activated based on dust levels recorded by the fixed environmental monitoring systems
	• NIHL	• Environmental monitoring systems • Less noise-inducive RBE	• Additional warning can be issued to miners to wear ear plugs when noise levels exceed mine standards
	• Compressed air shortages	• Smart sensors to detect leakages in pipes	• System is able to determine location of leakage along the length of pipes sooner
Other Challenges			

Underground environmental conditions	• High temperatures	• Environmental monitoring systems • Ventilation-on-demand system	• Automated water sprays to offer additional cooling down
	• Low-grade reserves	• 4D real-time reserves monitoring • Digitalisation of production	• Digitalisation offers an opportunity to mine lower grade reserves at a profit
	• Mining remnant areas	• 4D geotechnical hazard assessing	• Real-time monitoring of seismicity and geological features
	• Uneven face shape	• UAV	• Blasting pattern of each shift can be reconfigured to rectify face shape
	• Illegal mining	• Personnel and equipment geospatial tracking • Underground surveillance • UAV	• Cameras should be installed underground covering haulages and crosscuts

			• UAV can be used to surveillance stopes
	• Old infrastructure	• Survey and inspection robots	• A working prototype available at CSIR
	• Remote working places	• Wireless communication network	• Underground workers should be issued with communication devices
	• Communication only by telephone available at the waiting place or refuge bay	• Wireless communication network	• Underground workers should be issued with communication devices
	• Long travelling distances	• AHS	• RBE can be scheduled daily for men, materials and ore transportation
Labour	• Labour intensive industry	• Automation • Robotics	• Safety will be improved through digital technology

		• Remote operation of drones via VR and AR	• Expect a reduction in labour in the industry as some work may become redundant
	• Limited education and digital skills	• Upgrade trainining facilities • Higher institutions to incorporate Mining 4.0 in their syllabus • Collaboration between industry and MQA • Open innovation approach to fill the skills gap	• New skills and knowledge will be required in a digital mine
	• Conventional PPE used	• Upgrade PPE to detect environmental conditions, track employees and offer distress communication	• The control room to have access to data logged from PPE worn by employees
	• Lack of PPE compliance	• PPE compliance detection equipment	• System to be installed prior underground access gates

	- Lack of compliance to safety standards	- Surveillance cameras - UAV	- Surveillance cameras offer live feed
	- Short effective shift length due to long travelling distances	- AHS	- AHS is able to schedule the transportation of men, materials and ore
	- Knocking off late therefore delaying blasting time	- Automate production - Personnel geospatial tracking and real-time communication	- Communication devices should also offer warning signals when knock off time approaches
	- Unauthorised access	- Personnel geospatial tracking	- Additional tracking of personnel through camera surveillance is required
	- Theft of company property	- WUSN - UAV	- System offers asset tracking and inventory

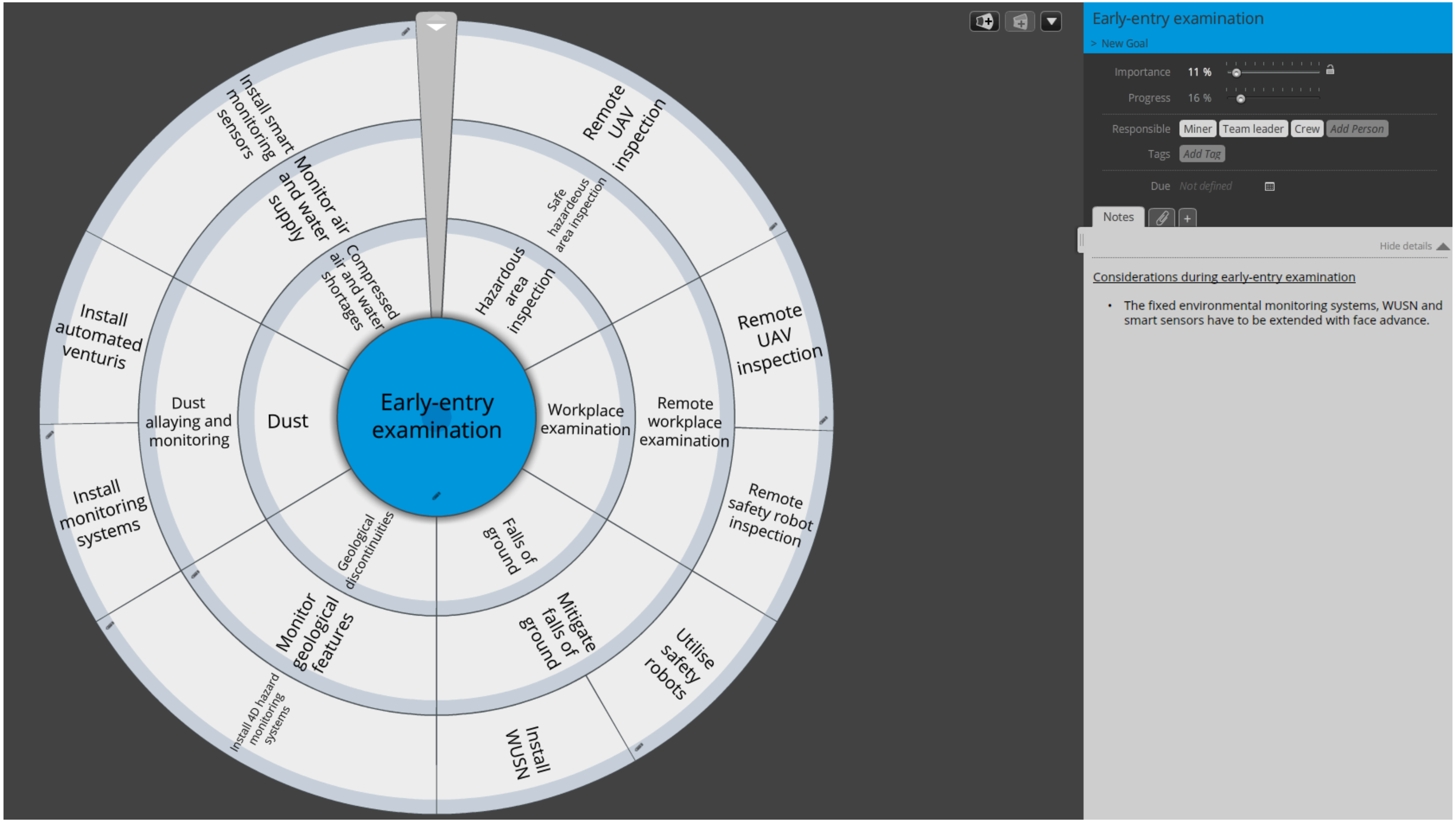
			management in real-time
	- Wage disputes	- Transparency through digital applications	- Wage negotiations still have to be conducted regularly
Reporting and communication	- Conventional control room set-up	- Systems integration - Video wall display of different systems	- Control room requires an ecosystem of vendors for integration
	- Conventional recording of identified hazards (logbook, safety and compliance auditing)	- Digital recording of hazards	- Employee logbooks can be replaced by electronic tablets
	- Lack of regular management and employees engagement	- Remote streaming of management meetings underground	- Employees can be offered a chance to engage with management
	- Communication only by telephone available at the waiting place or refuge bay	- Wireless communication network	- Underground workers should be issued with

			communication devices
	• Lack of reporting refuge bay compliance	• UAV	• System can be remotely controlled through VR
	• Inability to report breakdowns and malfunctions during shift	• Wireless communication network • Digital twinning of equipment	• Manufacturer and vendor can offer assistance remotely
	• Lack of MCF monitoring in real-time	• WUSN • UAV	• Systems offer ore monitoring from the stope to the plant • Inconsistencies can be seen throughout the mining cycle
	• Lack of inventory management: Material cars getting lost, ordering too much materials, etc.	• UAV • WUSN • RBE geospatial tracking	• Algorithms can predict which material needs to be ordered with face advance

