IMPROVING SAFETY AND HEALTH IN UNDERGROUND MINING BY EMPOWERING WORKERS AND CONTROL ROOM OPERATORS TO RESPOND TO TYPICAL EXPOSURE RISKS IN THE PRODUCTION ENVIRONMENT

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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.

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DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted to the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before, for any degree or examination to any other university.

Signed:

Peter TCN Rungani

This **14th** day of **September** year **2020**

ABSTRACT

Generally there have been significant improvements in the fatality record of the South African mining industry, from more than 1200 per year in 1950 to 51 in 2019. The continued loss of life in the mining industry shows that, although there are significant improvements in mine safety, much still has to be done. There are generally less fatalities in the mining industry in developed countries due to adoption of various technologies. The current risk management and assessment systems being used in the South African mining industry prove not to be adequate to stop people from losing lives underground. What is missing from the currently used systems is a comprehensive and integrated system which can empower workers and control room operators to respond to typical exposure risks in the production environment. Mine statistics also show that there are a considerable number of past accidents that occurred underground due to the 'blame game' between miners and mine management on the issue of entering and withdrawing from dangerous workings. Miners claim that their right to withdraw from dangerous workings is usually difficult to exercise especially when there is no real-time evidence to substantiate the presence of dangerous conditions. To the contrary, mine management claim that miners are sometimes negligent and usually enter unauthorised, risky working areas, regardless of them being empowered to use their right to withdraw from dangerous workings. Technology such as real-time atmospheric monitoring and personnel monitoring can be used in risk management and assessment in such situations. In this research, the impact of using technologies in preventing and reducing fatalities is briefly discussed. There are a number of leading practices and technologies that can be adopted to improve health and safety in the mining industry. The research critically analyses four case studies of fatality incidents which occurred in the South African mining industry and how they could have been avoided. By testing some of the available leading technologies in the areas of real-time personnel and equipment monitoring, real-time atmospheric monitoring, and lamproom management systems, the research tries to prove that there is potential to improve health and safety in the mining industry. The research emphasises the need for the mining industry to give more or at least equal attention to health issues as they do to safety issues since the consequences of health risks are long term and cause more fatalities. The findings of the research show that there is a great potential in using technology to manage risks and enhance both health and safety in underground mines. It is concluded from the research that using some of the available technologies in the mining industry, control room operators can communicate health and safety decisions to the underground workers in real-time and help in eliminating fatal accidents. The research also shows that it is possible to implement Section 23 of the Mine Health and Safety Act, which empowers miners to withdraw from dangerous working by using technology. However, to realise the full benefits of these technologies, the study shows that there is a need to integrate the technology systems. The research developed a framework on how to integrate technology systems. The research showed that nurturing a solid safety culture in the mining industry is also important in the journey to achieving zero harm. Introducing technologies and other risk management tools will also be a good supplement on the safety culture. Ultimately, it is concluded in the research that there is great potential for the mining industry to achieve the goal of zero harm through the use of integrated systems. Miners and control room operators can be empowered through the use of technology to respond to typical health and safety exposure risks in the production environment.

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DEDICATION

To my late brother Gamaliel Tinofiraishe Jnr Rungani with whom I would have liked to share exciting moments such as this one. May his soul rest in peace.

To my father (Victor), mother (Anna), siblings and friends who supported me through this journey.

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
ADKAR	Awareness, Desire, Knowledge, Ability and Reinforcement
AI	Artificial Intelligence
AMANDA	Atmospheric Monitoring Analysis and Database mAnagement
AMS	Atmospheric Monitoring System
CMT	Change Management Team
COM	Chamber of Mines
COPs	Codes of Practices
CPDM	Continuous Personal Dust Monitor
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CWP	Coal Workers' Pneumoconiosis
DMRE	Department of Mineral Resources and Energy
DPM	Diesel Particulate Matter
EVADE	Enhanced Video Analysis of Dust Exposure
GDI	Gas Detection Instrument
GIS	Geographic Information Systems
GPS	Global Positioning System
GUI	Graphic User Interface
HMI	Human Machine Interface
INS	Inertial Navigation System
IOT	Internet of Things
IP	Internet Protocol

IR	Infrared
IT	Information Technology
IVPC	In-Vehicle-Personal Computer
JWR	Jim Walter Resources
LAN	Local Area Network
LED	Light Emitting Diode
LHD	Load Haul Dump
LMS	Lamproom Management System
MHSA	Mine Health and Safety Act
MIMACS	Mine Integrated Monitoring and Control System
MINER	Mine Improvement and Emergency Response
MMC	Minetec Mobile Client
MSHA	Mine Safety and Health Administration
MST	Mine Site Technologies
NIOSH	National Institute for Occupational Safety and Health
NLT	Northern Light Technologies
PC	Personal Computer
PDM	Personal Dust Monitor
PDS	Proximity Detection System
PMC	Palabora Mining Company
PMF	Progressive Massive Fibrosis
PLS	Programmable Logic Controller
PPE	Personal Protective Equipment

PwC	PricewaterhouseCoopers
R&D	Research and Development
RAM	Real-time Aerosol Monitors
RF	Radio Frequency
RFID	Radio Frequency Identification
SOPs	Standard Operating Procedures
SSs	Soft Starters
T&A	Time and Attendance
TARP	Trigger Action Response Plan
TBS	Tube Bundle System
TLVs	Threshold Limit Values
TOA	Time of Arrival
UPS	Uninterrupted Power Supply
VFDs	Variable Speed Drives
VOD	Ventilation on Demand
VSDs	Variable Speed Drives
WASP	Wireless Ad-hoc System for Positioning
WMI	Wits Mining Institute
WSN	Wireless Sensor Network

1 INTRODUCTION

In this section the background and context of the research is discussed and the problem statement of the research is also presented. The section further discusses the aims and objectives of the research and provides a motivation for the research.

1.1 Background and Context

Mining accidents threaten the sustainability of the mining industry, since they frequently lead to either death or injuries. Destruction of property and pollution of the environment are also some of their secondary effects (Bonsu, et al., 2017)**.** Generally there have been significant improvements in the fatality record of the South African mining industry, from more than 1200 per year in 1950 to 51 in 2019 as shown in Figure 1.1 (Leger, 1991; Chamber of Mines of South Africa, 2017b; Minerals Council South Africa, 2018; Anon., n.d.; Minerals Council South Africa, 2020b). Despite the improvements people are still losing their lives and the figures are still significant in comparison to other mining industries in developed countries like the United States of America (USA), Canada and Australia. There are generally less fatalities in the mining industry in developed countries due to adoption of various technologies. In South Africa underground metalliferous mines (gold and platinum) contribute about 75 percent of the fatalities. The coal mining industry is much safer when compared to the gold and platinum mining as shown in Figure 1.2 (Chamber of Mines of South Africa, 2017a; Chamber of Mines of South Africa, 2017b; Department of Mineral Resources, 2018; Minerals Council South Africa, 2020a). The major causes of fatalities in the South African mining industry can be classified into three umbrella terms namely rock engineering, mine ventilation and transport and machinery. There has been considerable research carried out in the area of rock engineering and, in recent years, much less in mine ventilation. Although mine ventilation is a fundamental component of mine health and safety, most research in recent years in this area has been focussed on energy saving. Vogt et al. (2010**)** stated that great improvements can be achieved in the areas of health and safety through the use of real-time measurement systems to inform decision making. Modern technology can accelerate the mining industry’s goal to zero harm by providing timeous warning in order to remove people from high risk areas.

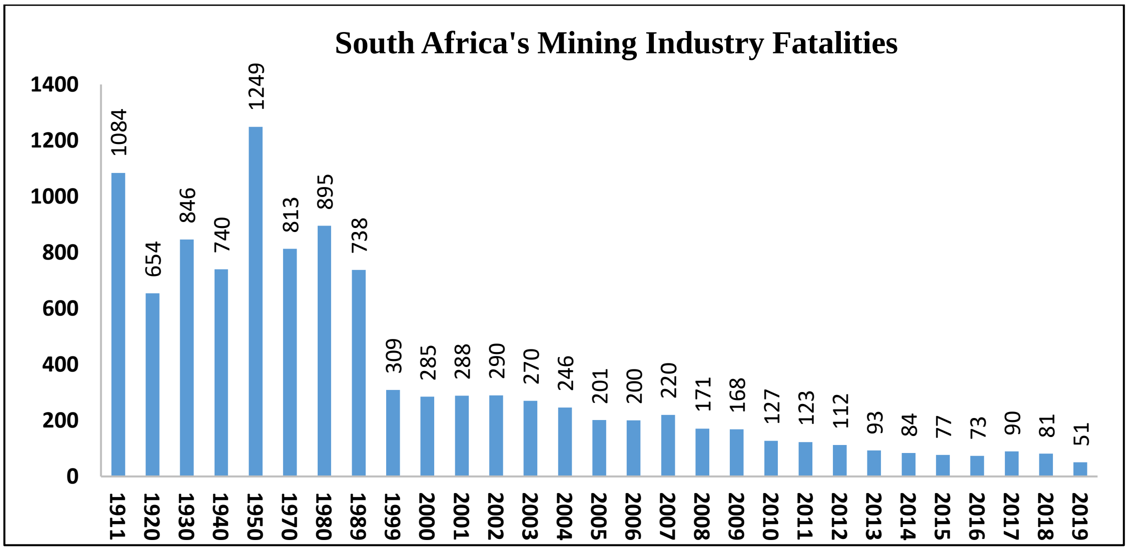


Figure 1.1 South Africa's Mining Fatality Trends (Leger, 1991; Chamber of Mines of South Africa, 2017b; Minerals Council South Africa, 2018; Department of Mineral Resources, 2019; Minerals Council South Africa, 2019; Minerals Council South Africa, 2020b)

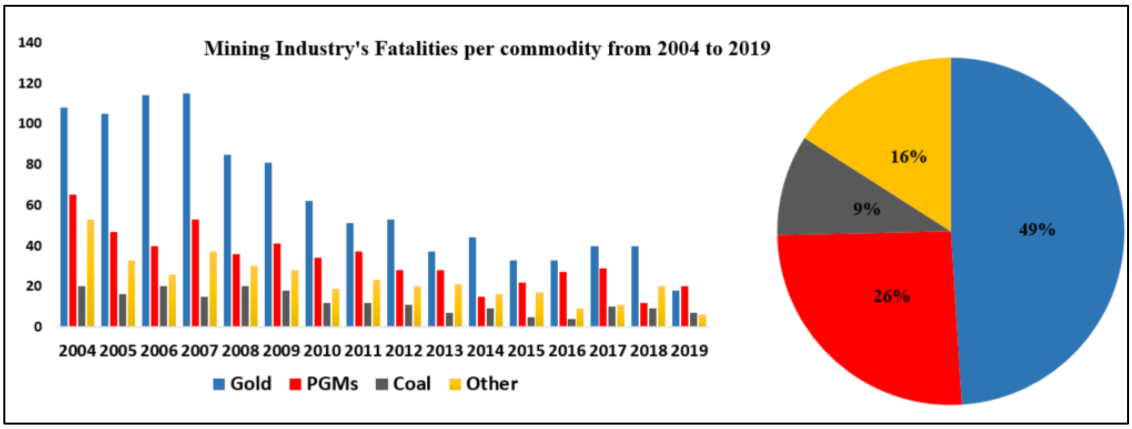


Figure 1.2 Mining Fatalities per commodity (Chamber of Mines of South Africa, 2017a; Chamber of Mines of South Africa, 2017b; Department of Mineral Resources, 2018; Anon., n.d.; Department of Mineral Resources, 2019; Minerals Council South Africa, 2020a)

1.2 Problem Statement

Although the risks associated with individual mining hazards are now manageable and lead to tolerable or acceptable levels, the quest for zero harm in the mining industry continues (Harris, et al., 2014)**.** Workplace fatalities and injuries lead to significant suffering to the affected individuals, their families and society at large. The continued loss of life in the South African mining industry shows partial inadequacy in the systems and risk controls currently being used and implemented to eliminate injuries and fatalities.

Comparing the South African mining industry's fatality rate to other developed countries' industries, there is a significant difference (Kleyn & Du Plessis, 2016), perhaps because of different mining conditions but also perhaps because of inadequate systems or the lack of proper implementation of good systems (Codes of Practice, Standard Operating Procedures, etc). According to Webber-Youngman & Van Wyk (2013), the gold industry has the highest number of fatalities in South Africa (Figure 1.2). Although most fatalities and injuries are caused by rock engineering related incidents (falls of ground, seismicity and rockbursts), the severity of fatalities due to ventilation related incidents (explosions, fire, heat exhaustion and heat strokes) can also be very significant, in the sense that they are usually multi-fatality events. Safety incidents have cost implications through Section 54 stoppages from the Mine Health and Safety Act of 1996, compensation claims and legal fees. It is estimated that in 2015 the South African mining industry lost 4.84 billion rands in revenue through these stoppages (PricewaterhouseCoopers (PwC), 2017).

Notwithstanding that mine safety is of significant concern in underground mines, the health of mining personnel is also of paramount importance. Due to its nature, i.e. rock breakage, mining leads to the creation of large quantities of respirable dust which can result in serious health problems such as silicosis, pneumoconiosis, bronchitis and tuberculosis for mining personnel exposed to such conditions (Muduli, et al., 2018; Moridi, et al., 2015). Other issues such as the extensive use of diesel powered equipment underground also contribute to health concerns. It is difficult to get an actual figure of the number of miners who have died of or are living with occupational illnesses such as silicosis due to high levels of under-reporting in this area (Kohler, 2015; Minerals Council South Africa, 2020b). The biggest drawback in the treatment of occupational illnesses such as silicosis is the fact that there is no cure for the disease and combined with the high incidence of tuberculosis and HIV/Aids the prognosis for affected workers is very poor. In May 2018, seven mining companies namely Harmony Gold, Sibanye Stillwater, AngloGold Ashanti, Anglo American, Gold Fields, Pan African Resources and African Rainbow Minerals agreed to the setting up of a 5 billion Rand trust fund as a settlement to compensate workers and former workers affected by silicosis (Seccombe, 2018).

Section 23 of the Mine Health and Safety Act (MHSA) of 1996 empowers mine employees to withdraw from dangerous working areas (Webber-Youngman & Van Wyk, 2013). However, Geng & Saleh (2015) allege that on numerous occasions workers are intimidated and afraid to withdraw from dangerous workplaces which in some cases has led to fatalities. The authors state one of the major contributing factors being the failure of mine management to choose between production pressures and safety boundaries. On another hand, mine management frequently blame mineworkers for not being risk averse and for following substandard work practices, which usually lead to injuries and fatalities.

At a time when improvements in safety have appeared to have stalled and the statistics have plateaued, some technological breakthrough is needed to continue the momentum towards zero harm. Continuous real-time monitoring of the underground environment has a critical role to play because of the environment's complex and dynamic nature. The implementation of such systems helps both mine personnel and management to make real-time decisions regarding the health and safety of underground personnel, thus ultimately preventing injuries and fatalities.

The current risk management system being used is not adequate to stop people from losing lives underground. What is missing from the currently used systems is a comprehensive and integrated system which can empower workers and control room operators to respond to typical exposure risks in the production environment. However, some of the incidents which have occurred could have been avoided if some of the readily available technologies were in place at the mines. A brief discussion on the specific incidents will be discussed in the following chapters of the research. To be able to solve these problems the following fundamental questions need to be addressed:

1. Can the surface control room workers communicate health and safety decisions in real time to workers in the production environment?
2. How can Section 23 of the MHSA be implemented using technology?

1.3 Aims and Objectives of the Study

1.3.1 Aim of the study

On the 11th of June 2018, five mining employees lost their lives at one of the deep level gold mines (Mine X) in South Africa. According to media reports from different stakeholders, the fatal incident was due to miners succumbing to heat exhaustion. However, the area where this fatal incident occurred was said to have been abandoned. Mine management claim that the deceased did not follow proper procedure of entering the area. On the other hand, organised labour claim that they had evidence that the deceased were forced to go to the abandoned area and denied their rights to withdraw from the dangerous workings. The investigations to ascertain the real reason why the deceased went to work in these areas have not yet been completed. The main aim of this study is being able to answer and address the following:

1. How can the mining industry avoid incidents such as what happened at Mine X?
2. Identify current solution(s) to the problem through
    - Review of leading practices;
    - Link that to the reality at the mine.
3. Why is it (still) a problem?
    - Can current systems give alarms and real-time dashboards on major risks?

1.3.2 Research Objectives

The objectives of the research are as follows:

1. Understand what happened at Mine X fatality incident;
2. Identify monitoring systems and ways to communicate data to control room;
3. Establish rules for data entering the control room to be measured against Standard Operating Procedures (SOPs), the Mine Health and Safety Act (MHSA), Analytics and Predictions;
4. Determine how real-time risk management can be achieved in mines;
    - Data flow from control room to responsible person(s) and control room to the production environment.
    - Determine how the previous and current research in real-time monitoring and control systems can be integrated to achieve zero harm.
5. Determine data architecture for empowering workers and allowing the control room operator to respond to typical exposure risks in the production environment.

1.4 Motivation and Justification of Research

Following the fatality incident at Mine X which led to the loss of 5 lives, the researcher was motivated into pursuing this research, which has a number of potential benefits. The justification of doing the research is the following:

1. The need to prevent loss of life;

2. To have a better understanding of the underground mine environment and personnel location;
3. The need to prevent loss of production due to Section 54 Stoppages;
4. To promote lawful and compliant mining operations;
5. To have mine health and safety improvements through prevention enabled by early-detection of hazards;
6. To realise that great energy savings can be achieved by applying Ventilation on Demand through real-time monitoring and control systems;
7. The need to reduce the risk of additional regulatory burden to the mining industry;
8. The need to prevent reputational risk for mining companies.

1.5 Structure of Dissertation

This dissertation has been divided into eight chapters. The following summarises the chapters.