	- Lack of communication and transparency between different mining departments	- Shared database for sharing of information - Promote virtual meetings in case of physically absent members	- Digital technology promotes open discussion and communication between various mining departments
	- Lack of adequate communication between different shifts	- UAV - WUSN	- Safety and production data of each shift can be uploaded on electronic tablets and available for the next shift - Instructions for each shift can also be uploaded on the tablet
	- Overbooking: Reporting inaccurate daily face advance and square metres achieved after blast	- UAV	- UAV and algorithms can be used to predict whether production call can be achieved at the end of the month

			• System accurately measures the square metres achieved with face advance

Appendix 3: State of Modernisation During Early-entry Examination



Early-entry examination

> New Goal

Importance 11 %

Progress 16 %

Responsible: Miner, Team leader, Crew, Add Person

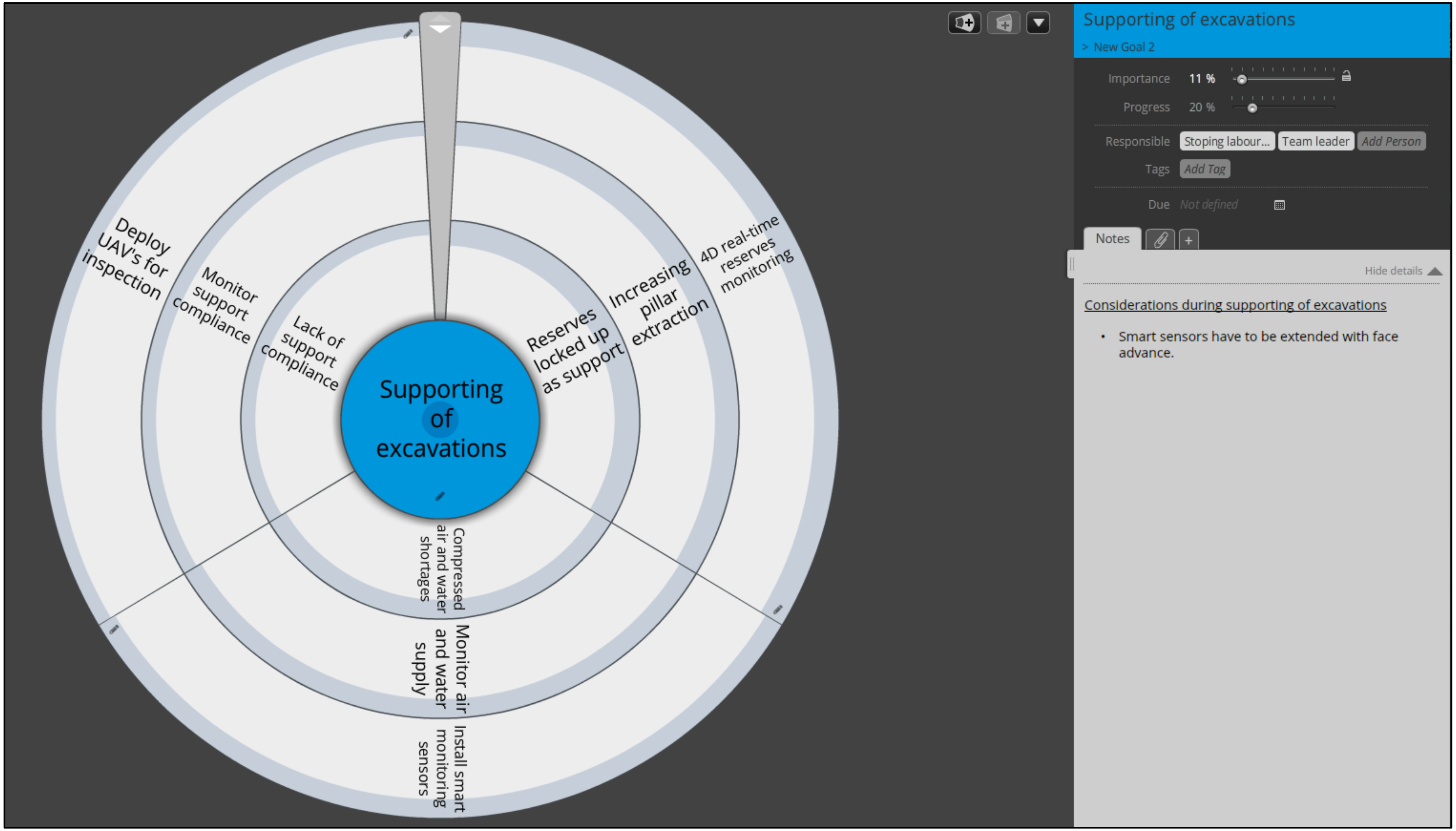
Tags: Add Tag

Due: Not defined

Considerations during early-entry examination

- The fixed environmental monitoring systems, WUSN and smart sensors have to be extended with face advance.

Appendix 4: State of Modernisation During Supporting of Excavations



Supporting of excavations

> New Goal 2

Importance 11 %

Progress 20 %

Responsible: Stoping labour... | Team leader | Add Person

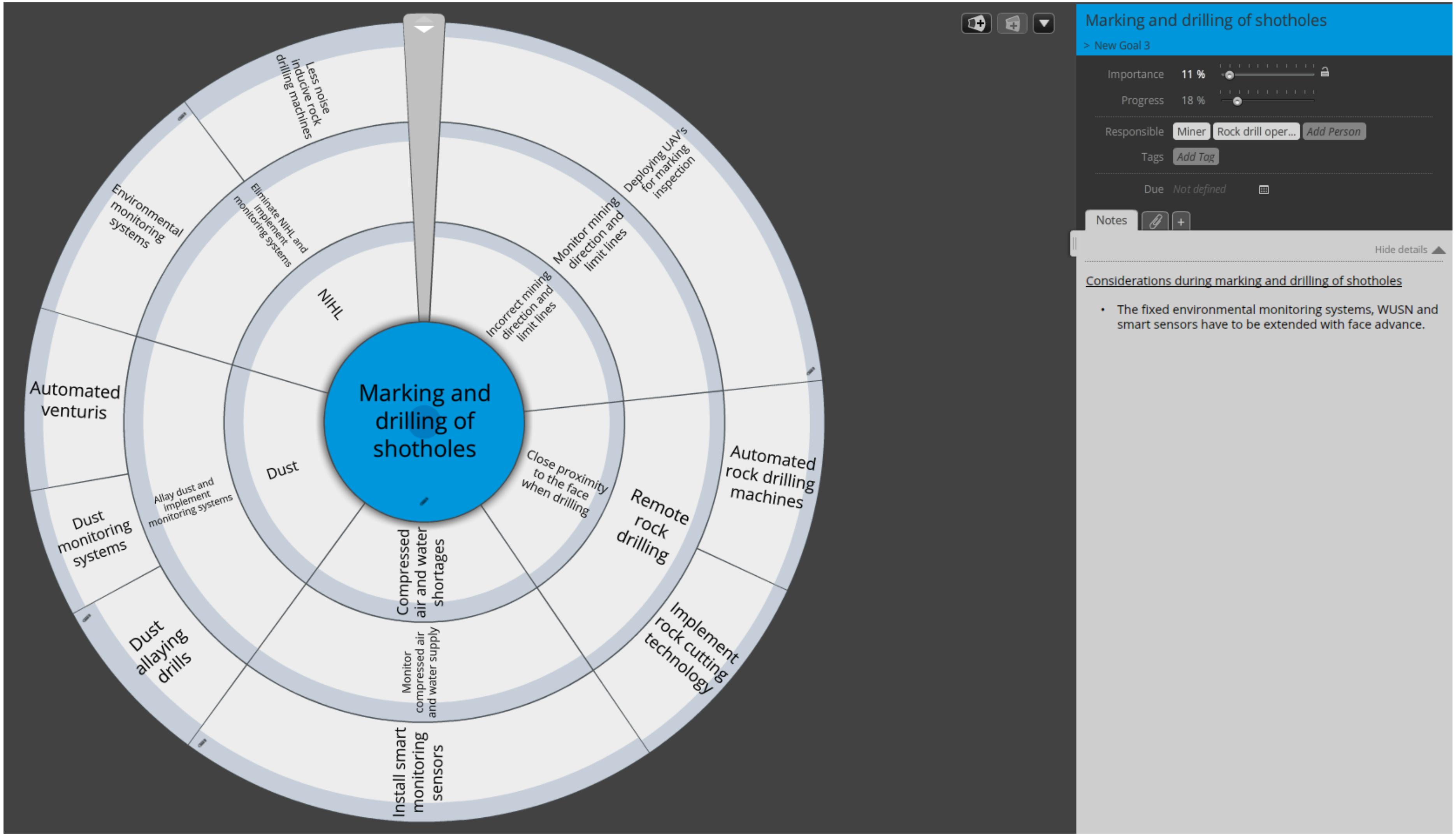
Tags: Add Tag

Due: Not defined

Considerations during supporting of excavations

- Smart sensors have to be extended with face advance.

Appendix 5: State of Modernisation During Marking and Drilling of Shotholes



Marking and drilling of shotholes

> New Goal 3

Importance 11 %

Progress 18 %

Responsible Miner Rock drill oper... *Add Person*

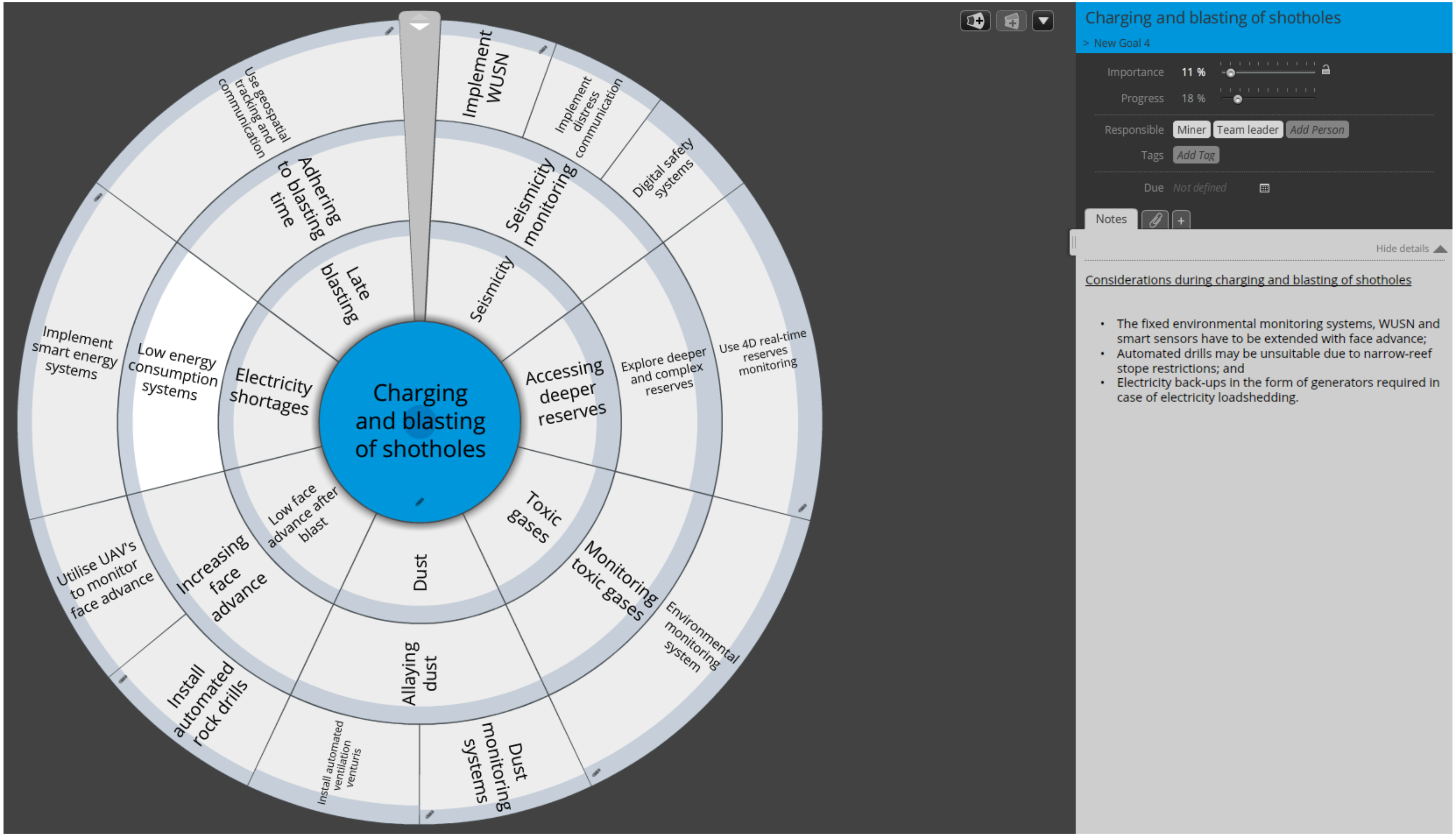
Tags *Add Tag*

Due *Not defined*

Considerations during marking and drilling of shotholes

- The fixed environmental monitoring systems, WUSN and smart sensors have to be extended with face advance.