Chapter 1: Introduction

This chapter presents the background of the research as well as introducing one of the case studies to be addressed by the research. It also illustrates the aim, objectives and motivation of the research.

Chapter 2: Literature Review

This chapter is devoted to the review of case studies on historical mine fatalities and disasters in the mining industry due to both health and safety issues. The chapter will also provide a brief discussion on how technology can be used in risk management and assessment in underground mines. Mine fatalities which could have been prevented using some of the now available technologies will also be discussed in this chapter.

Chapter 3: Leading Practices and Technologies That Can Prevent Fatalities

In this chapter the leading practices in the global mining industry being used in the areas of health and safety are identified and discussed briefly. The chapter also focuses on the various technologies being used in the industry for real-time monitoring and control of underground mining personnel and the environment. The impact of these technologies in preventing and reducing fatalities is also discussed further in this chapter complementing the brief discussion in the literature review section.

Chapter 4: Case Studies on fatal incidents in the South African Mining Industry

This chapter will briefly discuss a number of fatal incidents which occurred in the South African mining industry with emphasis on ventilation related causes. The fatality incidents are discussed under four case studies. The case studies include the Middelbult explosion of 1993 which claimed fifty three lives; the Ermelo Mine Services explosion of 1992 which claimed six lives, the Mine X heat exhaustion incident of 2018 which claimed five lives, and the Palabora Mining Company fire incident which claimed six lives. The chapter will delineate the possible causes on each of the aforementioned incidents. The lessons from each case study are also analysed and leading practices which could have stopped the fatalities from happening are also discussed in this chapter. Furthermore, for each case study recommendations on how the now available technologies could have avoided the incidents from occurring.

Chapter 5: Testing Available Systems for Systems Integration

The other major themes covered in this chapter include the Wits Mining Institute DigiMine research and lessons to date in the area of mine health and safety. These themes are aimed at justifying how the use of integrated risk management and control systems can reduce mine occupational diseases and mine fatalities. Four leading technologies in the areas of real-time personnel and equipment monitoring, real-time atmospheric monitoring, and lamp room management systems are tested in this chapter. The strengths and limitations of each standalone system are also discussed in this section. The chapter also discusses how the tested technologies' functionalities could have avoided the fatalities discussed in the case studies in chapter 4. The findings from the tests form the foundation of the integration framework put forward in chapter 6.

Chapter 6: Framework for Integrated Monitoring and Control Systems in Underground Mines

This chapter discusses the data and components required to integrate the different technologies identified in the leading practices and the ones discussed in chapter 5. The process of system integration is discussed and the various technologies which can be integrated. The section also explores some of the few examples of the integrated systems and their functionalities. The framework for executing real-time environmental and personal monitoring and control using integrated systems is put forward and discussed in this chapter. The role played by each standalone component in the proposed integration framework is also discussed in this chapter.

Chapter 7: Implementation plan

This chapter puts forward the factors which must be considered to successfully implement technologies in the mining industry. This chapter discusses the skills required for the adoption and use of integrated systems and the training needed for the effective use of the systems. Furthermore, this chapter considers the human factors involved when implementing new technology. The chapter will also explore the risks which might be posed by the systems when implemented in the underground environments.

Chapter 8: Conclusion and Recommendations

This chapter discusses the findings and conclusions from the study and, based on these, recommendations are made.

The reference section is at the end of study.

2 LITERATURE REVIEW OF HEALTH AND ISSUES THAT CAN BE IMPROVED BY TECHNOLOGY

The continued loss of life in the mining industry shows that, although there are significant improvements in mine safety, much still has to be done. In any mining environment, every company has an obligation to assess and manage risks with respect to both safety and profitability. Mine fatalities pose potential reputational risk and embarrassment for the leadership of both government and mine companies (Geng & Saleh, 2015). Griffin et al. (2013) add that workers' health and safety, a company's reputation, cost, efficiency, work force morale and environmental impacts can be directly and negatively affected by the company's risk management and assessment processes. Mine safety in South Africa has become a great public concern and as such it has become a priority of the DMRE, labour unions and mining companies (PwC, 2017). In recent years the expectations of mining stakeholders on the companies' corporate social responsibility and environmental performance now have significant impacts on mines' social licence to mine (Griffin, et al., 2013).

Although it is difficult to prove, mine workers working in a healthy and safe environments yield better productivities (Wallace, et al., 2015) hence the journey to zero harm is beneficial in both saving lives and enhancing mining companies' profitability. According to Njini (2017), mining unions in South Africa are advocating for the government to make and hold mine management to be personally liable for the deaths of miners as this will make them spend more money on protecting mine workers. Njini further states that mining unions allege that mining companies "are maximising profits while violating safety procedures". The blame game between workers, government, organised labour and mine companies can only be resolved when a safety system which needs minimum human interference is implemented at the mines.

2.1 Mining Accidents and Fatalities

Historically the global mining industry can be characterised by high accident and fatality rates. According to Leger (1991), 600 to 800 deaths were recorded annually in the 1980s in the South African mining industry (Figure 1.1 in Chapter 1). However, Sidler (2015) states that since 2013, fatalities recorded in the South African mining industry have reduced to less than 100 per annum and this is supported by the Chamber of Mines of

South Africa (2017b) statistics shown in Figure 1.2. These improvements are comparable to the ones recorded in countries such as the USA, where in 1910 there were 3000 fatalities recorded annually (Dhillion, 2010) and only 28 in 2017 (Casey, 2018; Mine Safety and Health Administration (MSHA), 2018). However, despite great improvements in mine safety, the goal for zero harm has not yet been achieved.

Exposure to mine gases, respirable dust, rockfalls, mine fires and machinery are the major hazards in an underground mining environment. Dhillion (2010) shows that of the 27 world major mining disasters (6 or more fatalities in one incident (Leger, 1991)) in countries such as United States, United Kingdom, China, Australia, Canada, Poland, Russia, Ukraine and South Africa; 55% of the accidents were due to methane gas explosions and 20% because of fire. This is supported by the 2014 Turkey's Soma mine methane gas explosion or fire which claimed 301 lives (Grinter, 2014; Mining Prospectus, 2014). Looking at the period 1983 to 1993 in the history of South African Coal industry, 190 people lost their lives due to explosions. These incidents include the Hlobane Colliery explosion of September 1983 where 68 people were killed, the Middelbult Colliery explosion of August 1985 were 34 people lost their lives, Ermelo Mine Services explosion of April 1987 were 35 people died, and the Middelbult Colliery explosion of May 1993 were 53 people lost their lives (Gouws & Phillips, 1995; Brandt & Phillips, 1995). Although not classified as a disaster (usually considered as 6 or more fatalities), four Impala Platinum employees lost their lives following a fire which occurred underground at Impala Rustenburg 14 Shaft on the 22nd of January 2016 (Implats, 2016).

Mine fires are also another major hazard, which not only endanger lives but also cause considerable economic loss for mining companies. Fox (2016) cited in Rungani (2016) attests to this by stating that the Impala Rustenburg 14 Shaft fire accident did not only lead to the loss of lives, but also millions of dollars were lost due to stoppage of production. The conveyor belt also burned out, along with other mining infrastructure and electrical cables, which were of a significant cost to replace (Rungani, 2016). Although fire accidents are less frequent, their consequences are more severe than rock collapses. In their study, Geng & Selah (2015) stated that rock falls on average lead to 4 fatalities, gas explosions on average 8 fatalities and fire accidents on average 13 fatalities. However, from various research and incidents it is evident that explosions in fiery mines usually result in higher fatalities and injuries (Kohler, 2015).

Mining accidents and fatalities vary in different commodities especially in South African mines**.** According to Kleyn & Du Plessis (2016), the safety performance in South African gold mines is below the counterpart sectors in developed countries although there are significant improvements. However, the safety performance of South African coal mines (Figure 1.2) is better than that of other developing countries like China. For a company to run smoothly and function successfully, the health and safety of its employees is of vital importance. Chen & Zorigt (2013) add that in any organisation, health and safety are the determining factors in organisational effectiveness.

Mine safety generally affects profitability in the sense that, when there is a mine accident or fatality, production stops. In the case of South Africa, Section 54 of the Mine Health and Safety Act (MHSA) of 1996 restricts any mining activity after a serious accident or any fatality until a full investigation and the cause of the accident has been determined (Creamer, 2012). This is a major issue for mining companies as it means as production stops; mine workers will still have to be paid without ongoing production. Creamer (2012) stated that by 2012, Section 54 stoppages had cost the South African mining industry US$500 million due to the loss of 300 000 precious metal ounces of production. South Africa is at risk of losing revenue worth billions if the mines continue to shut down due to accidents (Bonsu, et al., 2017). Similarly in 2013, the USA MSHA estimated that annual accident costs were approximately $910 000 per occupational death, $28 000 per lost work day cases, and $7000 per reportable case without lost work days (Griffin, et al., 2013). The cost of losing lives in the mining industry is not only a social loss but also an economic one. Hence the goal to zero harm does not only support the preservation of lives but it also directly impact on productivity and profitability of its mines. However, Reason (1998) states that it is important that the mines' pursuit of achieving commercial goals must always strike a delicate balance with their safety goals.

2.2 Health Issues and Fatalities

Health issues just like safety issues are of great importance for the wellbeing and protection of underground miners. Saleh & Cummings (2011) state that the only significant difference between health issues and safety issues is the difference in the time scales of the effects of the hazard sources. For instance, when an explosion or mine collapse occurs, there will be immediate results which can either be injuries or fatalities and this is a typical example of a safety issue. However, when a miner is exposed for a long period of time to silica or coal dust, this usually results in devastating and fatal consequences in the form of lung diseases such as silicosis, pneumoconiosis, coal workers' pneumoconiosis (CWP) (Guild, et al., 2001; Saleh & Cummings, 2011; Cecala & O'Brien, 2014; Haas, et al., 2016). These are typical examples of health issues. Figure 2.1 elaborates the relationship between the severity of impact and the time of impact of safety issues as well as health issues.

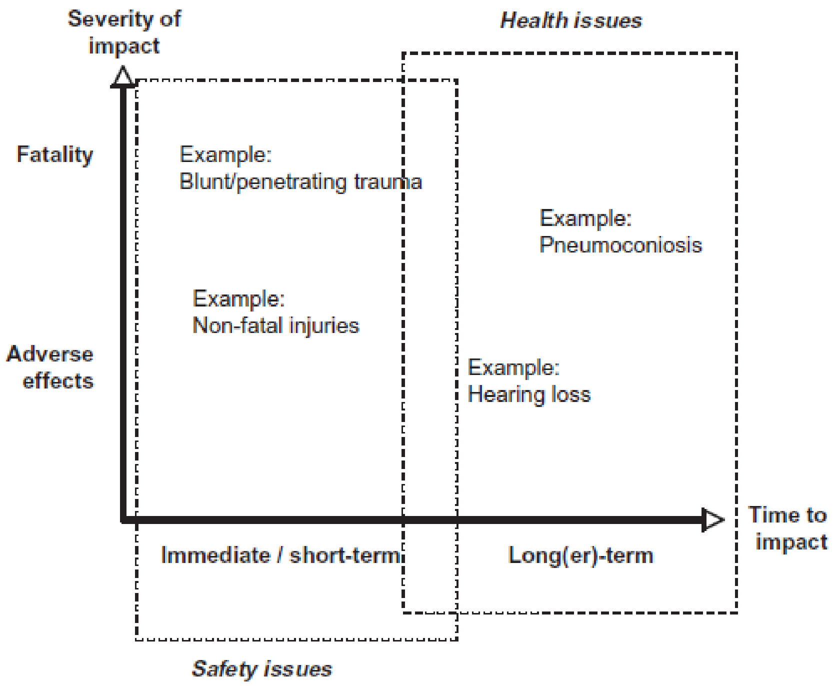


Figure 2.1 Classification and examples of safety and health issues in the mining industry (Saleh & Cummings, 2011)

In their study Saleh & Cummings highlighted that the scale of health issues is considerably high when compared to that of safety issues. The US mining statistics show that 10406 miners died of pneumoconiosis (health issue) alone in the period 1995 to 2004 (Saleh & Cummings, 2011; National Institute for Occupational Safety and Health, 2008). To the contrary, the United States Department of Labor (2019a,b) indicate that 730 (Figure 2.2) safety related fatalities were recorded in the same period 1995 to 2004 from all US underground and surface mines (coal, metal and other non-metals). Considering that the 10 406 health related fatalities did not consider fatalities due to other diseases such as silicosis and asbestosis, the number is devastatingly alarming when compared to the safety related fatalities.

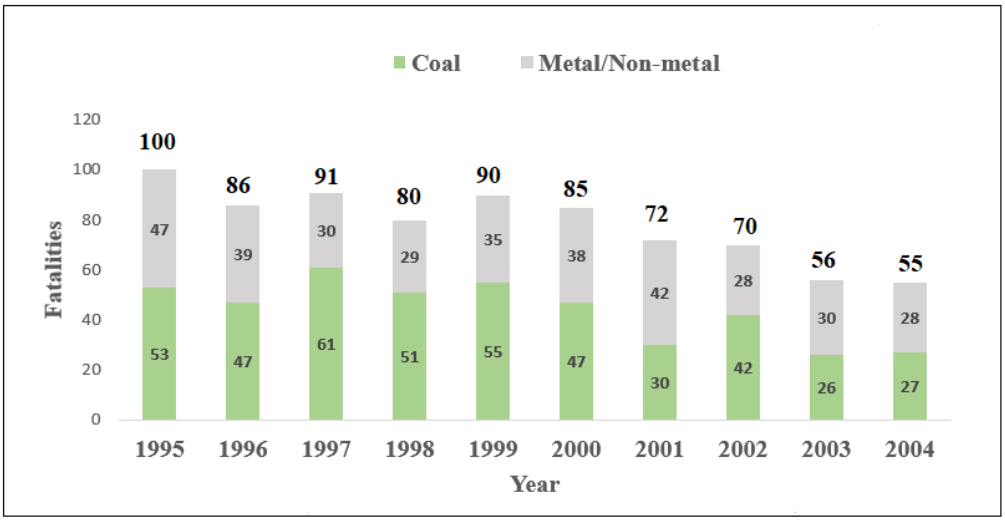


Figure 2.2 Safety related fatalities for Coal Mines, Metal and Non-metals (United States Department of Labor, 2019a; United States Department of Labor, 2019b)

Although emphasis is always placed on underground mine safety, the health of mine workers is also of paramount importance and this includes prevention of occupational diseases such as pneumoconiosis or fibrosis, silicosis and tuberculosis through inhalation of respirable dust. To be able to have good quality underground health conditions a good ventilation system is a prerequisite. Good understanding of mine ventilation practices include dust control, heat stress management, refrigeration and/or air heating, control of mine gases and Diesel Particulate Matter (DPM), radiation control, explosive gas and dust and mine fire risks, escape and rescue planning, noise minimisation, fan operation and theory and mine ventilation economics. It is also critical that the ventilation Engineers have an understanding of occupational exposure limits of airborne pollutants and also be able to sample the pollutants (Wallace, et al., 2015).

Mine dust monitoring is another critical aspect in environmental monitoring. The initial control of dust generation is preventing it at the point of formation. Wet drilling and watering down the muck piles are some of the effective ways of suppressing dust generation. Allowing dust into the main airways makes the dust control task more difficult. It is imperative to maintain the air velocity at the face between 0.3m/s – 0.5m/s to ensure immediate dilution and removal of the dust at the face. However, extremely high air velocities in the ranges 1.52m/s – 2.03m/s tend to raise settled dust, hence it is critical to always maintain the velocities below the above mentioned (Marshall, 1982).

Short-term exposure of mining personnel to airborne contaminants can become a serious health issue. There are currently no common mechanisms to control or mitigate these localised short-term high exposures to contaminants. One of the shortcomings of the currently used airflow and contaminants monitoring is the use of once-off full-shift sampling which usually does not identify repeated short-term high-level exposures of airborne contaminants (Raj, et al., 2017). The use of real-time monitoring and controls allows mines to have the opportunity to monitor contaminants and implement controls in real-time.

Davis (2018) claims that the South African mining industry, due to its reactive nature, has taken decades for the industry to implement the leading practises in areas of dust monitoring and control from other developed industries such as Australia and Canada. She highlights that for instance the silica exposure limits are well above international standards which were reduced a decade ago in countries like Australia and the USA. However, in South Africa it was only in 2003 that a target to restrict silica dust to less than 0.1mg/m^3 of air by 2008 was put forward. Davis further alleges that this target is proven not to be sufficient for protecting miners against silicosis. Nelson & Murray (2013) support Davis's claims, as they state that the current research from other mining countries have shown that the safe levels for respirable silica dust must be below 0.025mg/m^3. However, this is in contrast with the 2024 milestone target of 0.05mg/m^3 of respirable silica dust (Martin & Magampa, 2018) set by the South African mining industry. This means with the current targets in the South African mining industry, new cases of silicosis can still be expected as the current targets are not sufficient.

In her report, Davis (2018) also states that, although mining companies have implemented various techniques such as wearing of dust masks and watering down of underground areas to reduce workers exposure; the two are unreliable. She reports that workers often do not wear their dust masks due to heat and claims that watering down of underground areas usually leads to increase in humidity. These claims and the continued emergence of new occupational diseases (silicosis) makes the need for adoption of new technologies and leading best practises from developed countries like Australia, Canada and the USA critical. The biggest challenge with most the occupational diseases like silicosis is that they do not have cures and there is still a high level of under reporting.

Most governments usually react to high fatality incidents from safety related issues as they have high chances of causing media attention which sometimes cause quick legislative and political action. In South Africa the Department of Mineral Resources and Energy consistently update and release the safety statistics every year end, however, they are always inconsistent in health related performance statistics (Minerals Council South Africa, 2020b). Although safety related fatalities have gained a higher media publicity than the health related ones, there is a high prevalence of the latter and it is a silent killer of miners and as such they should not be forgotten or disregarded by decision makers (Saleh & Cummings, 2011).