Appendix 6: State of Modernisation During Charging and Blasting of Shotholes



Charging and blasting of shotholes

> New Goal 4

Importance 11 %

Progress 18 %

Responsible: Miner, Team leader, Add Person

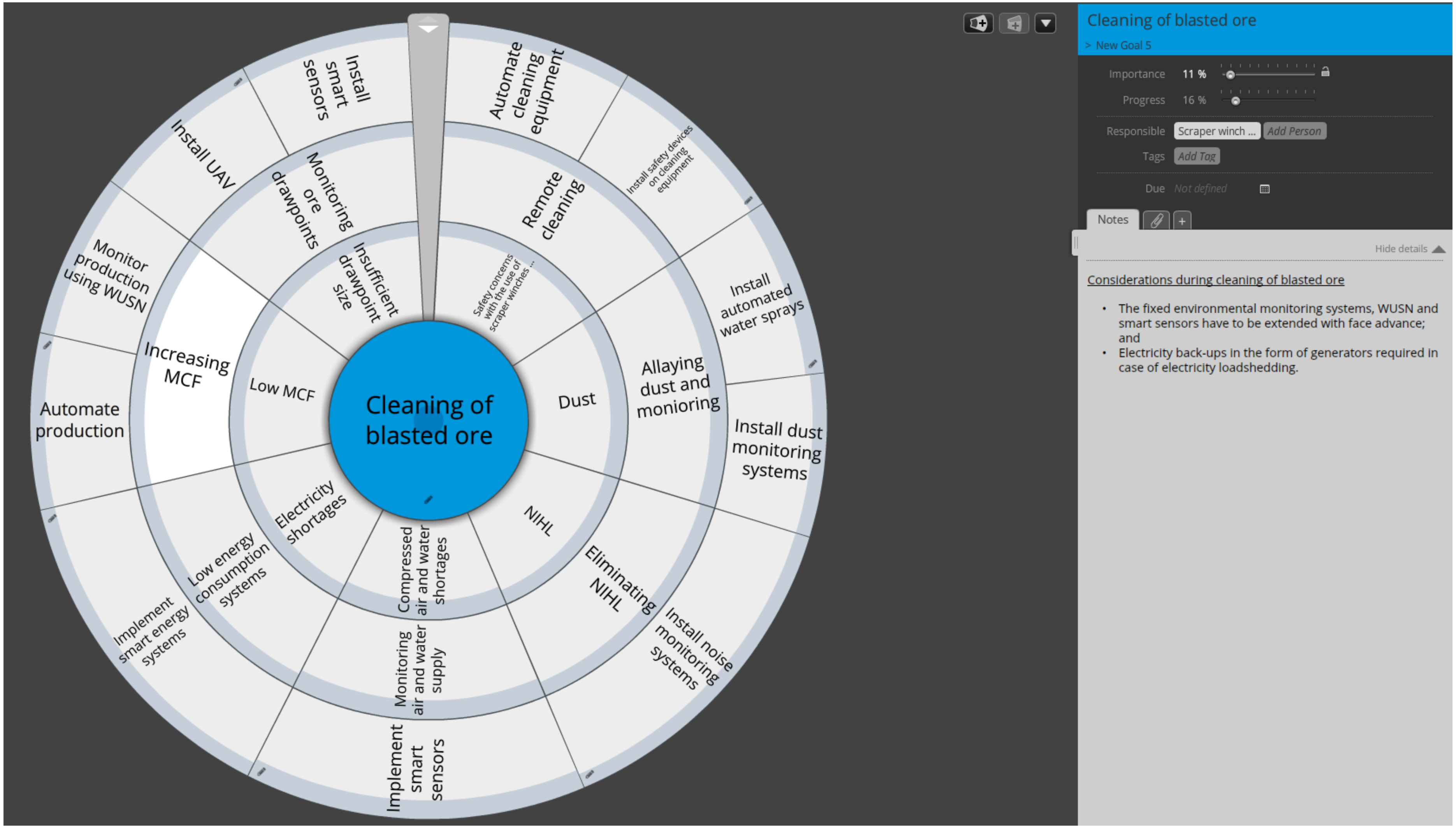
Tags: Add Tag

Due: *Not defined*

Considerations during charging and blasting of shotholes

- The fixed environmental monitoring systems, WUSN and smart sensors have to be extended with face advance;
- Automated drills may be unsuitable due to narrow-reef stope restrictions; and
- Electricity back-ups in the form of generators required in case of electricity loadshedding.

Appendix 7: State of Modernisation During Cleaning of Blasted Ore



Cleaning of blasted ore

> New Goal 5

Importance 11 %

Progress 16 %

Responsible Scraper winch ... Add Person

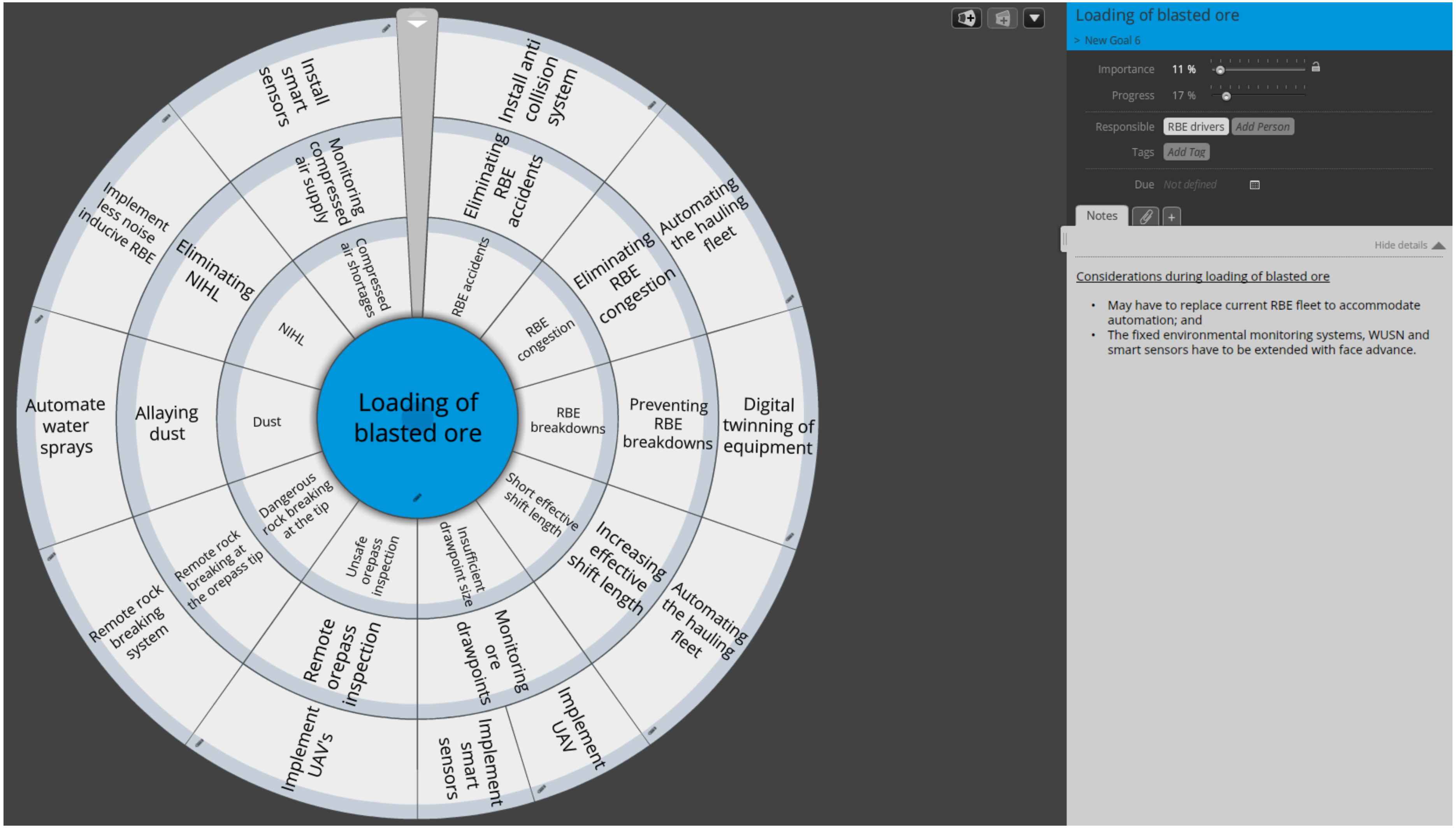
Tags Add Tag

Due Not defined

Considerations during cleaning of blasted ore

- The fixed environmental monitoring systems, WUSN and smart sensors have to be extended with face advance; and
- Electricity back-ups in the form of generators required in case of electricity loadshedding.

Appendix 8: State of Modernisation During Loading of Blasted Ore



Loading of blasted ore

> New Goal 6

Importance 11 %

Progress 17 %

Responsible RBE drivers Add Person

Tags Add Tag

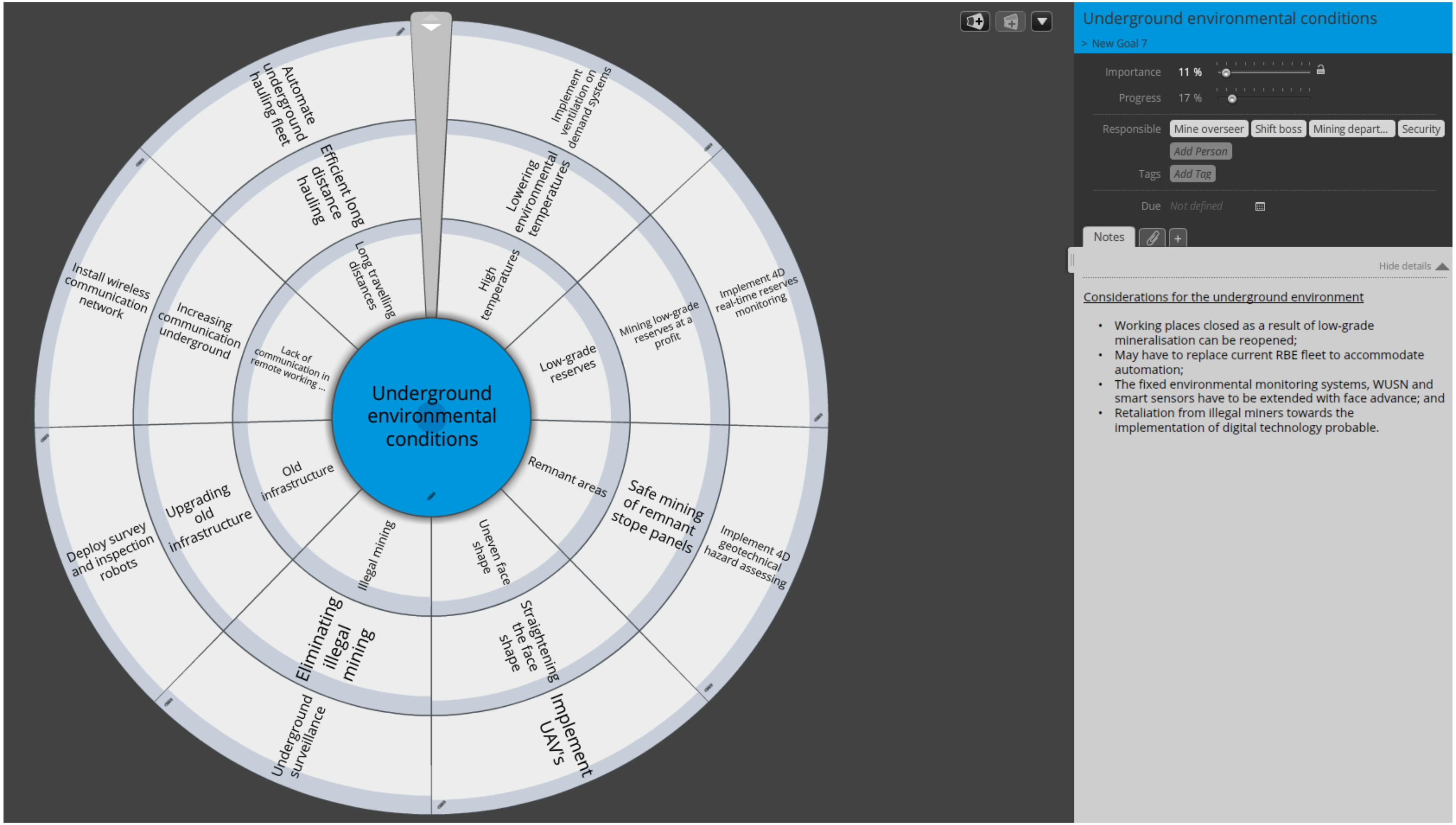
Due Not defined

Notes

Considerations during loading of blasted ore

- May have to replace current RBE fleet to accommodate automation; and
- The fixed environmental monitoring systems, WUSN and smart sensors have to be extended with face advance.

Appendix 9: State of Modernisation of the Underground Environment



Underground environmental conditions

> New Goal 7

Importance 11 %

Progress 17 %

Responsible Mine overseer | Shift boss | Mining depart... | Security | *Add Person*

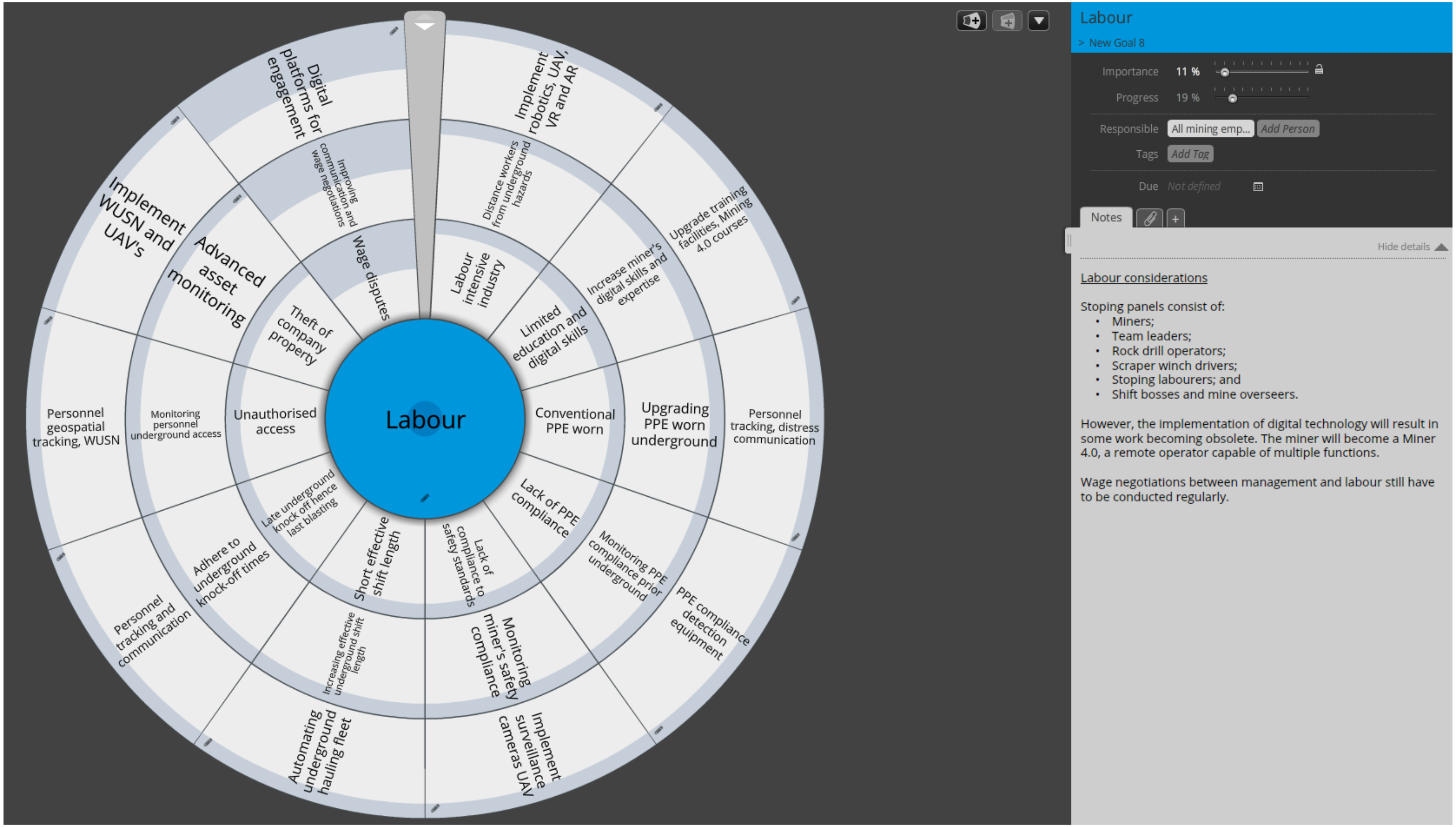
Tags *Add Tag*

Due *Not defined*

Considerations for the underground environment

- Working places closed as a result of low-grade mineralisation can be reopened;
- May have to replace current RBE fleet to accommodate automation;
- The fixed environmental monitoring systems, WUSN and smart sensors have to be extended with face advance; and
- Retaliation from illegal miners towards the implementation of digital technology probable.

Appendix 10: State of Modernisation of the Mining Labour



Labour

> New Goal 8

Importance 11 %

Progress 19 %

Responsible All mining emp...