Saleh & Cummings (2011, p. 769) emphasise the need of paying more or equal attention to health issues in the mining industry by paraphrasing a saying by Mark Twain as follows: "While thunder (safety) gets the attention, it is lightning (health) that does most of the sinister work". The aforementioned discussion proves that risks regarding the health and safety of mine workers must all be dealt with, at an order of equal importance. It is alarming that in recent research it has been found that there are a significant number of new cases of younger miners being diagnosed with silicosis and other respiratory diseases regardless of their limited mining experience (Haas, et al., 2016). The realisation that health related diseases might be causing more devastating numbers of fatalities is critical and this must be addressed in order to improve the overall health and safety of mine workers. Nelson & Murray (2013) also emphasise that it is important for South African miners unions to not only focus on issues of safety and wages but also promote occupational disease prevention.

2.3 Risk Management through Technology

It is important that the mining industry moves away from risk assessments leading to prescriptive standard operating procedures to proactive risk assessments. Prescriptive regulations allow operators to comply with the minimum safety regulations and often force compliance or increased regulatory oversight. There is great potential of preventing some accidents underground by integrating safety systems and developing technologies, however a compliance culture in the mining industry accepts the unfortunate and occasional loss of life (Griffin, et al., 2013; I-CAT, 2017). For instance, compliance in the mining laws and regulations in the mining industry suggests "that the existing levels of atmospheric monitoring are sufficient, but recent loss of lives in the mining industry suggest otherwise" (Griffin et al., 2013, p. 4)**.** Reason (1998) states that the best way for mines to avoid accidents is by making sure that they gather the right kind of data. Reason further states that the data gathering must be done through a system that is able to collect, analyse, and disseminate information from all the mining incidents and near misses, as well as what he calls "regular proactive checks on the system's vital signs". Such systems allow for mining personnel and management to always be informed on the human, technical, organisational and environmental factors that directly and indirectly affect the health and safety of workers. The use of technology can help in setting up such effective systems and have a proactive risk management setup in underground mines.

Risk management is key to the determination of the level of atmospheric monitoring required to ensure a mine is safe. Atmospheric monitoring, risk management and increasing the acceptance of behaviour-based systems have a potential to increase the level of accident prevention and awareness within the industry (Agioutantis, et al., 2015). Above all, a safety culture is of paramount importance because it is through it, that individual safety attitudes can develop and safety behaviours are promoted (Moridi, et al., 2015). Vogt et al. (2010) attests to this by adding that no technology can replace the requirement for a culture of safety among mine workers.

The introduction of new technology has undoubtedly contributed to the continuous reduction in the injury and fatality rates in the mining industry (Dozolme, 2018; Zhang, et al., 2009). One good example is the introduction of anti-collision systems, which have significantly reduced the number of transport related accidents in the mining industry. In addition, the use of communication technology has resulted in great improvement in mine safety and profitability. Geng & Selah (2015) suggested that the two most effective ways to improve safety in mines are, the need of technical competence amongst the workers and the adoption of safety technologies and behaviours. Opiti (2017) emphasises that real-time monitoring and control systems such as digital sensor systems and real-time spatial analysis systems enable efficient monitoring and gathering of information relating to health and safety risks i.e. prediction of risks.

Various researchers (Zhang, et al., 2009; Rungani, 2016; Carroll Technologies Group, 2018; Dozolme, 2018) in countries such as Australia, USA and South Africa support these findings. Recommendations from inquiries held after various mining disasters in countries such as the USA and Australia introduced mining regulations which require every mine to have real-time monitoring systems for both gases and the location of mining personnel. Queensland's Coal Mining Safety and Health Regulations of 2001 have resulted in Australia being regarded as having the best mine gas monitoring systems internationally (Brady, 2008). The protection against spontaneous combustion has contributed to the low fatality rates in Australian mines. Similarly, the Mine Improvement and Emergency Response Act (MINER Act) of 2006 contributed to significant improvements in mine safety in the USA mining industry (National Institute for Occupational Safety and Health, 2011).

The South African mining industry, due to its history, has been slow to catch up with the rest of the world in terms of health and safety. Because of its reactive and historically prescriptive nature, the industry and the Department of Mineral Resources and Energy (DMRE) have, in general, only considered catching up with the rest of the world after major incidents which claim a considerable number of lives and resulting in public outcry (I-CAT, 2017). The Chamber of Mines (COM) of South Africa (now Minerals Council South Africa) stated that, in the ten years (2006-2015), a 66% reduction in fatalities in the mining industry was noted due to improved mine monitoring systems and equipment reliability (Scanimetrics, 2015). Scanimetrics (2015) further states that the fatality numbers in the USA and Canada also improved by 47% and 25% respectively over the same period due to monitoring systems and other safety technologies. As an example, in 2014, AngloGold Ashanti managed to evacuate 3300 miners from underground through the use of communication technology after an earthquake of a magnitude of 5.3 rocked the Northwest province of South Africa (Sinclair, 2015).

Although accident rates are still high in China, better communication systems have improved the fatality rates (Chang, et al., 2009). Mining accidents in China are said, amongst other things, to be have been caused by inadequate communication between underground and surface personnel. Other main direct causes of accidents in underground mines are; poor ventilation management, late evacuation of personnel in the case of a power and consequent fan failure, unauthorised access of dangerous or old working areas, out of order gas monitoring equipment and operating in risky areas (Chen, et al., 2012). Kohler (2015) suggests that the mining industry needs tools to help identify and assess some pertinent risks. The mining industry must take advantage and adopt best practices in the military, NASA and other industries as this can help the industry move to its target of zero harm (Kohler, 2015).

A good and efficient ventilation system is the first goal towards a health and safe environment underground. According to Wu & Gillies (2005, p. 383), “the fundamental requirement of ventilation is to provide controlled air distribution within the underground mining operations to satisfy statutory and safety requirements with respect to air quantity and quality”. Health and safety management systems rely on all levels of management from the top down fully believing in the system being implemented and reinforcing the system with incentives and goals for employees to work towards (Griffin, et al., 2013; Geng & Saleh, 2015) . Both risk assessments and management processes and behaviour based safety systems will be overridden if the company culture does not value safety in the mine (Griffin, et al., 2013; Kleyn & Du Plessis, 2016).

Comprehensive atmospheric monitoring can provide early warnings and potentially prevent occupational diseases, injuries, and fatalities. The adoption of a large number of sensors can facilitate the gathering of dynamic information which may include smell, pressure and deformation (Zhang, et al., 2012). The selection of an Atmospheric Monitoring System (AMS) for an underground mine should be based upon baseline ventilation parameters for each mine. It is critical that a mine does not use blanket systems, for example, a coalmine with low methane content seams and a low propensity for spontaneous combustion should have a less comprehensive AMS than a mine with high methane content (Griffin, et al., 2013). On the contrary, the latter point may lead to complacency in low methane mines because in high methane generally everyone stays on their toes and follow safety guidelines. For risk management purposes it may be suggested that blanket systems be implemented in all mines with methane regardless of the methane contents.

Real-time environmental monitoring of air quality, noise, dust and gas has the potential to make a significant difference in the mining industry. Currently most of South Africa’s older, traditional mines are not implementing these technologies (Mining Safety, 2018), which may be one of the reasons mines are lagging behind in terms of safety. In high risk industries, a reporting culture is critical to identify prevalence and causation of incidents and sharing of lessons learnt from the investigation reports (Harris, et al., 2014).

In their study, Geng & Selah (2015) stated that in some cases, miners identify serious hazards in production zones and when they request production suspension, mine management usually rebuffs them. They further claim that many of these incidents were subsequently tragic, killing many miners. Problems in health and safety management arise when different levels of management prioritise and reinforce conflicting goals and emphasise productivity over completing jobs according to the safety system. Kleyn & Du Plessis (2016) attest to the findings by stating that supervisory and management aspects have shown to contribute directly and indirectly to accidents.

Zhang et al. (2012) state that at the moment it is very difficult for mine management to effectively supervise underground unsafe behaviours of people, unsafe condition of the environment and the flaws of management. Zhang et al. (2012) further assert that these difficulties are one of the reasons why there is still high occurrence of serious accidents underground. In general, production personnel are the employees who perform substandard practices and unsafe acts (Kleyn & Du Plessis, 2016). However, Zhang et al. (2012) state that the latter occurs because mine production supervisors lack the informational means to enforce the avoidance of illegal and violating acts and also understanding of unsafe behaviours. Njini (2017) adds that the occurrence of accidents is not usually caused by failure of implemented systems or inadequacy of the systems, but mainly because of the failure of the persons required to implement the systems.

The dynamic nature and uniqueness of every single mine makes it challenging to implement advanced monitoring and analysis systems in mines. However, the benefits in health and safety because of informed decision-making which come with the systems are well worth the investment in resources and technologies (Agioutantis, et al., 2014). Situational awareness of the mining environment is a key factor in trying to enhance miners' health and safety. Situational awareness using real-time data namely; environmental data, physiological data and physical location data can contribute significantly in achieving health and safe mining (Smutný & Farana, 2003).

According to Zhang et al. (2012), one of the innovations the mining industry can adopt to enhance health and safety is the adoption of the Internet of Things (IOT). Health and safety are some of the key factors pushing the mining industry into adoption of the IOT to meet the demands and needs of staff, governments, the environment and shareholders.

Short (2019, p. 2) defines the IOT as “the concept of attaching sensors or controls to normally inert objects so they can connect to the internet and communicate with other connected ‘things’”. This definition is close to that of Chaulya & Prasad (2016, p. 280) who define the IOT as a “network of physical networks embedded with electronics, sensors, software, and network connectivity”, which enable objects to collect information and exchange data. The objects in the network are assigned a unique Internet Protocol (IP) address and the network allows automatic transfer of data over the internet without human to human or human to computer interferences (Chaulya & Prasad, 2016; Enaleni, 2018). Short (2019) describes the IOT as being made up of three basic components namely: the things, the network and the systems. Figure 2.3 gives a brief overview on these components.

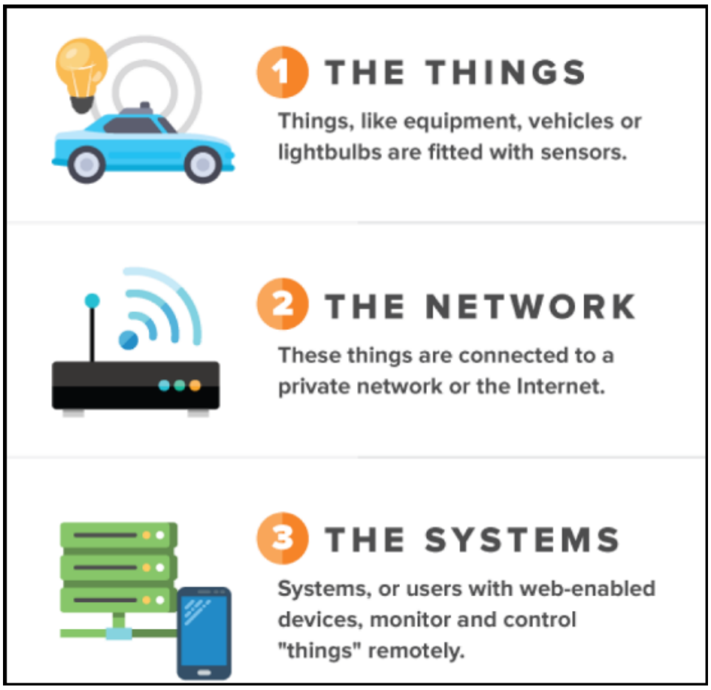


Figure 2.3: Components of the IOT (Short, 2019)

To complement on Short (2019), Chaulya & Prasad (2016) describe sensors as major elements of the IOT. They highlight that sensors play a very important role in bridging the gap between the physical world and the information world. Sensors collect data from their environment and through these sensors a change in the environment “can be monitored and corresponding things can make some responses if needed” (Chaulya &

Prasad, 2016, p. 280). The transfer of data through the IOT is transmitted through but not limited to Infrared (IR) sensors, geographical information systems (GIS) and radio frequency identification (RFID) devices. Short (2019) emphasises that the IOT allows for immediate tackling of issues as they arise through the use of real-time analytics, giving a holistic view of the operation. The latter point is supported by Inmarsat (2017) who states that the real-time component of monitoring of the mining environment using automated devices and sensors is made to be an easy reality by the use of the IOT as it “provides a digital nerve system for the network”. The real-time analytics can range from environmental data, equipment data, production data and it can be broadened to real-time risk assessments (Ismail, 2018).

Zhang et al. (2012) point out that the introduction of the IOT can help in achieving remote dynamic supervision in mines as well as realising the capacity of early warning systems, emergency response and investigations. Achieving all these ultimately leads to both health and safe production. The IOT has a capacity to enhance supervision and decision-making which can lead to the avoidance of accidents and losses. The realisation of remote dynamic supervision will allow mining supervisors to track inspections of illegal actions (Zhang et al, 2012). Singh et al. (2018) attest to the massive role the IOT can play in the mining industry to improve safety of mining personnel with enhanced productivity. Adoption of the IOT technology can enable mines to install ‘nanoscale sensors’ for sound, frequency, image and other information monitoring at various key locations (Zhang et al., 2012). Nevertheless, one of the impediments to the adoption of IOT is the inadequacy of connectivity in mining areas due to their geographical locations, which in most cases are in remote areas.

The theories of accident causation, safety management and IOT can be combined “to focus on prevention in advance, emphasise early warning, guide emergency rescue and assist accident investigations”. The realisation of the “interconnection of goods, intelligent perception, interaction of goods and the intelligent disposition in safety supervision” is also made possible through the combination of IOT, safety management systems and analysis of accident causation models (Zhang et al., 2012, p. 235).

The adoption of Geographic Information Systems (GIS) is also beneficial as, through GIS, users are able to view, understand, question, interpret and visualise data in many ways that reveal relationship patterns and trends in the form of maps, globes, reports and charts. A combination of GIS and IOT makes it easy for a mine to be divided into several scanning areas and ID scanning sensors can be installed in each area to scan IDs of corresponding staffs (Zhang, et al., 2012). Virtual Reality is another technology that mines can use to educate workers on how to deal with risks. It is important for the industry to use modern technology such as virtual reality tools to assist in the quest of achieving zero harm.

Kleyn and Du Plessis (2016) emphasise that in deep-level mining environments there is a need for mine workers to commit and adhere to health and safety standards. In these particular environments, temperature and humidity monitoring are critical because these two can significantly affect both the physical and physiological states of mining personnel working underground (Marshall, 1982; Muduli, et al., 2018). Marshall (1982) defines the monitoring of underground temperature and humidity as comfort control. In essence, workers must in general be comfortable physically and physiologically in the environment they work in.

Using gas, airflow and temperature sensors offer a great number of safety and operational benefits to the mines. Provided the data is used, atmospheric sensors play a critical role in detection of dangerous gases, changing airflows and temperature variations (Stewart, et al., 2016). Temperature and humidity monitoring are critical because these two significantly affect the state of mining personnel working underground. The effects of the two are usually seen in a high dry bulb temperature (Muduli et al., 2018). The installation of sensors allows real-time transmission of data like gas concentration to a data processing unit. The data processing unit has a capability of processing and preserving the data. The system is programmed to automatically implement effective measures and alert the workers of the changes when some of the data goes beyond the threshold limits, (Zhang et al., 2012). Most alert systems are alarm based. According to Brady (2008), alarms can be generated from absolute concentrations, gas ratios or explosibility. Alarms are said to be most useful as early warning systems, not as an alert to an emergency or a need to evacuate the mine. Brady (2008) further states that an early alarm allows a mine to have enough time to take remedial actions necessary to rectify problems which could have arisen.

Although real-time monitoring is available at some mines, most mining operations use multi-sensor systems with no interconnection between individual vendor systems or to any central management, and mine personnel (Agioutantis, et al., 2015). In most mines, it is not currently possible to effectively supervise underground unsafe behaviours of people and monitor unsafe conditions (Zhang, et al., 2012).

2.4 Underground Real-Time Monitoring and Control Systems

According to Rungani (2016), there are a number of companies in South Africa which offer real-time underground monitoring and control systems. These systems are capable of monitoring and tracking miners underground in near real-time. The systems capabilities range from tracking the location of underground personnel, equipment and assets using Radio Frequency Identification (RFID) as well as Wi-Fi technologies. The systems are also capable of monitoring gas concentrations in real-time and alarm when threshold limits are passed. The other capabilities of these systems include the proximity detection systems used to avoid collisions of mining equipment and mining personnel. The systems are also capable of enforcing compliance of Personal Protective Equipment (PPE) of mining personnel going underground.

There are also systems which are available to remotely control the ventilation of different mining areas. These systems are flexible and supply air depending on the demand in a certain area. The systems utilise the Ventilation on Demand (VOD) principle. It is possible with this kind of system to control even the temperatures in the underground environments. Rungani (2016) claims that the Schauenburg MIMACS system is one of the leading systems believed to be a solution for the South African mining industry in achieving the goal for zero harm. The system is a product of a South African based company, Schauenburg Systems Private limited. The company produces safety products and systems for the South African mining industry and other mining countries. Rungani (2016) further states that apart from the Schauenburg Systems, there are other companies leading in the production of digital mining technologies in the mining industry especially in countries such as USA and Australia. Similar leading systems include Northern Light Technologies (NLT), Newtrax Technologies and Mine Site Technologies (MST). These companies also utilises RFID technology and Wi-Fi technologies in their systems.