Due Not defined

Labour considerations

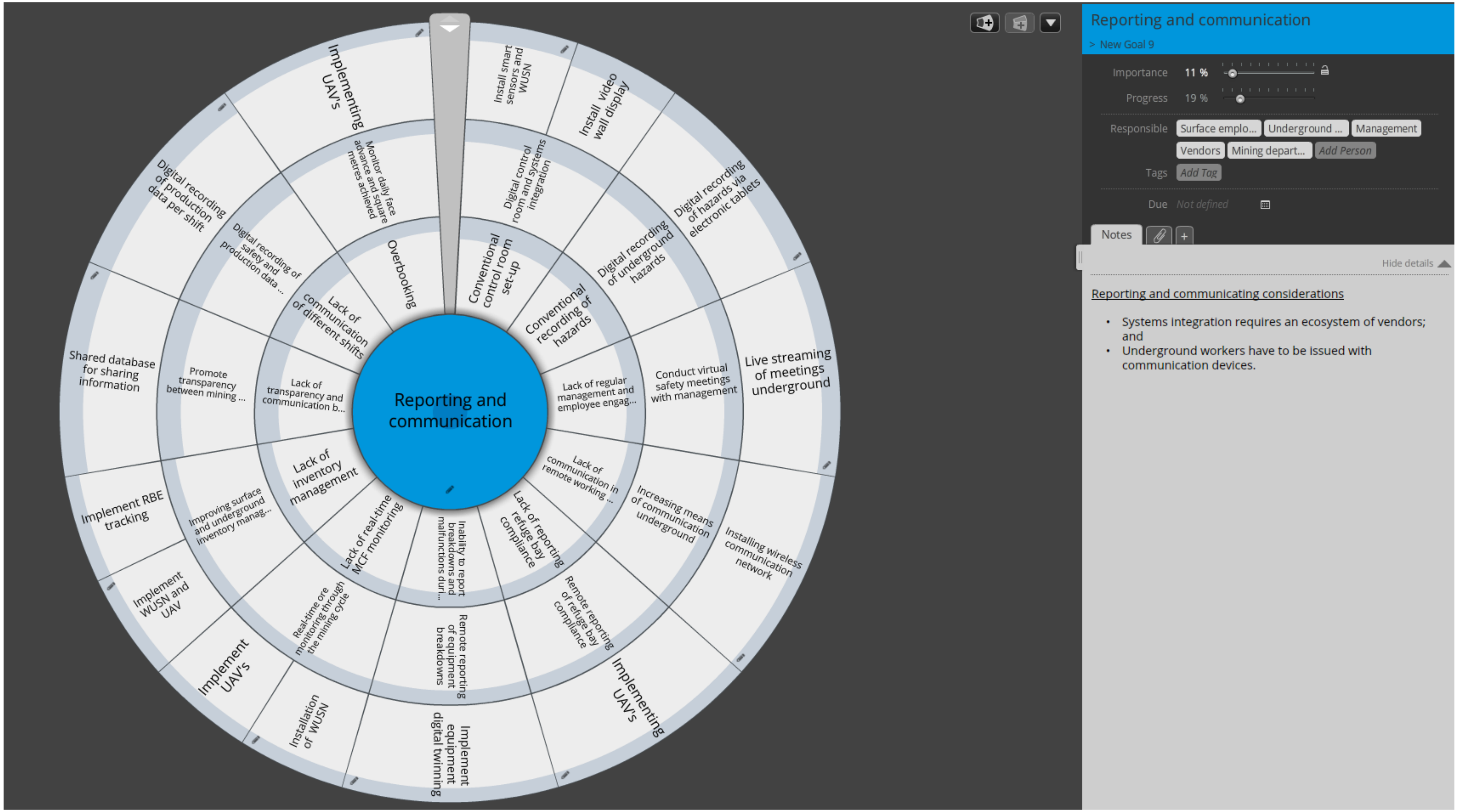
Stoping panels consist of:

- Miners;
- Team leaders;
- Rock drill operators;
- Scraper winch drivers;
- Stoping labourers; and
- Shift bosses and mine overseers.

However, the implementation of digital technology will result in some work becoming obsolete. The miner will become a Miner 4.0, a remote operator capable of multiple functions.

Wage negotiations between management and labour still have to be conducted regularly.

Appendix 11: State of Modernisation when Reporting and Communicating



Reporting and communication

> New Goal 9

Importance 11 %

Progress 19 %

Responsible: Surface emplo... | Underground ... | Management | Vendors | Mining depart... | Add Person