2.5 Conclusion

From the literature review, it is clear that significant research has been done on the benefits of proactive risk management and adoption of technologies in the mining industry. Fatality statistics in countries such as the USA, Australia and Canada showed that the implementation of various technologies in the risk management processes can have significant positive impact on health and safety. Although there is evidence that South African mining industry is lagging behind in the adoption of these technologies there is great potential in achieving zero harm through technologies. By analysing fatalities due to health related issues and safety related issues separately, it was shown that there is need for the global mining industry to focus on equally improving both health and safety issues. The section also discussed some of the available technologies already being used to improve health and safety in the mining and highlighted how adopting technologies such as the internet of things can also accelerate achieving the goal of zero harm in the mining industry.

In the following chapters the researcher will identify and discuss the leading practices in the global mining industry being used in the areas of health and safety. Focus will be put on the various technologies being used in the industry for real-time monitoring and control of mining personnel, mining equipment and atmospheric conditions. The impact of these technologies in preventing and reducing fatalities will be elaborated further in these chapters thereby complementing the brief discussion in this chapter.

3 LEADING PRACTICES AND TECHNOLOGIES THAT CAN IMPROVE HEALTH AND SAFETY IN MINES

The South African mining industry like other global mining industries has adopted various leading or best practices in the areas of health and safety i.e. gas monitoring, heat monitoring and control, dust monitoring, personnel monitoring etc. The leading practices include technology adoptions as well as implementing programs to encourage an effective safety culture in the mining industry. When it comes to the technologies, the global coal mining industry (South Africa included) is leading when compared to the metalliferous and other mining industries. The coal mining industry's adoption of technologies may be attributed to the high number of fatalities from past explosions of methane and coal dust. In the ventilation space there has been a highlighted need for implementing the ventilation on demand (VOD) practice in deep level metalliferous mines, due to the increased mine ventilation costs. The implementation of VOD does not only help in energy savings but it is also a major contributor to the health and safety of mine workers as it is capable of supplying adequate air and maintain a health and safe environment through the use of sensors to control the mine ventilation systems in an underground environment. In the following sections of this chapter the various leading practices in atmospheric monitoring, real-time assets and personnel monitoring, communication systems, dust monitoring systems, heat stress management and other leading practices that may help prevent fatalities are discussed.

3.1 Atmospheric Monitoring

To be able to maintain a healthy and safe underground environment, one of the key aspects is the ventilation specialist's understanding of the occupational exposure limits for airborne pollutants. The ventilation specialist must also have a solid understanding on how to sample the pollutants (Wallace, et al., 2015). It is also important for the specialist to understand statutory requirements as well as the best engineering practice. Good practice goes beyond compliance, it implies having a system that ensures that all the statutory requirements are fulfilled not because of pleasing the inspectorate but because it is best practice in protecting the workforce. Babu et al. (2015) assert that there are three factors which usually affect the performance of a ventilation system, these are:

- Underground atmospheric conditions

- Ventilation fan designs
- Power consumption

It is imperative for the mining industry to put in place systems and practices that are able to monitor and control the aforementioned factors. It is important to note that most of the global mining countries have adopted various technologies after past disasters in order to enhance safety in underground mines. According to Griffin (2013) and Zipf et al. (2013), Australian mines were mandated to install atmospheric monitoring systems in every underground mine after the Moura No. 4 coal mine explosion which caused 11 fatalities. Griffin (2013) did a study based on mines in Australia, Canada and the United States to determine the best approach to comprehensive monitoring in underground coal mines. The author investigated the Atmospheric Monitoring Systems (AMSs) worldwide in the aforementioned countries including those used in underground hard rock mines. He also investigated the sensor performance and simulation of several incident scenarios and analysed the benefits of monitoring in past disasters. In his study of analysing the best practices in atmospheric monitoring systems being used in the underground mines, Griffin (2013) found that the majority of the mines in the USA and internationally (i.e. including Australia and Canada) were using the following for atmospheric monitoring:

- Handheld Personal Gas detection devices;
- Fixed methane and carbon monoxide detection devices;
- Tube bundle systems;
- Continuous Fixed Real-time Monitoring (CO, CO_2, CH_4, O_2, and NOx).

Abu-Mahfouz et al. (2014) agreed with the aforementioned as a leading practice in the South African hard rock mines. They mention that most South African mines only use handheld personal gas detectors.

3.1.1 Handheld Personal Gas detection detectors

Griffin (2013) states that the global trend (USA, Canada, and Australia) is that personal gas detectors (Figure 3.1) are carried by supervisors, inspectors, equipment operators and miners travelling alone. Similarly, the South African mining industry applies the same criterion in issuing personal gas detection units (Rungani, 2016). The number of gases which can be detected by a personal gas detector vary, ranging from one which can measure at least 3 gases to some which can measure more. The most commonly monitored gases are oxygen, carbon dioxide, carbon monoxide, methane and nitrous fumes. However, Griffin (2013) states that the use of personal gas detectors is limited in emergency situations and also in areas where there are high gas concentrations, for example goafs in underground coal mines where high methane concentrations are expected.

Figure 3.1Typical Handheld Personal Gas Detectors (Schauenburg Systems, 2017b; Dräger, 2019a; MSA, 2019)

3.1.2 Fixed methane and CO detection

In his study Griffin (2013) found that most mines were using fixed carbon monoxide and methane sensors in both coal and hard rock mines in the USA, Canada and Australia. These monitoring systems are placed at strategic positions in the mine. The handheld gas detectors are used to measure other gases (e.g. O_2, CO_2, and NO_x). The fixed gas detectors (Figure 3.2) are programmed such that when one of the detectors records a reading above the set threshold limit an alarm rings to notify the miners of the danger.

Figure 3.2 Typical Fixed Methane and CO Gas Detectors (Schauenburg Systems, 2017a; Dräger, 2019b)

3.1.3 Tube bundle Systems

The tube bundle system (TBS) (Figure 3.3) is said to be a very popular form of gas monitoring in Australian underground coal mines. However, Zipf et al. (2013) state that South African underground coal mines do not routinely use TBSs. In this monitoring system, gas monitoring is achieved by using a mechanical system where vacuum (purge) pumps are used to pump gas samples from different underground locations through tubes or boreholes. The pumps which are connected to programmable logic controllers (PLCs) and valves, direct the samples to the gas analysers where they are analysed. TBSs are usually used to analyse gases such as carbon dioxide, carbon monoxide, methane and oxygen (Chaulya & Prasad, 2016). The gas analysis for methane, carbon dioxide and carbon monoxide is done using infrared detectors and the one for oxygen uses paramagnetic detectors (Zipf, et al., 2013; Watkinson, et al., 2016).

The data from the gas analysers is then interpreted by software which also allows the data to be displayed on computer screens. This analysis is usually done in surface control rooms. The software which interfaces with PLCs allows for the generation of alarms and warnings on gas levels at different locations in the mine depending on the analysed data. The warnings and alarms are generated depending on the gas rules and thresholds set by the ventilation officers or control room operators (Zipf, et al., 2013; Watkinson, et al., 2016). The software that interprets the data from the analysers is also responsible for calibrating and troubleshooting the analysers (Zipf, et al., 2013).

For control room operators to easily interpret the data from the software, Trigger Action Response Plans (TARPs) are used for this purpose. Watkinson et al. (2016) state that the TARPs are programmed such that they define the gas levels to be considered normal and abnormal, as well as the actions to be undertaken after a certain level of gas is triggered. Watkinson et al. (2016) further state that the conditions set for the triggering of TARPs are often grouped into three or four levels. With level 1 being for normal conditions and levels 3 or 4 for abnormal conditions which require immediate evacuation. To confirm the accuracy of the TBS, most mines occasionally take gas measurement samples, from different Tube bundle sampling stations, in bags to surface for analysis. Although the TBS is an effective gas monitoring system, one of the limitations of the system is that it does not offer continuous gas monitoring but rather continual monitoring. This is due to the delay in gas travel times from the sampling points. The tube bundle system is mainly used to confirm the results from the real-time monitoring systems mainly in Australian underground coal mines (Griffin, 2013). Figure 3.3 illustrates a basis Tube Bundle system of a coal mine with four sampling pipes. The water traps shown in Figure 3.3 are installed at a low point at the bottom of sample lines or boreholes to allow for water accumulation. These traps are useful from making sure that the gas samples are free of water and in most mines a maintenance system is put in place to empty the traps.

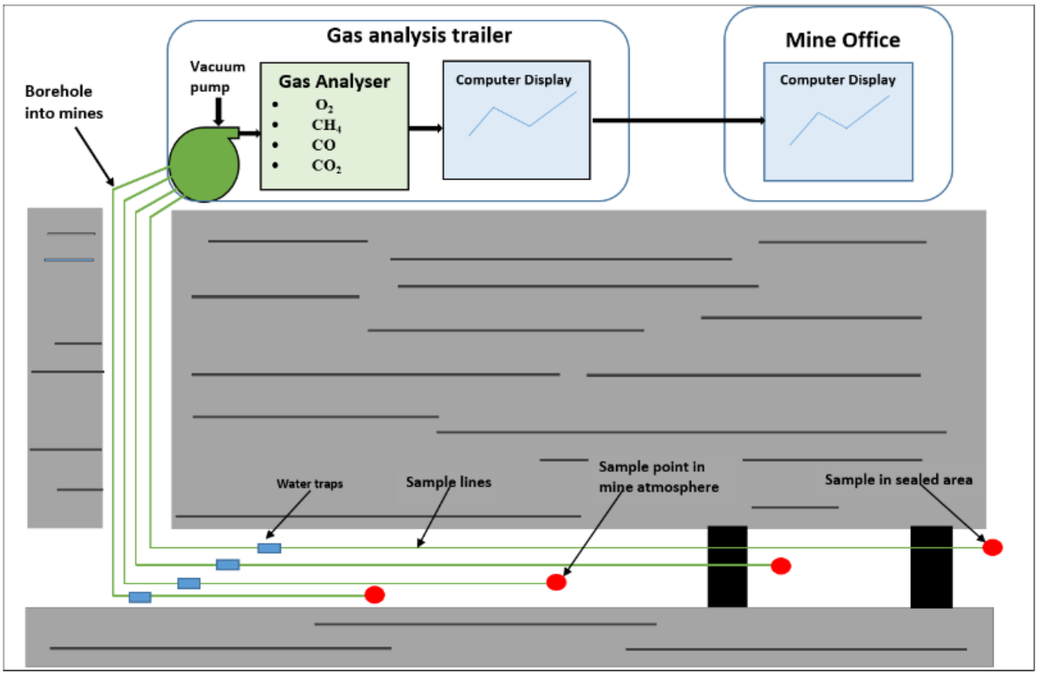


Figure 3.3 Schematic diagram of Typical Tube Bundle System (Adapted from Zipf, et al., 2013)

3.1.4 Real-time monitoring

According to Griffin (2013) and Brady (2008) in Australia it is mandatory to have real-time monitoring of CO_2, CO, O_2 and CH_4 in their underground coal mines. Similarly, the USA coal mines are mandated by their law under the MINER Act of 2006 to monitor the atmospheric conditions in real-time (Griffin, 2013; Agioutantis, et al., 2014; Rungani, 2016). However, in the South African mining industry there are no laws which give mines a mandate to have real-time monitoring systems. The real-time monitoring systems use different communication systems to transmit data to the surface control room from the sensors. The communication lines are either wired or wireless. The sensors must be calibrated on either a daily, weekly or monthly basis. Real-time sensors can either be fixed or handheld. The upside of real-time monitoring systems is that they offer continuous results and readings from different locations which can be analysed and real-time decisions can be taken (Griffin, 2013; Rungani, 2016). However, Rungani (2016) emphasises that real-monitoring systems are only used as an early warning signal hence it is imperative to have a reliable and robust communication system attached to them. The measurements from a real-time monitoring system are transferred to a surface control room where they are analysed. The different communication systems used for the real-time monitoring are discussed in section 3.3 of this dissertation.

3.2 Real-time Assets and Personnel tracking

The tracking of employees allows mine management to account for the location of every worker at all times and by knowing miners' locations it is easier to check that miners do not enter prohibited mining areas or abandoned mining areas (Short, 2019). Rungani (2016) states that real-time personnel and assets tracking is not yet popular in the South African mines, however this practice is mandatory in the USA, Canada and Australia. According to Short (2019), real-time monitoring of miners and mine assets underground allows the mine to do the following:

- Tracking miners using tracking devices fitted on their helmets;
- Monitor adherence to safety i.e. not entering prohibited areas or abandoned areas;
- Tracking of pieces of equipment using tracking devices on the equipment;
- Implementation of Ventilation on Demand (VOD) strategies through both the tracking of miners and pieces of equipment and providing both sufficient air supply and efficient energy use.

Both real-time atmospheric monitoring systems and tracking systems must be linked to a communication system. The communication system must be able to transfer the data to and from the control room on surface. In his study Griffin (2013) claimed that, on one of the Canadian mines which was utilising a real-time tracking system, the control room server was installed with RS-View software. The RS-View software is an integrated Human Machine Interface (HMI) from Rockwell Software Company, the software allows for the monitoring and controlling of automated machines and processes. The software generates visual displays of the problems it finds, in clear and simple forms for miners to monitor and react to. The RS-View software has a button to send warnings to all the radios in case of an emergency. The author further states that the software compiles a list of miners that are working alone in a shift. The software is programmed to record the last time each radio was used by a solo miner and if that miner has not used their radio at least once in the last two hours, then the miner is marked as missing and further action is to be taken. However, Griffin (2013) states that each time the radio is used, the timer is reset to zero. Rungani (2016) also highlighted the great benefits of tracking both miners and assets such as LHDs stating that this can be used for locating miners to ensure their safety and to ensure compliance to various safety acts, regulations and Codes of Practice by tagging a miner to a specific asset.

3.3 Communication Systems

Communication systems form the backbone of the aforementioned monitoring systems. Establishing a robust ad reliable communication channel is a hard and/or very challenging task for underground mining due to the extremely difficult conditions for example rock falls, heat, humidity, complex and different geologies, distance, and confined working spaces. A robust communication infrastructure will result in quick response to emergencies (Singh, et al., 2018). Agioutantis et al. (2014) stated that one the biggest challenge in mine communication systems is to design a technology that is portable, rugged and safe for use in underground mines as well as designing a software that rapidly conveys emerging data trends to mine personnel.

Wired communication is the most used system in these underground environments and it is at higher risk of failure and suffers from many shortcomings i.e. damage of cables, high fault rate, inconvenient system maintenance (Muduli et al., 2018). However, Singh et al. (2018) state that in recent times wireless communication has gained momentum in underground mine communications. Due to the uniqueness of each underground mines' environmental characteristics, any standard radio communication must be designed to fulfil the specific conditions (Yarkan, et al., 2009).

Both wired and wireless communication systems have their advantages and disadvantages. Griffin (2013) states that the use of state-of-the-art communication and monitoring systems overcomes wireless and wired technology disadvantages. The authors highlight that one of the typical drawbacks of hardwired networks is the need of physical connection of the source to the communication line via a cable and if the cable is compromised communication will cease. On the other hand, wireless communications also suffer some drawbacks due to electromagnetic interferences, poor propagation distances and generally lower bandwidths when compared to wired systems.

Many mine accidents have shown the great need for reliable two-way communications between underground miners and rescuers located on surface. When choosing a mine communication system, it is important to choose a system that is capable of surviving after an accident i.e. (mine fire, roof fall or explosion) since this is key to maintaining mine wide operational integrity (Gürtunca, 2008). Gürtunca (2008) explains that survivability of a communication system consists of two principle aspects, namely hardening and redundancy. He further states that hardening involves measures taken to improve the ability of the system to continue to perform after mine incidents and this includes hardening of the cable and other components that are part of the communication system.

Redundancy allows the system as a whole to remain operational even if a section of the cable is damaged by an event. Gürtunca (2008) recommends the use of a wireless mesh network as he states that it offers reliability and redundancy. Griffin (2013) supports Gurtunca's claims by stating that wireless mesh systems have an inherent redundancy and have what he calls 'self-healing capabilities'. The author further states that through the 'self-healing' capabilities of a wireless mesh systems, the system is able to reroute the signal if one pathway becomes blocked or communication is lost between communicating fixed nodes.

Radio Frequency Identification (RFID) is another communication system which can play a critical role in underground mining. Rungani (2016) states that the real-time location and tracking systems in underground mines use this technology. RFID systems consist of readers and tags. For tracking purposes in underground mines, tags can be placed in the hardhats of the miners, and at different locations underground readers will be able to read the tags as the personnel is in the radius or proximity to the reader. However, the current placing of tags in hard hats may not be the solution for tracking of mining personnel, as very often the hard hats are blown off by explosions or rock bursts. The better solution is to mount the tag in the cap-lamp battery since these remain on the miner's belt in most incidents. One of the limitations of the RFID technology is that it does not provide means of voice or text communication (Griffin, 2013; Rungani, 2016).

Griffin (2013) states that one of the greatest developments which has positively impacted underground communication systems is the development of fibre optics. The author asserts that contrary to the old communication systems, fibre optics offer an intelligent communication solution. The solution includes (but is not limited to) higher bandwidth speeds, relatively low costs, operates in severe environmental conditions and can be ruggedised for underground conditions.

It is important to note that the advancements in communications systems enable the remote monitoring of underground environments through the integration of sensors into the communication system. These sensors can then be used in tracking systems as well as for monitoring and measuring mine gases, pyschrometric properties, dust content, air velocity and other events. In his findings Griffin (2013), stated that the main communication systems for real-time atmospheric monitoring and personnel monitoring are leaky feeder, wireless mesh networks, wired, and fibre-optics based systems.

3.4 Dust Monitoring and Respirable Dust Overexposure Prevention

Excessive dust emissions can cause both health and industrial problems such as: (1) occupational respiratory diseases, (2) risk of dust explosions and fire, (3) damage of equipment (4) impaired visibility (Raj et al., 2017). Recent research has shown that underground miners are still exposed to respirable coal dust and respirable crystalline silica dust. This is evident in the significant number of young miners with very few years of mining experience being diagnosed with silicosis and other respiratory diseases (Haas, et al., 2016).