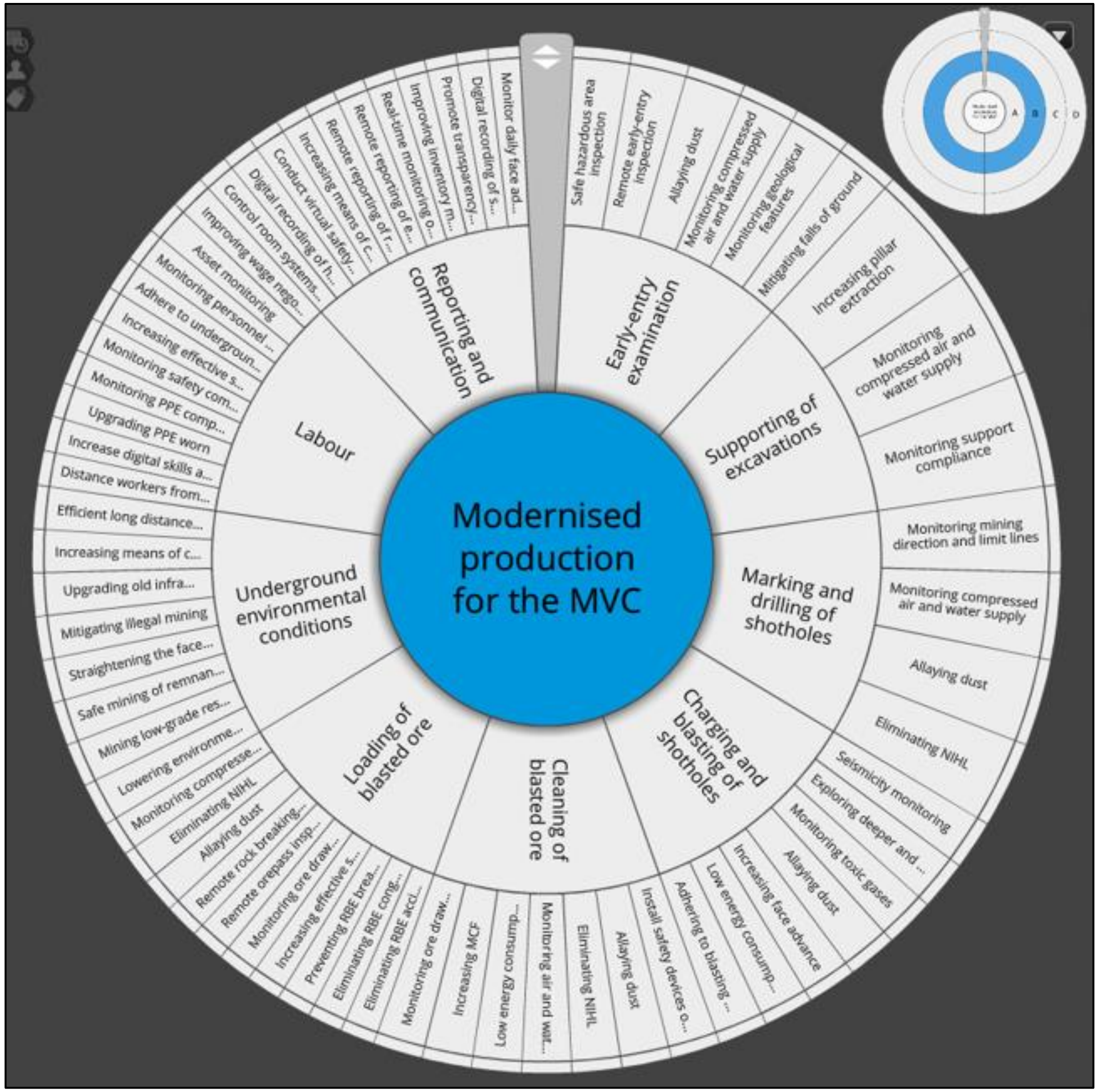
Tags: Add Tag

Due: Not defined

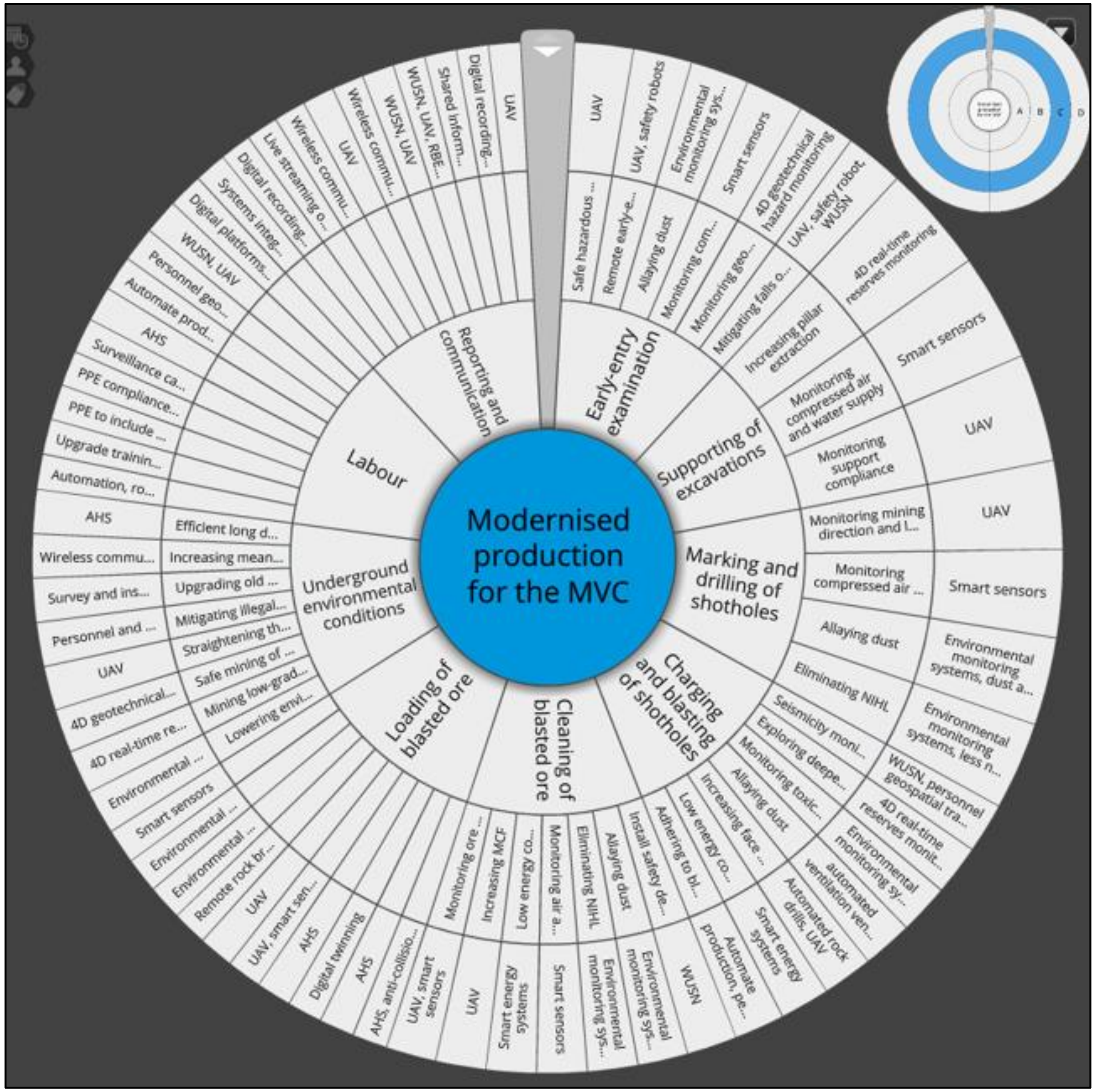
Reporting and communicating considerations

- Systems integration requires an ecosystem of vendors; and
- Underground workers have to be issued with communication devices.

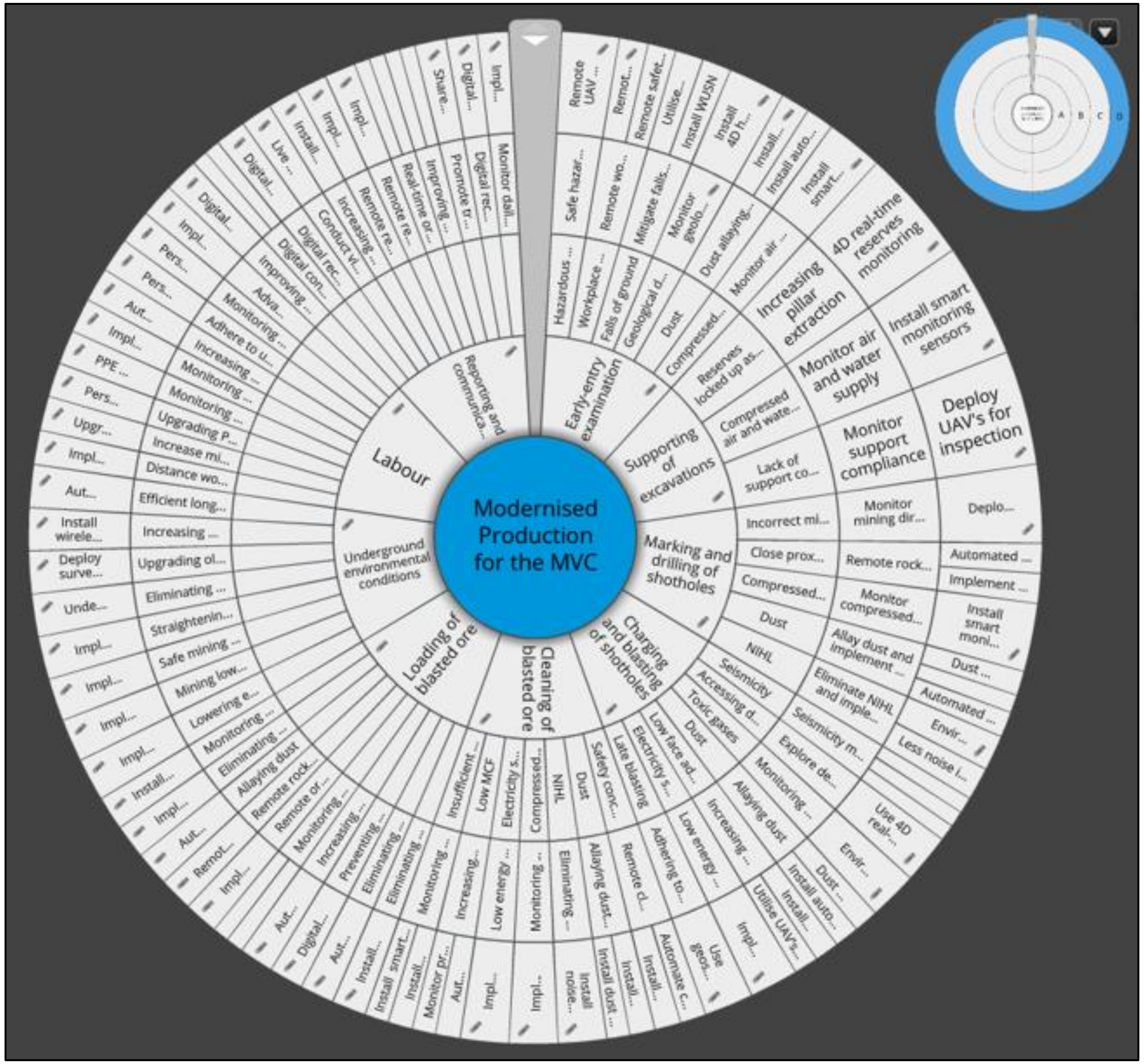
Appendix 12: Challenges in Each Stage of the Mining Cycle



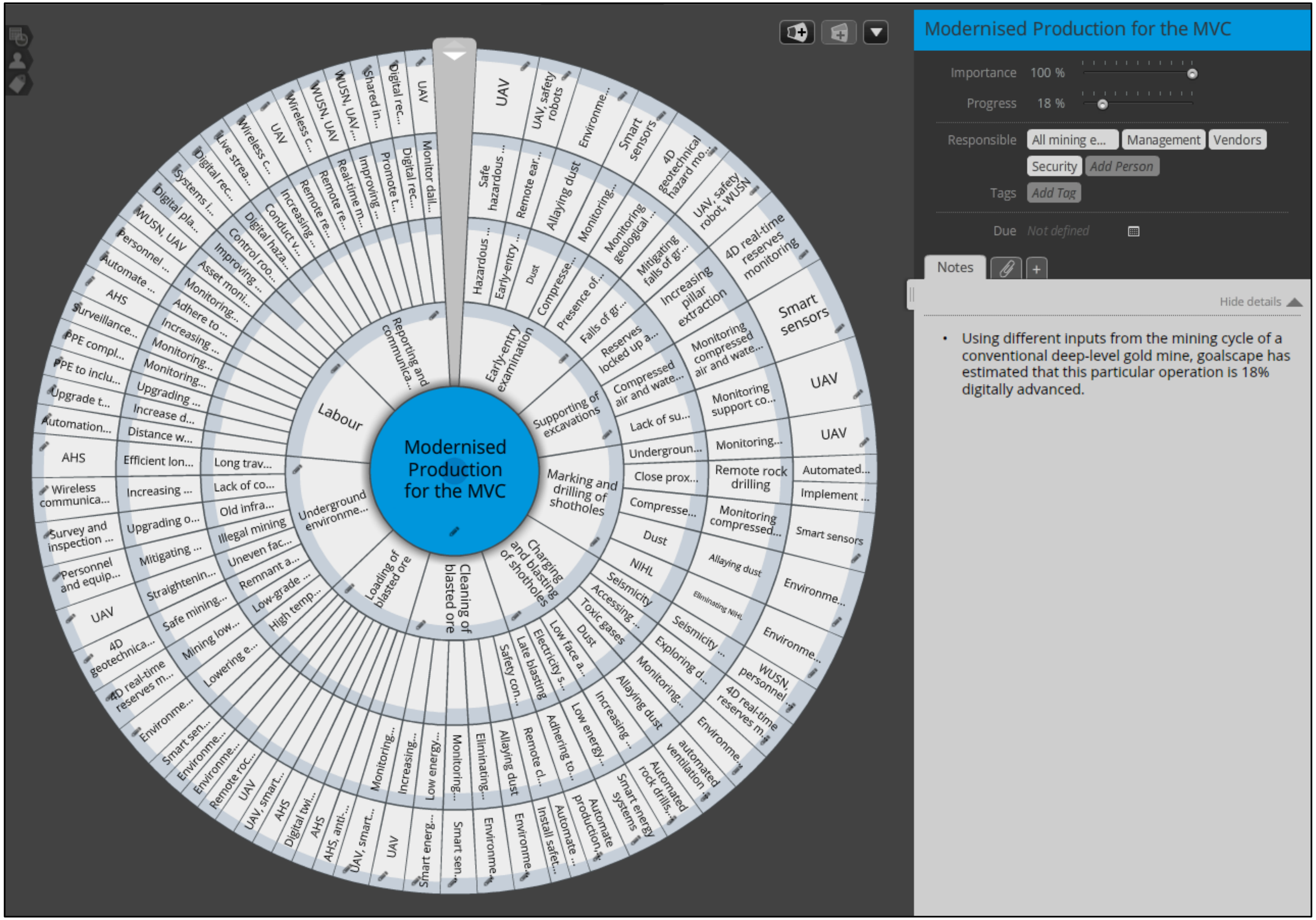
Appendix 13: Output of Proposed Technology for the Mining Cycle



Appendix 14: Digital Technology for the Mining Cycle



Appendix 15: The Conceptual Mine Modernisation Blueprint for a Conventional Mine in the Production Phase of the MVC



Modernised Production for the MVC

Importance 100 %

Progress 18 %

Responsible: All mining e... | Management | Vendors | Security | Add Person

Tags: Add Tag

Due: Not defined

Notes

Hide details

- Using different inputs from the mining cycle of a conventional deep-level gold mine, goalscape has estimated that this particular operation is 18% digitally advanced.

Appendix 16: Roles and Responsibilities of the Stoping Workforce

Mining Cycle Activity	**Responsible Personnel**	**Roles and responsibilities**
Early-entry Examination	• Miner • Team leader • Crew	• Identify hazards and geological features • Check ventilation flow • Water down • Bar down loose rocks • Install temporary support • Treat misfires; and • Thereafter, declare the stope safe
Supporting of Excavations	• Team leader	• Supervises the installation of support
	• Stoping labourers	• Assists with the transportation of support to the stope and the installation thereof
Marking and Drilling of Shotholes	• Miner	• Marks the location of production and preconditioning holes on the face
	• Rock drill operators	• Drills roofbolt support as well as production and preconditioning holes as marked
	• Miner	• Charges shotholes with explosives

Charging and Blasting of Shotholes		• Connects shotholes with fuses and initiates blast
	• Team leader	• Assists the miner in the charging and tamping of shotholes
Cleaning of Blasted Ore	• Scraper winch driver	• Cleans the stoping face and gullies with the scraper winch
	• Water jet operator	• Cleans the face and gullies with the water jet equipment
Loading of Blasted Ore	• RBE drivers	• Loads blasted ore from the orepass to hoppers attached to locomotives for transportation to the internal tip

Appendix 17: Qualification of the Stoping Workforce

Personnel	**Qualification**	**Issuing body**	**Pre-requisite certification**
Miner	Blasting certificate for metalliferous mines	DMR	Grade 12 certificate
Team leader	Team leaders' certificate	Internal	ABET or AET
RDO	Rock drilling operator's license	Internal	ABET or AET
Scraper winch driver	Scraper winch driver license	Internal	ABET or AET
Water jet operator	Water jet cleaning license	Internal	ABET or AET
Stoping labourers	Support installation training	Internal	ABET or AET
RBE drivers	Loco driver license	Internal	ABET or AET

Appendix 18: Required Competence for a Twenty-first Century Mine

Miner 4.0	Team leader	RDO’s	Scraper winch drivers	Stoping labourers	RBE drivers
• Conduct remote early-entry examination • Use 4D hazard monitoring systems • Use real-time reserves monitoring systems • Remotely mark the stope face • Use and interpret results from digitally twinned equipment • Interpret results from different installed systems as projected on the video wall	• Conduct remote early-entry examination • Remotely determine support compliance at the stope • Remotely inspect orepasses • Utilise smart sensors for inventory management • Use smart sensors to monitor the underground environment and production	• Operate automated rock drills or rock cutting machine • Interpret warning signals issued by smart sensors on the rock drill • Monitor drilling rate in real-time	• Use automated cleaning equipment • Interpret warning signals issued by smart sensors on the cleaning equipment • Remotely break rocks at the tip • Remotely monitor orepass capacity through	• Remotely determine support compliance • Interpret results from the support compliance report	• Operate an autonomous hauling fleet • Remotely monitor capacity of the orepass • Remotely track other RBE • Use the safety features on the equipment • Interpret and adhere to RBE schedules

• Use smart sensors to monitor the underground environment and production • Utilise smart sensors for inventory management					