In one case study done in the USA, one miner as young as 29 was diagnosed with progressive massive fibrosis (PMF) which is a more advanced form of Coal workers' pneumoconiosis (CWP) (Sparkman, 2019). Sparkman (2019) states that PMF is another a form of silicosis, however, its effect on miners are seen in long periods of times when compared to other respiratory diseases caused by respirable dust. However, there are a number of ways to prevent overexposure of respirable dust. The mining industry has come a long way in trying to prevent and lower the exposure levels of miners to respirable dust. To achieve the aforementioned, various dust monitoring and control methods have been implemented.

According to Griffin (2013), the current dust sampling methods include cyclone samplers, gravimetric dust samplers (stationary and mobile sampling), real-time aerosol monitors (RAM), and personal dust monitors (PDM). From the study carried out by the National Academies of Sciences, Engineering, and Medicine (2018) for the dust monitoring and sampling systems used in 7 top coal producing countries (China, USA, Australia, India, South Africa, Germany and Poland), it was found out that the gravimetric personal dust sampler is the most commonly used for dust monitoring and sampling. However, the best practices of dust monitoring that stand out from various recent studies (Federal Information & News Dispatch, Inc., 2009; Federal Information & News Dispatch, Inc., 2010; Cecala & O'Brien, 2014; Haas, et al., 2016; Belle, 2017; National Academies of Sciences, Engineering, and Medicine, 2018) are the continuous personal dust monitor (CPDM) or Personal Dust Monitor (PDM) and the Helmet-CAM dust monitoring technology.

3.4.1 Continuous Personal Dust Monitor (CPDM) or Personal Dust Monitor (PDM)

The CPDM or PDM (Figure 3.4) is a dust monitor which was developed in the US by the National Institute for Occupational Safety and Health (NIOSH). The CPDM allows the miners to monitor their dust exposure in a continuous and real-time manner. The PDM alerts miners when they are reaching overexposure limits of respirable dust. This monitor allows miners to react and move away from the dust sources as well as taking corrective measures to mitigate high dust exposure limits. The real-time monitoring aspect of PDM is very substantial when compared to that used in the old gravimetric sampling methods which yielded results after a week or two (Belle, 2017). However, from research studies (HT Digital Streams Limited, 2010; National Academies of Sciences, Engineering, and Medicine, 2018) the two major drawbacks of the CPDM are its cost and weight.

Various researchers highlight that although the PDM has a great potential in reducing overexposure of mine workers to high dust levels, the current design cannot be used for crystalline silica measurements (National Academies of Sciences, Engineering, and Medicine, 2018; Sparkman, 2019). It is important to note that there is progress on the development of real-time silica measurements, but at the moment mines use data from gravimetric sampling to identify mining areas which high potentials of silica exposures. The use of supplementary technology like the Helmet-CAM can be very beneficial in identifying high silica exposure areas for miners. The USA is leading in the implementation of the use of CPDMs as it made it compulsory and mandatory for every coal mine to use CPDMs since 2016 (Belle, 2017; National Academies of Sciences, Engineering, and Medicine, 2018). Belle (2017) also states that some Australian mines also approved the use of PDM3700 which a type of CPDM for their underground mines. The National Academies of Sciences, Engineering, and Medicine (2018) attests to this by stating that South Africa and Australia mining industries are considering of adopting CPDMs.

It is important for engineers and industry to make affordable, light and real-time silica measuring PDMs and ultimately adopting the CPDMs as a compulsory Personal Protective Equipment (PPE) as at present the mines using this technology only allocate CPDMs to miners who work in presumed high level dust areas (National Academies of Sciences, Engineering, and Medicine, 2018). The realisation of the CPDMs as a compulsory PPE will impact significantly in the prevention of respirable diseases.

Figure 3.4 Real-time Continuous Personal Dust Monitor (CPDM)/PDM3700 (National Academies of Sciences, Engineering, and Medicine, 2018; Belle, 2017)

3.4.2 Helmet-CAM technology

The Helmet-CAM technology (Figure 3.5) was developed in the US by NIOSH in collaboration with a company called Unimin. The technology was developed specifically to identify the various jobs, tasks and locations where mining personnel are exposed to high levels of respirable dust so that quick fixes or engineering controls can be put in place. The Helmet-CAM is made up of a small video camera attached to the side of a miner’s hard hat and a real-time instantaneous personal dust monitor (Cecala & O'Brien, 2014; Haas, et al., 2016; Haas & Cecala, 2017). The data gathered from the video camera and personal dust monitor is transferred to a computer and it is analysed using a software called the Enhanced Video Analysis of Dust Exposure (EVADE) (Haas, et al., 2016). The EVADE software merges and synchronise the dust data and the video produces a record which simultaneously show the position and dust count. The record (merged video) allows for a quick assessment of the various areas, jobs and roles that contributed to the miner’s different levels of exposure to respirable dust. The merged video has playback capabilities which allows for any time viewing and analysis of high respirable dust sources by both workers and mine management (Haas, et al., 2016; Haas & Cecala, 2017).

Old practices of dust measurements in underground environments were not capable of pin-pointing the exact locations in which mining personnel with high mobility jobs were exposed to high dust levels. However, the Helmet-CAM technology is capable of giving the ‘where and when’ answers of the miner’s dust exposure (Cecala & O'Brien, 2014 Haas, et al., 2016; Haas & Cecala, 2017). The immediate insight on the tasks and locations with high exposures is a great tool in making health and safety decisions. Engineering controls, administrative controls, good working practices and work behaviour changes can be implemented to reduce respirable dust exposures and production. The recommended way of setting up the Helmet-CAM dust monitoring is shown in Figure 3.5.

In their research, Haas & Cecala (2017) found out that to reap the full benefits of using technologies such as the Helmet-CAM, there is need to integrate the technology into mine management and mine workers’ behaviour. The research referred to the need of open communication on health behaviours between the mine management and the workers. It is only through open communications and open engagements that the results from the Helmet-CAM can lead to implementation of controls to respirable dust exposures. However, the Helmet-CAM technology when used properly has potential in enhancing the health and safety of mine workers through the identification of jobs, areas and locations of high respirable dust exposure. The integration of this technology with the CPDM and other dust monitoring systems can help alleviate and prevent respirable diseases.

Figure 3.5 Typical Helmet-CAM technology Setup on a miner (Cecala & O'Brien, 2014; Haas, et al., 2016)

Unsted (2001) puts forward a classification of airborne dust sources in most underground environments with a scale of the severity of dust generation from 1 to 9 (Table 3.1). The Helmet-CAM can be used to confirm the findings from the Unsted (2001) study and recommendations on the dust control measures to be implemented in these areas highlighted in Table 3.1 will be put forward.

Table 3.1 Table Dust Sources in a Typical Underground Gold Mine (Unsted, 2001)

Approximate Severity	Dust Producing Operation
1	Blasting
2	Drilling
3	Crushing
4	Grinding
5	Scraping
6	Barring
7	Lashing
8	Tipping
9	Loading

3.4.3 Medical Surveillance

The effectiveness of dust prevention and monitoring strategies for respirable dust exposures in the mining industry can only be proved through medical surveillance. In support of these assertions the National Academies of Sciences, Engineering, and Medicine (2018, p. 25) states that to determine and assess the “efficacy of exposure reduction efforts”, there is need of a “suitable and acceptable system of medical surveillance that provides regular, no-cost medical examinations for all miners”. Medical surveillance of mine workers varies within different mining countries. In most countries every worker must undergo a medical examination to ascertain the workers’ health status before being employed at the mine and then again at the time of leaving the company.

In the case of respirable diseases, regular medical surveillance of mine workers can help in the early detections of the diseases and help in removing the affected person from high exposure areas. Mines can develop medical surveillance programs according to different miners’ classifications for example job titles and duties. The use of data from monitoring systems like the CPMD and the Helmet-CAM technology can also be utilised to advice on the different miners who must undergo medical surveillance. Medical surveillance is capable of providing respirable disease trends and these trends can help the mines to identify the most affected people and their jobs.

The National Academies of Sciences, Engineering, and Medicine (2018) carried out a study to ascertain and compare the different dust monitoring and medical surveillance practices in seven coal producing countries namely USA, China, Australia, India, Germany, Poland, and South Africa. The research findings showed that all the countries except India and Poland required mandatory medical examinations of miners before commencing work and when leaving the mines, with all the costs covered by the employer. However, after a miner is employed, the regulations require periodic medical surveillances which can either be voluntary or mandatory. The following is a summary on the findings from the National Academies of Sciences, Engineering, and Medicine (2018) study on the different periodic medical surveillances:

- USA – it is mandatory to conduct a medical surveillance for every miner after every 3 years and voluntary surveillance after 5 years. For respiratory diseases the surveillance is mainly a chest radiography examination.

- Australia – similarly to the USA, it is mandatory for New South Wales coal miners to undergo a medical surveillance after every 3 years after the pre-employment examination. However, the Queensland regulations for coal mines specify that miners must have a minimum one medical surveillance in a period of 5 years. The regulations further state that the mine workers are allowed to request a medical surveillance test at any given time at the expense of the employer.
- Germany – no specific interval is stated in the regulations. However, the study found out that on average a 2 year interval on medical surveillance is followed by most mines.
- India – the regulations recommends annual based medical surveillances.
- China – similarly to German regulations, the Chinese regulations are not specific on the intervals in which medical surveillances must be carried out. The regulations just state that the employer must organise for medical surveillance of workers during their work service.
- Poland – from the research findings the Polish regulations only state that the coal mines must carry out medical surveillances based on individual agreements with the regulator. No specifics are given.
- South Africa – the medical surveillance regulations are different from all the aforementioned countries. The law requires the filling out of health related questionnaires by the miners on an annual basis. The research findings also state that the regulations do not give any umbrella periodic regulations but depending on a specific miner's health status, the medical surveillances can be done quarterly, semi-annually or annually.

White (2001) attests to the findings from the National Academies of Sciences, Engineering, and Medicine (2018) on the medical surveillances conducted in the South African mining industry for all respirable dust related diseases. White (2001) explains the regulations in a more detailed way as shown in Table 3.2.

The guidelines (Table 3.2) are directly derived from the South African Mine Health and Safety Act (MHSA) of 1996. The MHSA is the law that guides all the operations and practices in the South African mining industry.

Table 3.2 Medical Surveillance Regulatory Guidelines of the South African Mining industry Respiratory Diseases (White, 2001)

Examination	Tests to be performed
Initial — carried out on starting or before undertaking work.	Respiratory questionnaire Cardiorespiratory examination Chest x-ray (large plate) Lung function test (spirometry)
Periodic — every three years	Cardiorespiratory examination Chest x-ray (large plate) Lung function test (spirometry)
Exit — when employment terminated for any reason	Cardiorespiratory examination Chest x-ray (large plate) (not necessary if done < 3 months before) Lung function test (spirometry) (not necessary if done < 1 year before)

In his research, White (2001) also compiled the Department of Minerals and Energy's elements and aims guidelines of every medical surveillance to be conducted in South African mines. The author tabulated the summarised guidelines as shown in Table 3.3. From the guidelines (Table 3.3), it is clear that South African regulations do not necessarily specify the period to be followed when conducting medical surveillance, but state that after the pre-employment medical examination the employer must choose the 'appropriate intervals' for the periodic surveillances.

To realise the full benefits of implementing real-time dust monitoring systems for prevention and reduction of respirable dust diseases it is important that an integrated system is used. The system must encompass an efficient medical surveillance system as well as miners and management behaviour modification when it comes to dealing with the respirable dust risks. Research studies have shown the active participation of miners in the medical surveillance programs and risk assessment and management trainings can have positive results in minimising and ultimately preventing respirable diseases. From the aforementioned discussion the integration of the current dust monitoring practices in the mining industry with CPMDs, Helmet-CAMs and regular medical surveillance have a great potential to address the problem of new miners contracting respirable dust related diseases such as silicosis, CWP, lung cancer and PMF.

Table 3.3 DMRE Aims and Guidelines for Medical Surveillances in the South African Mining Industry (White, 2001)

A medical surveillance programme of employees should:

- Be appropriate to the health hazard
- Provide information that the employer can use in determining measures to –
  - Eliminate, control or minimise the health risk and hazards
  - Prevent, or detect and treat occupational diseases at an early stage
- Consist of an initial medical examination and other medical examinations at appropriate intervals
- Establish a baseline against which subsequent changes in the health status of employees can be evaluated over time
- Be designed to identify medical conditions that may render employees temporarily or permanently unable to perform their occupations
- As far as reasonably practicable ensure that –
  - Employees are fully informed of the health risk and hazards associated with their occupations and of the measures to eliminate, control and minimise the health risk and hazards
  - The health status of employees does not place their health at increased risk in a particular working environment nor place other employees or the public at increased risk

3.5 Heat Stress Management

Kielblock (2001, p. 234) defines heat stress as "the net load on the human body from the combined contributions of metabolic heat production and external environmental factors". Kielblock states these factors as the air temperature, water vapour content of air, relative humidity, air movement, relative humidity, globe temperature (radiant heat), dew point temperature and clothing. Various researchers (Kielblock, 2001; Wagner, 2013; Kocsis & Sunkpal, 2017; Roghanchi, 2017; Nei, et al., 2018; O'Connor, 2018) have shown that heat stress can have significant effects on the health, safety and productivity of mine workers especially in deep-level mining. The safety, health and productivity effects of heat exposure to miners are summarised in Table 3.4.

Table 3.4 Effects of Heat Exposure to Underground Miners (Kocsis & Sunkpal, 2017)

Safety	**Health**	**Productivity**
Fatigue	Heat rash	Decrease in productivity
Fainting	Heat syncope	Accident and Injuries
Loss of concentration	Heat cramps	Time losses
Impaired mental capacity	Heat exhaustion	Production delays
Inability to make quick decisions	Heat Stroke	Sustainability

The duration of exposure to heat underground is an important factor in the manifestation of the different health, safety and productivity of miners (Roghanchi, 2017). Roghanchi (2017) summarises how the duration of the miners exposure to heat gives rise to different heath and safety effects (Figure 3.6). A comprehensive description of the effects of heat stress are found in (Kielblock, 2001; Kocsis & Sunkpal, 2017; Roghanchi, 2017; O'Connor, 2018).

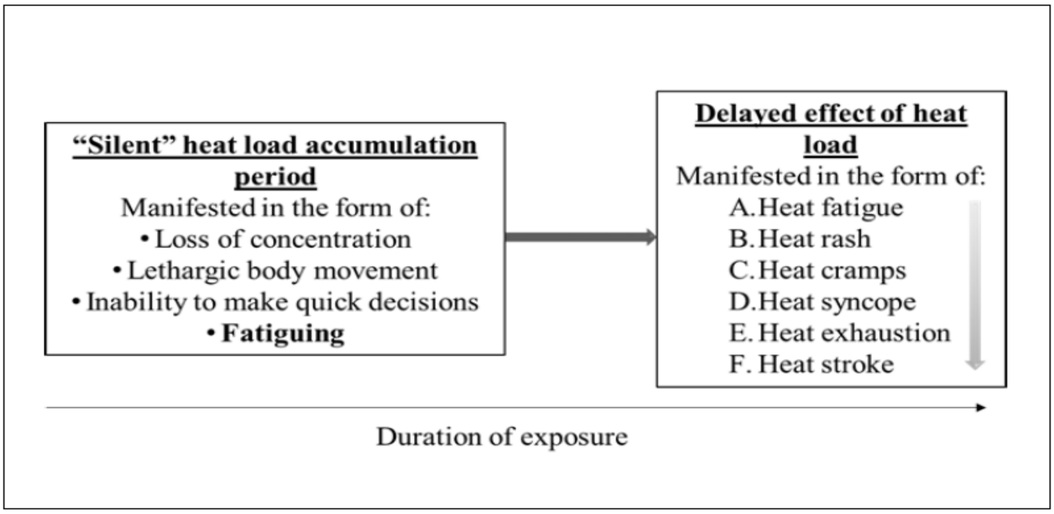


Figure 3.6 Effects of duration of heat exposure on health and safety on miners (Roghanchi, 2017)

The two biggest contributors of heat are virgin rock temperature and diesel equipment. According to Wagner (2010; 2013), the virgin rock temperature contributes more than 75% to the total heat load in deep-level mines. South Africa having the deepest mines in the world, there have been a considerable number of cases of miners suffering from heat exhaustion and heat strokes (O'Connor, 2018). The latter has caused a number of injuries and fatalities in the South African mining industry. The gold and platinum industries are the most affected (Wagner, 2010; Wagner, 2011) and this might be attributed to the similarities in the underground environmental conditions as well as mining methods of the two sectors.

Kielblock (2001) adds that some open pit operations in the areas of Messina and Phalaborwa are also significantly affected by heat stress effects. Furthermore, Kielblock (2001) states that the South African underground coal mines generally experience low heat exposure challenges, however, Tshikondeni Coal mine is highlighted as unique because it is characterised by a significantly high geothermal gradient (25°C/km). As aforementioned the exposure of miners to excessive heat stress can lead to a number of health and safety effects and most critically fatalities. The following sections will describe some of the most often recommended strategies to eliminate and minimise the effects of heat stress.

3.5.1 Heat Indices

Various researchers highlight that establishing heat indices for hot and humid underground environments is the first step in eliminating and minimising heat related injuries and fatalities. Heat stress indices are used to define the hot and humid underground environments. After defining the hot environments, heat stress indices are used for regulation of heat stress values in specific areas as well as determining allowable working times in the hot areas (Roghanchi, 2017). Heat indices are said to be the easiest method of providing personal protection to worker against heat related injuries and most critically a fatality. There are three common heat stress indices used in mining countries namely, the Dry Bulb temperature, Wet Bulb temperature and the Effective temperature. The South African mining industry uses the Wet bulb temperature index to define the hot-humid underground environments (Wagner, 2013).

3.5.2 Acclimatisation

According to Kielblock (2001, p. 233) “rudimentary” acclimatisation programs for underground miners were first introduced around 1920 in the South African gold industry. Kielblock (2001) further states that a scientifically based acclimatisation program was later introduced in 1932 and ultimately a formal Heat Stress Management program was introduced in 1991. Heat acclimatisation procedures are carried out to prepare workers to go and work in hot humid environments. The procedure is also used to identify and screen workers who are heat intolerant (Kielblock, 2001; Wagner, 2011; Wagner, 2013). Acclimatisation of workers who are exposed to hot and humid mining environments is very critical.

Research studies have shown that when underground miners undergo proper acclimatisation procedures the risk of heat related illnesses is reduced. It is recommended that workers must go for at least 7 to 14 shifts in the acclimatisation monitoring programme (Kocsis & Sunkpal, 2017; Roghanchi, 2017). Acclimatisation procedures must be run by competent and experienced medical practitioners who must not hesitate to deem a worker heat intolerant when their heat acclimatisation is not satisfactory (Kielblock, 2001; Health and Safety Executive, 2006). The medical practitioners must also have first-hand information and experience in the environments for which the workers are being acclimatised. Special emphasis on acclimatisation must be given to older people, generally above the age of 50, who visit hot working areas irregularly. Wagner (2010; 2013) states that workers falling in this age group tend not to acclimatise to hot environments. The failure to acclimatise is attributed to their thermoregulatory system not working the same way as the younger working group. Vitamin C supplements are recommended for this age group. It is imperative that there are solid medical surveillance programmes to regularly monitor the workers who work in hot environments and ensure they are still acclimatised. Workers who are absent from work for a long period of time must undergo acclimatisation procedures when they resume work. This must also apply to workers entering old workings which are characterised as hot-humid areas.

3.5.3 Environmental and Employee monitoring

Environmental monitoring is one of the key aspects of managing heat stress. This must include the monitoring of the air temperature (wet bulb and dry bulb), radiant heat, air movement and humidity. However, monitoring the underground environment alone is not sufficient to combat heat stress prone conditions. The monitoring system must be connected to a ventilation and cooling system which is capable of initiating countermeasures to maintain a good working environment. Examples of these systems include Ventilation on Demand and Cooling on Demand. In the case where it is not possible to initiate countermeasures, the monitoring system must inform the decision-making person who is sending workers to excessively hot and humid environments.

Roghanchi (2017) did an extensive study on the various continuous climatic monitoring systems being used in the USA Nevada mines. In his study he classified the climatic monitoring systems into three categories namely real-time monitoring systems, hand-held climatic instruments and continuous monitoring systems. The author highlights the three different monitoring systems must be used in a complimentary way to each other to realise the maximun benefits in heat stress management.

An effective monitoring system is one that is capable of monitoring both the environment and employees working in the environment. Employee monitoring must be both technology based and human based. The technology based monitoring is one that is tied to a monitoring systems using tags (e.g. temperature). The system is capable of showing the employee's location and the environmental conditions in their area. The human based monitoring system is whereby an employee is continuously being supervised and monitored by someone. This is usually important for new employees working in hot-humid areas or employees who might have previously shown signs of heat related sicknesses. Kielblock (2001) states that environmental and employee monitoring must be part of the mining company's risk assessment and management plan for heat stress management.

3.5.4 Cooling Strategies

Deep-level mining is generally associated with high temperatures beyond which work cannot be done without adequate ventilation and cooling strategies. It is important that the mine ventilation department ensures that they make the underground work environment conducive for safe working. Wagner (2013) emphasises that the two critical aims of any mine cooling system are (1) to maintain the environmental conditions within the levels which avoid heat stress related conditions on mine workers, (2) to control the flow of heat from rock strata into the underground workings. There are various cooling strategies available for the mining industry. These include surface bulk cooling systems, underground bulk cooling systems, spot cooling systems and microclimate cooling systems (Roghanchi, 2017; Kocsis & Sunkpal, 2017; O'Connor, 2018).

The cooling system selection cannot be generalised as it is supposed to be done according to every mine's demand and unique underground conditions. Surface bulk cooling and underground bulk cooling systems are the widely used refrigeration systems in underground mines and they are mine wide systems. However, surface coolers have a depth limitation making underground bulk coolers popular in deep-level mines. Microclimate cooling are unique systems. The systems are not mine wide systems but specifically cool the area directly in close proximity with the miner. These systems include cooling garments (e.g. dry-ice vests, ice jackets) and air conditioned cabs (Health and Safety Executive, 2006; Kocsis & Sunkpal, 2017; Roghanchi, 2017; O'Connor, 2018).

Microclimate cooling systems play a very important role in heat stress management especially in emergency work and rescue operations (Schutte, et al., 1994). Schutte et al. (1994) state that cooling garments provide a form of added protection for miners working in abnormally hot environments. Schutte et al. (1994, p. 59) further state that cooling garments are critical "especially where conditions cannot be predicted or change unexpectedly". Miners entering old working areas can utilise these cooling garments as the conditions in these areas are usually unknown. However, it is imperative to highlight that no cooling system is the best but using them in an integrated system reaps the full benefits of heat stress management.

3.5.5 Integrated Framework of Heat Stress Management

There are various ways which have been found to be effective in minimising and preventing the aforementioned. Kielblock (2001) developed a framework (Table 3.5) for heat stress management after looking at the major causes of heat strokes in some cases recorded in the South African gold industry. The framework works as a guideline on how to deal with different cases of heat stress before hitting the heat stroke stage which usually leads to either lifetime disabilities or death.

Table 3.5 Framework for Heat Stress Management Work Practices (Kielblock, 2001)

Causal Factor	Work Practice
Strenuous work	• Adequate physical work capacity (physical evaluation) • Self-pacing (educational) • Work-rest cycles
Suspect heat tolerance	• Overall fitness for work in hot environment • Medical evaluation • Physical evaluation • Screening for heat intolerance
Dehydration • alcohol-induced • insufficient fluid replacement	• Education • Provide portable and palatable water at place of work • Introduce water breaks
Excessively hot environments	• Ongoing monitoring and control • Actions plans • Emergency planning

In addition to the work practices Kielblock (2001) prepared an overall guideline (Table 3.6) for heat stress management formed in accordance with the MHSA of South Africa as well as international best practices. The guideline put forwards the basic features which must be included in every heat stress management programme. It basically summarises the various heat stress management strategies aforementioned.

Heat Stress management in deep-level mining is critical as the environment is characterised by high temperatures. A number of fatal cases, injuries and heat related illnesses have been recorded in South Africa and other mining countries. It is imperative for every mining operation which is exposed to hot-humid environments to put in place a heat stress management program where an adequate and fit for purpose heat stress index is used. Workers who work in hot environments are supposed to be regularly acclimatised for the specific environments they will work in and heat intolerant personnel must be reassigned to other jobs which do not expose them to hot environments. Where the temperatures are beyond the heat tolerance of workers, adequate ventilation and cooling strategies must be put in place. Environmental and personnel monitoring must be put in place to ensure workers safety and to help in the implementing of adequate heat stress management strategies

Table 3.6 Features for a Heat Stress Management Programme (Kielblock, 2001)

SA Gold Mines
Identify Heat Stroke Prone Jobs
Conduct engagement and periodic medical examinations
Screen for heat intolerance
Institute on the job heat acclimatisation (12 shifts / ongoing)
Supervise heat stroke prone work categories
Monitor environmental temperature
Introduce mandatory water breaks
Introduce education and induction programmes
Ensure Prompt recognition, treatment and availability of emergency facilities

3.6 Ventilation on Demand (VOD)

Mine ventilation is also a key health and safety component and is a “life-support” to underground mine workings (Basu, et al., 2013, p. 8). According to Wallace et al. (2015) there have been a number of technological advancements in the areas of mine ventilation and these include Ventilation on Demand (VOD), mine ventilation monitoring systems, software for ventilation planning, software to predict the impact of underground fire, advances in diesel engine technology to minimise DPM, remote monitoring of longwall goafs particularly when inert gas is injected, energy savings regarding ventilation and cooling systems and real-time monitoring of underground environment including devices to measure dust and DPM.

The concept of VOD is whereby air is supplied to the areas where it is needed and minimising or stopping the supply when it is not needed. This concept is typically common and applied in both metal and non-metal mines except for coal mines. Depending on the complication and design of the VOD system, Wallace et al. (2015) state that the system can be as simple as one which supplies air to a working area regardless of the working activity or a relatively complicated one that controls the flow based on air quality sensors.

Effective VOD is one which utilises a combination of real-time AMS and real-time assets and personnel monitoring. It is important to note that ventilation costs increase significantly as energy costs and mining depth increase. The business case for implementation of VOD system which also involves a knowledge of personnel location is based on energy savings, however VOD offers secondary benefits such as increased productivity and continuous monitoring of workplace environmental conditions. Other benefits of a VOD system include: electronic tag-in/tag-out boards, quick response of employee location in the event of an emergency, and awareness of a system efficiency through key performance indicators (Allen, 2008; Allen & Tran, 2011).

As mentioned earlier VOD systems can either be simple or advanced. Some of the advanced VOD systems comprise of Real-time Location Systems (RTLS) and environmental systems. The RTLS is used to monitor and track assets and mining personnel in the mine using radio waves in real-time. Looking at one of the VOD systems installed at Coleman mine in Canada, the environmental monitoring and control at this mine includes monitoring of the quality of the environment. The environmental parameters which can be monitored at this mine in real-time include airflow, wet and dry bulb temperatures, relative humidity, dust, carbon monoxide and nitrogen monoxide. VOD has the potential to solve various mining problems in areas of gas monitoring, dust monitoring and heat stress management.

3.7 Defence-in-Depth

The defence-in-depth concept is a safety principle used by the United States Nuclear Regulatory Commission to manage risks related to their nuclear power stations. The principle is built upon the idea of having multiple lines of defence or safety barriers along accident scenarios, and it avoids the dependence of safety on one element (Sorensen, et al., 1999; Saleh & Cummings, 2011). The latter is what brings about the 'depth' qualifier in the principle. The main goal of the defence-in-depth principle is to prevent, mitigate or contain unwanted releases of energy in cases of an incident (Sorensen, et al., 1999; Saleh, et al., 2010; Saleh & Cummings, 2011). The principles which define the defence-in-depth can be easily transferred to the mining industry. Saleh et al. (2010) and Saleh & Cummings (2011) state that accidents in the mining industry are typically as a result of breaches or absence of defences or violations of safety constraints. However, to be able to prevent accidents there are three important safety aspects that exist to control or influence an accident trajectory. Saleh & Cummings (2011, p. 765) term these aspects as "safety levers". These are 'technical levers', 'organisational or managerial levers' and 'regulatory levers'.

The 'regulatory safety lever' is one of the most critical levers when looking at the mining industry. When implemented correctly and efficiently it can yield considerable positive impacts to the health and safety of mine workers. According to Saleh & Cummings (2011), in order to realise the safety benefits through the regulatory safety lever there are three types of actions that have to be implemented. The three actions are summarised in Figure 3.7.

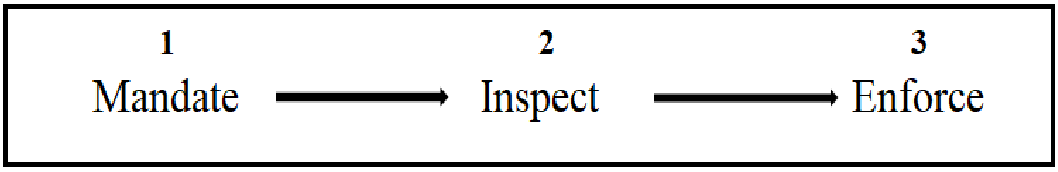


Figure 3.7 Three Types of Actions Required for Effective Regulatory Safety Levers (Adapted from Saleh & Cummings, 2011)

3.7.1 Regulatory Mandate

In the safety context of mining it is the regulatory agency’s duty to provide a clear mandate on the development, issuance and use of up-to-date technical standards and safety procedures for all the tasks and duties carried out. However, for this to be effective the standards and procedures must be supported by adequate research (Saleh & Cummings, 2011). In the South African context, the Department of Mineral Resources and Energy (DMRE) has the mandate to inspect and enforce the various regulations and standards that govern the mining industry. It is the mandate of the regulator to facilitate education and training of inspectors as well as facilitating accident investigations (Moore, et al., 2013).

3.7.2 Regulatory Inspections

With the right technical standards and safety procedures put in place, the regulatory agency must inspect and audit the compliance of the regulations. The inspection arm of the regulatory safety lever must provide the inspectors with enough apparatus and necessary resources to fulfil their duties. This encompasses funding and trainings of the inspectors to be adequately skilled for their jobs. For underground mining, it is important that the ‘regulatory safety lever’ gives emphasis on inspections of safety standards for some critical areas such as mine ventilation, gas concentration monitoring, rock support and safety trainings (Saleh & Cummings, 2011). Saleh & Cummings (2011, p. 772) argue that the effectiveness of the regulations put forward by the regulatory agency is “largely contingent on the ability to inspect the implementation of these standards in the mines”.

The inspection arm of the regulatory safety lever is usually lacking in most countries. For instance, Feickert (2013) claimed that although the Chinese mining regulations are quite good in the areas of technology and management, the Chinese inspectorate in mines is very poor. Feickert (2013) further states that although there is clear determination to improve the health and safety statistics in China there is still a big gap in the inspections and enforcements of the regulations and standards. The South African mining industry is not immune to the shortcomings in the inspections and enforcement of the regulations and standards. Nelson & Murray (2013) state that the Mine Health and Safety Inspectorate in South Africa is understaffed and does not have enough resources to facilitate adequate and efficient inspections and enforcements in all the mines. When the inspectorate arm of the regulatory authority is not fully funded or functions correctly it becomes near impossible for the regulator to institute its statutory duties as well as penalise and fine mines and miners when they willingly or unknowingly violate the law.

3.7.3 Regulatory Enforcement

To reap the benefits of the regulatory safety lever, the enforcement capability of the regulatory agency must be adequately supported with a legal framework that ensures there is full compliance with the safety standards and in the case that there are violations, prosecutions and fines must be raised (Saleh & Cummings, 2011). Various countries follow different prosecutions and penalty regimes. In the case of South Africa, the Chief Inspector of mines is endowed with powers to stop mine operations under Section 54 of the MHSA whenever he/she believes the mine has violated safety regulations or in the case of a fatal accident. Similarly, China is also said to have quite severe penalties for safety violations ranging from fines, dismissals, disciplinary actions and mine closures (Feickert, 2013). However, the enforcements of the safety regulations and standards must be done by competent and experienced inspectors because in the case of mine closures the reasons for such penalties must be solid and justified and necessary. Inspectors must also undergo training and also advise in the improvements of the policies and regulations depending on the best practices and lessons they learn through their experience and inspections.

3.7.4 Role of Miners and Management in the Defence-in-Depth principle

Like any other risk management system, the defence-in-depth method works with the principle of the bottom-to-top risk management rather than top-to-bottom risk management. This simply means that miners who are the front-end operators must be fully aware of the risks they are exposed to and how to manage them. Mining hazards can be managed and be prevented from escalating into accidents by ensuring that proper defences are put in place. Saleh & Cummings (2011) emphasise that for effective control of hazards there is need to identify the possible ‘ingredients’ for accident trajectories so that the right defences are put in place. The defence-in-depth safety principle pose many opportunities for hazard control as well as blocking accident trajectories in the mining industry. The defences are made such that they either prevent hazards from escalating into accidents or if it does happen that they escalate, other defences will be in place to contain or mitigate the consequences (Saleh & Cummings, 2011).

The defence-in-depth principle poses an opportunity to integrate different mining industry safety enhancement leading practices. Saleh & Cummings (2011) emphasise that in order to put up the necessary defences (technical, managerial or organisational, regulatory) for accident or disaster preventions, it is important to understand three critical aspects of hazard to accident and accident to disaster transitions. The authors mention that the first aspect is understanding what they referred to as the 'ingredients' that fuel the hazard to accident evolvement. The second aspect is understanding the dynamics involved in the hazard to accident transition as well as the speed of evolvement. The third important aspect highlighted by Saleh & Cummings (2011) is understanding what they referred to as 'signatures' (precursors and lead indicators) that show how a situation is transiting or developing into a progressively hazardous state. The understanding of the three aspects must be shared throughout the whole organisation from senior management down to the miner who is the front line operator. However, it is must be highlighted that the miners must play a major role in this understanding.

Reason (1997) and Saleh &Cummings (2011, p. 773) refer to frontline miners as being at the "sharp-end of safety". In simple terms this means miners are the closest to potential hazards hence they play a critical role in the defence-in-depth principle (Reason, 1997; Saleh & Cummings, 2011). Saleh & Cummings (2011) categorised the roles played by miners into 3 groups. The first role played by miners is by their virtue of being the front-end workers. Through the sharing of knowledge on the various 'ingredients' of the hazard build up, miners can contribute and put in effective controls for elimination of the ingredients and prevent accident build ups. Miners can play a more paramount role in some cases where their active intervention can help in de-escalating "unfolding accident sequences" and help bring back a mine from a hazardous state to normal working conditions (Saleh & Cummings, 2011, p. 773). Miners also play a critical role in identifying the hazard build ups and identifying the different precursors and lead indicators in the accident build ups.

Saleh & Cummings also state that the ability of miners to perform the aforementioned roles of identifying various hazards make them crucial “sensors” in the defence-in-depth principle. Miners’ ‘sensor’ role enables them to monitor hazardous states and provide “the prerequisite information for the triggering of active safety interventions in lines of defences” (Saleh & Cummings, 2011, p. 773). However, Saleh & Cummings state that the aforementioned roles of miners in the defence-in-depth can only be effective when mine management play a role in organising regular safety workshops in which both management and the miners actively participate. These regular safety workshops must have sole agendas of discussing various mining hazards, accident build up ‘ingredients’, the different dynamics of hazard escalation and precursors and lead indicators of various hazardous states. The other benefit of having regular safety workshops is sharing of what Saleh & Cummings (2011, 773) refer to as “collective wisdom” and experience of miners on some issues that may be overlooked or of which the mine management is unware. These may include some “finer details of the local conditions” (Saleh & Cummings, 2011, p. 773).

Saleh & Cummings (2011) put forward another critical role for miners which they term decentralised decision-making. The authors state that ‘safety competent’ miners are capable of using decentralised decision-making as the final line of defence in accident prevention. The decentralised decision-making can be described as the decisions which a miner must take to ensure the best safety course of action in a situation where the supervisors are not available or are unware of the local conditions that would need urgent action and attention to stop accidents or disasters.

Miners’ decentralised decision-making role is most critical in emergency situations where in most scenarios there will be no communication with the central decision makers or in some cases where the central decisions are flawed (Saleh & Cummings, 2011). However, Saleh & Cummings emphasise that miners must be properly trained for them to be able to be competent decision makers. Proper training will enable miners to make risk averse decisions regardless of what the supervisor says or if he or she is not available. Saleh & Cummings (2011, p. 774) further state that “in extreme cases, this role of decentralised decision-making may justifiably lead to miners refusing to comply with orders that are clearly dangerous”. In the South African mining industry context, Section 23 of the MHSA empowers miners to withdraw or refuse to enter dangerous working areas. When miners exercise this right it is a clear example of decentralised decision-making. Effective use of decentralised decision-making can clearly serve as a final line of defence.

3.7.5 Case Study Illustration of the Defence-in-depth Principle

To illustrate how the defence-in-depth principle can be implemented in the mining industry, Saleh & Cummings (2011) analysed a methane explosion accident which occurred at Jim Walter Resources (JWR) No. 5 coal mine the US. The explosion claimed 13 lives. According to Saleh & Cummings (2011), the accident investigation report reviewed that 2 days prior to the mine explosion, there was a roof fall in one of the coalmine's sections. After the roof fall, water ingress was reported in the same area where the roof fall had occurred. However, instead of the mine management to take extra precautions and supporting the area before allowing work in that area that had the roof fall and showed bad ground conditions, "a large battery (weighing 6 tons) and battery charger were brought and placed under" the unsupported roof which showed great instability" (Saleh & Cummings, 2011, p. 769). After ignoring the aforementioned lead indicators, there was another roof fall 2 days after the first incident, which damaged the battery and the damaged battery was likely the source of ignition spark for the methane outburst due to the rock fall.

Four miners who were working in the section were injured due to the outburst. One was so seriously injured that he could not move. The first explosion also damaged the mine's ventilation system in the section. Moreover, coal dust was generated after the first explosion. However, due to the inadequate rock dusting at this mine and the accumulation of coal dust there was another great risk of a coal dust explosion. Saleh & Cummings (2011, p. 771) state that the coal dust became the "major fuel source of the second explosion". Because of the roof fall, it would have been anticipated a bigger flow of methane but unfortunately the mine management did not evacuate the miners or de-energise energy sources in the mine and because of that the second explosion occurred due to the ignition of the coal dust by the block lights in the same section which were energised.

Saleh & Cummings state that the second explosion was more violent than the first and it claimed 13 lives and destroyed a greater part of the mine. Saleh & Cummings illustrate the various defences in Figure 3.8 which were flawed and could have been used to prevent first the roof fall and ultimately the second explosion which claimed the lives of 13 miners. Figure 3.8 shows an example of how the defence-in-depth principle can be used in the mining industry to effectively prevent hazard build up or the escalation of accidents into disasters like the JWR No. 5 disaster.

From their analysis illustrated in Figure 3.8, Saleh & Cummings (2011) state that the first line of defence which failed was the lack of adequate roof support which could have prevented the roof fall. The second flaw in the defences was lack of proper training. The authors argue that if there was proper training on the various risks of roof falls there would not been a battery being placed in the high risk zone knowing that the mine was classified as gassy. It is also clear that the evacuation and emergency preparedness of the miners was flawed. There is also a sign of a flawed regulatory safety lever for not ensuring that there was adequate rock dusting and the managerial safety lever was also flawed since the block lights which ignited the coal dust was not de-energised. If the miners were well trained to be able to make decentralised decisions the evacuation safety defence would have saved the 13 lives lost in the explosion (Saleh & Cummings, 2011). In Figure 3.8 every **X** symbol represents a failed defence in the system. The first **X** represents the roof support defences which failed and led to a roof fall. The second **X** represents the failed risk assessment defences which allowed the scoop battery to be in the unsupported area leading to its damage due to the roof fall and ultimately becoming the ignition source for the methane explosion. The third **X** represents the failure of the defences such as miners' risk assessment, evacuation safety defences and decentralised decision-making which if present there would not been injuries and fatalities.

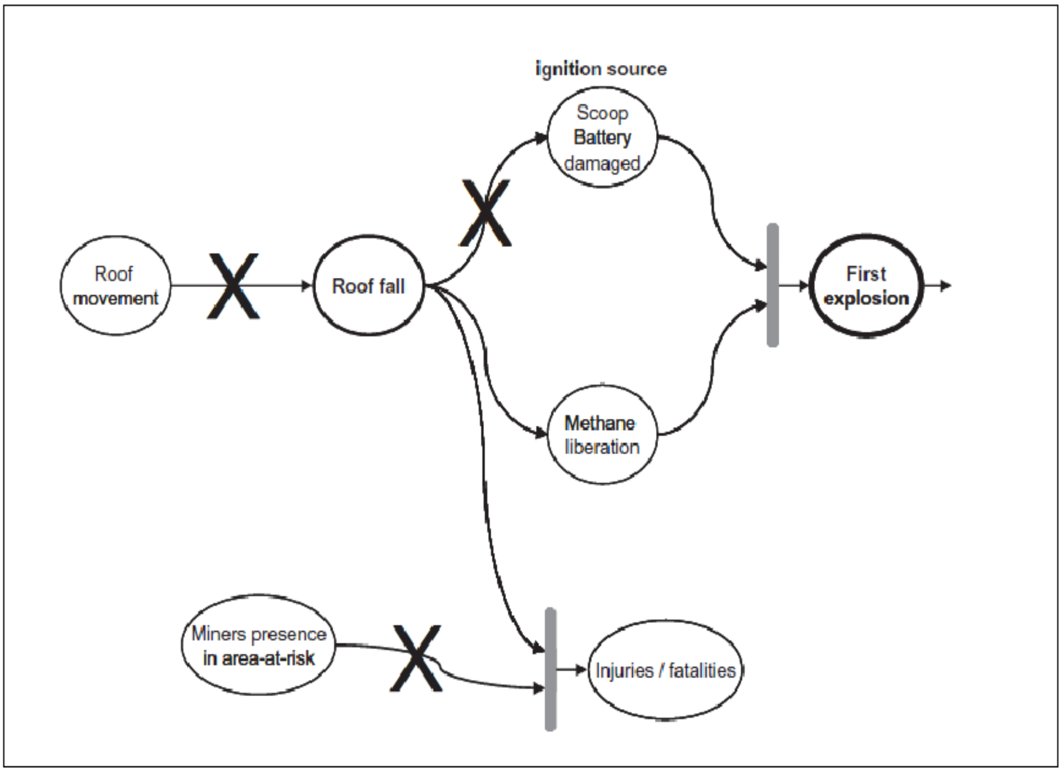


Figure 3.8 Illustrations on the defence flaws in safety system at the JWR No.5 Coalmine Explosion (Saleh & Cummings, 2011)

3.8 Conclusions

Due to underground mines' hazardous and dynamic nature, technologies in these environments must be able to give accurate information on the state of the environment and most importantly the well-being of the miners. The systems must be able to warn miners underground when high risk circumstances are developing. An AMS can be utilised to monitor and analyse ventilation parameters underground in real-time. For the systems to be reliable, it is critical to maintain the comprehensive monitoring systems installed in a mine because their installation costs are usually high. Griffin et al. (2013) in the conclusions to their study emphasised that maintenance is also crucial to ensure that systems function properly in cases of an emergency and more importantly in the prevention of the emergencies. Generally, with the exception of underground coal mines, there is still limited use of AMS and other real-time monitoring systems in South Africa's underground mines. The reasons to monitor mine atmospheres include, but are not limited to a rise in safety standards, higher production demands, equipment speed increases, variability in mining conditions and weather fluctuations affecting the mine atmosphere. The effective use of AMS and other leading practices can enhance mine safety in underground mines. It is also important to implement real-time monitoring of assets as well as the miners underground so that at any given time their location can be pin-pointed. Integrating the monitoring of mining personnel, assets and AMS can help in the implementing of real-time decision-making which will help in removing miners from areas identified as unsafe and risky especially in emergency situations. Communication systems make the back-bone for the aforementioned system because they allow underground miners and surface control room operators to communicate. Due to the high prevalence of respirable diseases the adoption of real-time respirable dust is also paramount. From the discussion it is clear that effective dust monitoring must be supported with regular and adequate medical surveillance. The various heat stress management strategies to address the heat illnesses and fatalities in deep level platinum and gold mines in South Africa are also put forward. VOD plays a critical role in AMS, dust management and heat stress management because all are usually caused by inadequate ventilation. The defence-in-depth safety principle summarises how different safety levers can be implemented in the mining industry to avoid different hazards eventually resulting in accidents as well as preventing escalation of accidents into disasters. The principle if used properly brings about significant benefits in the mining industry's thinking regarding risk management.

4 CASE STUDIES ON HEALTH AND SAFETY INCIDENTS IN THE SOUTH AFRICAN MINING INDUSTRY

Over the years, the global mining industry has claimed many lives due to a number of mining disasters. Scholarly evidence shows that the South African mining industry is no exception. However, when looking back on some of the mining disasters and accidents that happened in South African mines, many of these accidents and disasters could have been avoided by the use of some of the new technologies now available for the industry. These technologies coupled to an inclusive culture of safety amongst all mining stakeholders, have the potential of minimising the number of mining accidents and ultimately achieving the goal of zero harm. It is imperative to note that, when looking at the causes of accidents and fatalities in the South African mining industry, transport, machinery, and rock-related incidents dominate the statistics. However, there have been great strides made in the use of technology in reducing disasters such as transport related accidents, mostly in trackless mines by the adoption and use of collision avoidance systems.

The realisation of the benefits of using technology in enhancing mine health and safety is critical. Research has shown that technology can eliminate the human error causes of accidents and minimise the over-dependence on human beings in making life and death decisions. One of the areas, which has led to mining accidents and disasters, is the risk-taking behaviour of miners. Nevertheless, introduction of technology-based decision-making can minimise or eliminate those accidents and disasters based on human error. A number of case studies will be discussed in the following sections and these will try to highlight how, in some cases, the simple use of technology would have avoided the accidents, which occurred some time ago in some mines.

When looking at accident and incident reports in the mining industry, in most cases, there is the ‘blame game’ between mine management and the miners on the causes of deaths, with workers often blaming management for disallowing them to exercise their right to withdraw from dangerous workings. Again, there is great potential in implementing section 23 of the MHSA by using technology. This will also help in accident investigations as well as dealing with workers’ complains on being forced to go into dangerous workings. In addition to the case studies provided, the author will also refer to chapter 3 of this dissertation, where the various leading practises, which can help, reduce and ultimately prevent health and safety issues in the mining industry were identified and discussed.

4.1 Case Study 1: The Middelbult Explosion (1993)

On the 13th of May 1993, there was massive explosion in Section 38 at Middelbult coalmine, which led to fifty three fatalities (Phillips, 2015). According to Phillips, the cause of the explosion at Middelbult was due to deviation from the approved mining plan. This was said to have been attributed to some of the personnel in the section who were known to have raised concerns about production bonus losses due to the planning team being delayed in finishing the plans for a new panel. Phillips (2015) further states that the investigations into the explosion showed that the mining method which the crew used contravened the mine's standards and the ventilation change, which led to the explosion, was as a result of the removal of ventilation walls and this was not sanctioned by the ventilation department.

Phillips indicated that in the Middelbult incident, significant gas was detected earlier in the morning prior to the explosion. However, SASOL had a rule that the mine overseer had to clear the section prior to commencing work. Contradictory to this rule, the mine overseer was said to have been sitting on surface waiting for his annual appraisal. It is alleged that the mine overseer went on to get a new gas clearance certificate book from the stores and wrote out a clearance report and phoned the section to resume production without him doing the re-entry procedure and checking for gases (Phillips, 2018). In his analysis, Phillips (2018) emphasises that if all this was remotely and electronically monitored, using some of the real-time monitoring and control systems now available in the industry, the overseer could not have been able to issue a gas clearance certificate unless he was underground in the affected section. Phillips (2018) further concluded that if production had not commenced underground the explosion could have been avoided.

In the conclusion of his paper, Phillips (2015) proposed that real-time monitoring of coal mining section airflows are an absolute necessity and the data acquired from such monitoring should be displayed in a surface control room. He further recommends that the results should monitored "by a supervisor with no financial interest in any production bonus" (p. 8). Phillips suggests that the person must be given full authority of being able to stop production on the occasions when he notices that there is insufficient or unsatisfactory ventilation.

4.1.1 Lessons from the Middelbult Explosion

From the aforementioned discussion, the root causes of the explosion were put forward and a number of lessons can be deduced from the investigation findings. From the inquiries, it was found that malpractice and unauthorised mining without proper ventilation caused the explosions. Attesting to Phillips's recommendations, a real-time ventilation monitoring system would have avoided the accident. For instance, the findings showed that the mining crew changed the ventilation practices without alerting the ventilation department. However, if a real-time Atmospheric Monitoring System (AMS) had been available at that time and installed at the mine, the ventilation department would have been alerted immediately by the monitoring system.

When applying the defence-in-depth principle discussed in Chapter 3, it is also clear from the investigation that the miners who were working in the section where the explosion occurred did not apply proper decentralised decision-making. If the miners had applied the decentralised decision-making principle, they would have anticipated and be informed on the criticality and consequences of contravening ventilation standards in a mine known for methane accumulations. Another important aspect to note in the causes of the explosion is the behaviour and role played by the Mine Overseer.

From the investigations it was found that the Mine Overseer did not even go underground to test for the gases, instead he forged a gas clearance from a new book and this enabled him to call his team underground to commence production. When referring to some of the identified leading practices from chapter 2 and chapter 3, there are new systems now available for real-time personnel and asset management. These systems can be used for issuing mining equipment and assets to mining personnel. The systems can also be used to track the location of both mining personnel and assets underground in real-time.

Figure 4.1 shows a typical example of a personnel and asset management system that can be used in a lamproom and can also be monitored from a control room. Through the system's time and attendance (T&A) (Figure 4.1) functionality, it is possible to log in the time when a miner or an asset enters or leaves the lamproom through the walk-through frame. The gate controller agent and the passive tag reader send information on the date and time stamps of the asset or miner's movement through the frames. This system can generate attendance registers for everyone working on a specific shift. It also allows for easy shift management as well as the generation of shift clearance reports with the times the shift started and ended (Rungani, 2016).

By using these systems it would have been possible for the control room or lamproom personnel to ascertain that the mine overseer had not gone underground hence he could not have tested gases in his section, therefore production was supposed to be stopped. To confirm that the authorised person was not underground, the lamproom or control room operators could have downloaded location and movement reports using a similar system to that shown in Figure 4.1. It would also had been impossible for the Mine Overseer to forge a clearance report because, using the systems now available in the mining industry, gas testing and clearance reports can now be system generated. However, to able to download gas reports for clearance purposes, the asset and personnel management systems must be linked to a fixed, real-time gas monitoring system in the sections.

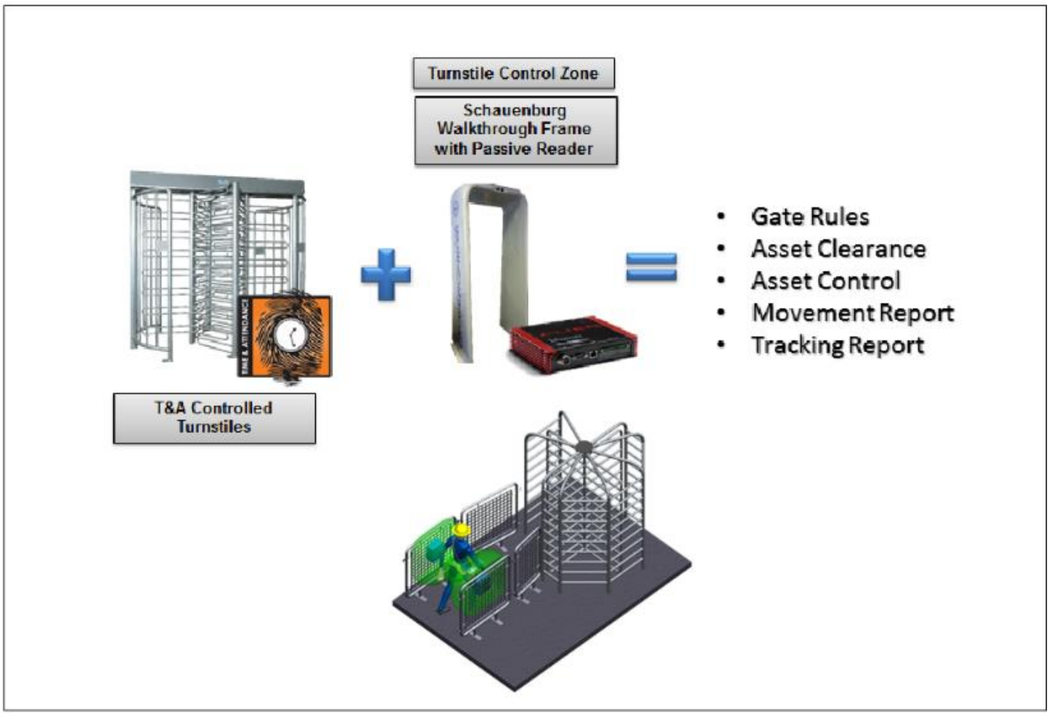


Figure 4.1 Showing a Typical Personnel and Asset Management System (Schauenburg Systems, 2015)

From the aforementioned discussions, the first line of defence would have been to identify that the Mine Overseer did not even go underground to test for gases through the time and attendance system (Figure 4.1) which is responsible for personnel management in the lamproom. The second line of defence would have been a fixed real-time atmospheric monitoring system (AMS) installed in the Mine Overseer's section, which could have informed the control room on the methane gas build up and concentrations in the area of concern. The third line of defence would have been the stopping of the production or section conveyor belt when the control room operators realised that the gas levels were high or increasing towards or beyond the explosive ranges. The final and ultimate line of defence would be the miners exercising their decentralised decision-making role by withdrawing from the section the moment they realised that the Mine Overseer did not come down to test for gases.

The researcher is of the view that the control room operators must have more authority delegated to them by management, which is of a higher level than to the mining personnel working underground that is Mine Overseers, Shift Supervisors, and Mine Captains. The main reason for this suggestion is that the control room operators should in any way feel intimidated to carry out their duties. They should do so without favour or fear of being victimised or threatened by people of higher authority working underground. This view cannot be underestimated, especially in mines where there is competition for receiving production bonuses. The researcher also supports Phillips' (2015) assertions that control room operators must not have any financial benefits from production bonuses. For instance, in the Middelbult incident, if the control room operator was of low authority, the Mine Overseer could still have managed to clear his section for production to commence by simply threatening or intimidating the operator into not stopping the conveyor belts in his section, despite there being evidence that he had not gone underground and tested for gases.

Moreover, if the control room operator also had financial benefits through production bonuses from the section s\he would not have stopped production. In order to minimise and eliminate the human error component in the decision-making in the control room, it is highly recommended that, for some decisions, artificial intelligent systems be employed. The combination of artificial intelligence (AI) and the internet of things (IOT) can minimise and eliminate human error in critical decision-making in the control room. The IOT will enable and allow everyone connected remotely to the mine to assist in the decision-making process in real-time. However, in some instances such as, systems malfunctions, a person of higher authority must also be capable of overriding some of the decisions done remotely or using AI. Extensive research and tests must be done on the recommended systems before installing or using them in a real control room or mining environments. Consequently, integrating these systems and having an inclusive safety culture will bring out a solid defence-in-depth strategy for avoiding similar incidences such as the Middelbult explosion and ultimately the goal of zero harm will be realised.

4.2 Case Study 2: Ermelo Mine Services Explosion (1992)

On November 7, 1992, there was a methane explosion at Ermelo Mine Services (Pty) Limited, and six fatalities were recorded. An investigation into the explosion was launched on the 9th of November 1992. The investigation team interviewed three of the personnel who were working in the panel and were involved in the blasting of a pillar where the explosion is said to have originated (Phillips, 2015). The Miner in charge who blasted the panel claimed and insisted that he had tested for gases on both sides of the pillar before blasting. However, his two assistants claimed that they did not remember witnessing the miner testing for gases. After conducting further investigations into the explosion, it was found that the mine had a custom of leaving some gas detection instruments in the lamproom over the weekends (Saturdays) for weekly inspections and calibrations. Through checking the lamproom records, it was found that the particular miner who claimed to have tested for gas before blasting did not have his Gas Detecting Instrument (GDI) with him on the day on the explosion (Phillips, 2015).

4.2.1 Lessons from the Ermelo Mine Services Explosion

The findings from the Ermelo Mine Services explosion were similar to the Middelbult explosion. The major findings were that the (1) Miner did not test for gas before blasting and (2) the Miner did not even carry his GDI underground. From the explosion investigations, it was further established that it was the company culture to leave GDIs for calibrations on Saturdays. However, it is important to note that in the initial stages of the explosion investigation the Miner insisted that he has tested for gases before blasting. The upside of the use of real-time asset and personnel management systems (such as the one shown in Figure 4.1) in the lamproom to issue pieces of equipment (e.g. GDIs) and to track the location and compliance of PPE for underground mining personnel is emphasised when looking at the similarity in the causes of fatalities in both the Ermelo and Middelburg explosions. The use of real-time AMS would also have prevented the six mine fatalities caused by the explosion.

The explosion was simply due to negligence and human error. In this case, the real-time monitoring system could not only had helped in preventing the fatalities but also in the accident investigation. It would have made it easy for the investigation team to realise at the beginning of the investigation that the Miner did not have his gas detection instrument with him. Lamproom records would have shown that his GDI was not issued on the day of the explosion. Moreover, even though the lamproom had records, it would have been easier to confirm from a computerised database. For instance, the system shown in Figure 4.1 allows for the control room and lamproom operators to be able to download instrument issuance reports, movement reports, tracking reports, asset clearance reports and clocking in/out times from a computerised database at any given time. It also allows for the downloading of old reports from a specific past date.

Not only, does the system allow for the downloading of reports but by using such a system as well a real-time personnel monitoring system, the lamproom or control room operator could have been able to stop the miner from going underground without the required, adequate PPE. The other line of defence would have been a fixed real-time atmospheric monitoring system (AMS) in the miner's section, which could have provided information on the methane gas build up and concentrations in the area of concern. The final and ultimate line of defence would be the miners exercising their centralised decision-making role by withdrawing from the section the moment they realised that the miner did not test for gases. It is important to note that the lamproom operators or the control room operators have a significant role to play for most of the lines of defences to work effectively.

The realisation of the benefits of technology, especially the real-time AMS, asset monitoring and location monitoring is further emphasised when analysing the findings from the Ermelo Services Mine explosion investigation. The investigation highlights how health and safety compliance systems may need the introduction of technology to minimise the risk of accidents through human error. This lays emphasis on how it is important to adopt systems which make decisions using AI. However, the author still alludes to the fact that the AI systems must allow a person of a certain higher authority to override some the decisions. This brings in the other critical component of the implementation of the IOT.

So, from the leading practices that were discussed in chapter 3, it is evident that the Ermelo Services Mine explosion would have been avoided if similar systems were available and installed at the mine. Application of a combination of these systems is clear implementation of the defence-in-depth principle in mine safety with a culture of safety as the final line of defence. The main benefit of using integrated systems with multiple layers of health and safety defences, is to ensure that when one defence system fails, the other defences either prevent hazards from escalating into accidents or in the case that they do escalate, other defences will be in place to contain or mitigate the consequences (Saleh & Cummings, 2011).

4.3 Case Study 3: Mine X fatalities (2018)

This case study will discuss a fatality incident which claimed lives of five miners in one of South Africa's deep-level gold mines. According to the company's media reports the deceased mine workers entered an abandoned working area and succumbed to heat exhaustion. The company claims that a Shift boss led his team into an area, which was temporarily abandoned and properly barricaded. The company further states that the five fatalities were due to the employees breaching and deviating from safety procedures as well as company policy. It is also important to note that it took the mining rescue team three days to recover all the bodies of the deceased from underground.

However, there were also allegations that the deceased were denied their right to withdraw from dangerous and unsafe workings in reference to Section 23 of the MHSA. Nonetheless, the company denied the allegations and emphasised that it had systems in place for mine workers to lay formal grievances and put forward anonymous tip-offs in scenarios where they are victimised or when given instructions that go against their rights enshrined in the law, particularly the right to withdraw from dangerous workings.

The company claimed that, although they were aware of the allegations, they had not received any formal complaints or tip-offs with regards to the incident or the issue of miners being denied their Section 23 right to withdraw from dangerous workings. The company further challenged any employees or other mining stakeholders with substantiating evidence to bring it forward and assist them with investigations. Moreover, the company claimed that a full investigation is still to be conducted by the Department of Mineral Resources and Energy (DMRE) and the full details of the fatalities and a full examination of events which led to the fatalities would be put forward. Even though currently there is not an official report on the full investigation from the DMRE, the 2018 year end statistics released by the Chief Inspector of Mines reported the cause of the five fatalities as being heat related.

Contrary to the mine's assertions, organised labour (Mining Unions) alleged that there was evidence that the deceased were forced to enter the area and were denied their rights to withdraw from the dangerous working environment in which they later succumbed to heat exhaustion. However, the only thing that the mine management and unions agreed on was the cause of the fatalities, which they referred to as heat exhaustion. The 'blame game' led to inconclusive results on what exactly transpired on the day. The 'blame game' between mine management, miners and organised labour is not a new concept, but one of the biggest setbacks in achieving healthy and safe working environments in the mining industry.

The miners and the unions always allege that mine management prioritise production and profits and on the other hand, mine companies assert that they have invested in fit-for-purpose safety systems and resources to ensure miners are healthy and safe. For example, the Chief Executive Officer (CEO) of Mine X stated that following the fatalities incident, the company was in the process of initiating what he described as a 'culture of transformation programme' with aims of influencing "attitudes to safety, promote compliance with safe work practices and instil a culture of effective risk management" at their mining operations. The CEO added that they also introduced an initiative of conducting safety summits with multi-stakeholders to discuss different critical measures to enhance the safety performance in their mining operations. One of the outcomes of the summits was the collaboration in the development of a Zero Harm Strategic Framework which will mainly be used to identify priority areas to be addressed to achieve enhanced safety performances.

4.3.1 Lessons from the Mine X Incident

The full investigation report of the incident which led to the five fatalities has not been published and finalised. However, there is consensus in the publicly available reports from the mine management and Chief Inspector of Mines that the causes of death for the five fatalities were due to heat exhaustion. The effects of exposing mine workers to heat are discussed in some detail under the heat stress management section in Chapter 3.5 of this dissertation. Mine X is classified as a deep level gold mine and because of the high virgin rock temperatures associated with depth similar cases of injuries and fatalities due to heat exhaustion and heat strokes have been witnessed many times in South Africa. Nonetheless, there are a number of heat stress management controls which could have avoided the five fatalities. Due to the lack of the full details on what led to the deceased entering the abandoned area, the author will recommend and propose different ways which could have avoided the loses of life by looking at the incident under two different scenarios.

Scenario one will assume that the miners were authorised to go into the abandoned area and scenario two will fall under the assumption that the deceased went into the abandoned area unauthorised.

4.3.1.1 Scenario One

Assuming that the miners were authorised to go and work in the abandoned area, the various ways in which the fatalities could have avoided from heat stress are proposed. The procedures of heat stress management range from determining the heat stress indices of underground environments, acclimatising miners before going to work in hot-humid environments, monitoring the underground environment (air temperature, radiant heat, air movement and humidity), real-time monitoring of employees working in all underground environments as well as employing some cooling strategies and also introducing water breaks. Working with the available reports it is clear that the workers went to work in an abandoned area, and from that alone, it is most likely that none of the deceased were acclimatised to work in this area since the heat conditions were probably not known. As stated in section 3.5.2 of this dissertation, underground miners who work in hot environments have to undergo proper acclimatisation procedures to reduce their risk of heat related illnesses or fatalities. It is through proper acclimatisation that workers who are heat intolerant are identified and in this case there is no evidence that any of the deceased were properly acclimatised for the environment they were working in.

Another key recommendation from section 3.5.4 of this dissertation, was that when workers go to areas where the conditions cannot be predicted or can change unexpectedly, the use of cooling garments is critical. These cooling garments include dry-ice vests and ice jackets. In this scenario, this PPE could have possibly saved the lives of the deceased who were declared to have died due to heat exhaustion. Similarly to the proposals in the previous case studies, real-time monitoring of the underground environment and mining personnel is emphasised. If there had been a real-time monitoring and control system installed in the abandoned area, the miners could had been informed on the environmental conditions (air temperature, radiant heat, air movement and humidity) and this would have avoided the fatalities.

To the contrary it can also be argued that unless there are exceptional circumstances, real-time monitoring cannot be used in abandoned areas because of the difficulty of maintenance and the issue of power in a possible methane area. Considering this incident as an exceptional circumstance, a real-time monitoring ventilation system supported by a Ventilation on demand (VOD) system and Cooling on demand system would have managed to control the environmental conditions by providing an adequate supply of fresh and cooled air to counter the hot environment thereby alleviating the risk of heat exhaustion and stroke.

Using the lamproom, it is also possible to track whether workers have proper PPE and adequate acclimatisation to go and work in the areas which they are allocated to in a specific shift. Another important thing to note is that workers who are assigned to hot-humid areas must be properly hydrated before going to their working areas. Taking into consideration that the fatality incident occurred on a Monday, it can be suspected that alcohol induced dehydration (from weekend drinking) could have been added to the causal factors leading to the heat strokes. This assumption is based on the well-documented drinking culture of mine workers, mining students and communities (Pick, 2003; Barnabas, 2015; Evans, 2018). The solution to this would be to conduct awareness and educational workshops on the effects of dehydration when working in hot-humid environments. Another solution is the strict enforcement of alcohol breathalyser tests on all workers going underground, particularly those going to hot-humid environments because this enables the screening and identification of those not fit to work. However, it is also important to note that for the systems to be effective, the people in charge of all the monitoring, from control room operators to lamproom attendants, must be empowered to enforce decisions affecting safety and health. This is to avoid intimidation and minimise the potential of bribery. Furthermore, integrating and connecting these monitoring systems to a real-time monitoring system, can help investigations and also be integrated to systems like IOT which will enable management to make real-time decisions in terms of safety.

4.3.1.2 Scenario Two

Looking at scenario two, there are two possibilities, (1) the workers wilfully did not follow safety procedures and went in to work in an abandoned area as claimed by mine management, and, (2) the workers were deprived of their Section 23 right to withdraw from dangerous workings and due to either intimidation or fear of losing their jobs, they complied and went in to work in the abandoned areas. It is important to note that the main aim of the proposed solution is not to give blame to either the workers or management but to propose a solution which could have avoided the fatalities. From the available information, it is clear that the workers died of heat exhaustion and this is classified as ventilation related fatalities. Unlike most of the other underground mining risks, ventilation risks can be easily monitored and controlled through the use of readily available sensors and devices. Using sensors for gas detection, temperature detection, humidity, air pressure and velocity measurements, countermeasures to ventilation risks can be implemented. These include, VOD and cooling on demand. It is also possible to implement Section 23 using these technologies especially when specifically targeting ventilation risks.

For instance, when looking at this case study, it would have helped for every miner who went to work in the abandoned area to be allocated a tag for location monitoring, an environmental monitoring device (for temperature, humidity, gas and air movement readings) and a communication device. With all these sensors and devices having direct communication to the control room, the fatalities could have been avoided in many ways. Firstly, the devices and sensors would have directly communicated to the control room that the working conditions were not suitable for working. An alarm or warning would have been rung as an indication that the threshold limits were being exceeded. Furthermore, the workers would have been able to exercise their Section 23 right without fear of intimidation and with evidence that is directly traceable. The aforementioned sensors and communication devices can also initiate evacuation signals or countermeasures like VOD and cooling on demand, depending on the type of risk. In the case of workers going into an unauthorised area, the control room operator/s can also send warning signals to the workers who are trying to enter an abandoned area, and this can be done in real-time. The unauthorised areas can also be geofenced, meaning that as soon as any mining personnel enter these areas, alarms will be triggered. The tracking of mining personnel can also help initiate reliable emergency evacuations and assist in locating people after incidents. In this case study it took the rescue teams three days to recover the bodies of the deceased, this would have been an easier task if location tags had been allocated to every miner.

If these systems were in place, it would have solved the issues of miners and mine management blaming each other on the issues of withdrawing from dangerous workings. However, as mentioned earlier, it is important that some of the control room operations are automated to minimise human error in some of the critical decisions such as withdrawing workers from dangerous areas as well as escalating issues in real-time of mining personnel entering dangerous workings unauthorised.

This incident also highlights the important role of miners and the other defences when looking at the defence-in-depth safety principle discussed in section 3.7 of this dissertation. If miners are properly trained or fully aware of the risks of hot environments, they would have put this knowledge to good use in their ultimate role of decentralised decision-making, which serves as the final line of defence. Emphasis must be given to this role because it is only through it that miners can refuse to comply with orders that are clearly dangerous. It is important to note that the aforementioned technologies can only be effective when the workers and mine management instil a solid culture of safety which goes beyond compliance.

When looking at both of the scenarios, i.e. one and two, it is evident that the use of continuous real-time monitoring and control systems for location purposes and environmental monitoring would have avoided the fatalities as well as helped in cases of locating miners after incidents. These systems can also enhance the implementation of Section 23 of the MHSA with the potential to enable miners to exercise their rights using informed and traceable decisions which management can track in real-time through the control room. The calibre of the control room operators was also fairly highlighted with an emphasis on making sure that control room operators must be empowered with a higher authority and remunerations than that of the people they monitor. This is to ensure that they are not intimidated, undermined or bribed in the critical decisions they make.

4.4 Case Study 4: Palabora Mining Company (PMC) Fire Incident (2018)

On the 15th of July 2018, there was a fire incident at Palabora Mining Company (PMC) which led to six fatalities. According to the Department of Mineral Resources and Energy's report, a newly installed conveyor belt caught fire (Chaoke, 2019). The report states that at around 0107hrs of the 15th of July, some employees who were working underground reported the smell of smoke from downstream of one of the mine's airflows. The employees further checked and confirmed that there was a fire and immediately informed the relevant stakeholders who then initiated an evacuation process. The report further states that some employees evacuated to the underground station and others proceeded to the underground refuge bays (Chaoke, 2019).

There were efforts to extinguish the fire but the report states that the existing fire suppression system at the mine was compromised and there was also no adequate water in the system to extinguish the fire. The employees tried to use fire extinguishers and some water from the cleaning hoses to extinguish the top side of the conveyor belt but unfortunately the fire escalated to quickly burning the bottom part of the conveyor belt towards the tail completely. Due to the burning of some combustible materials along the conveyor belt which included PVC pipes, electrical cables and other rubber materials, the fire suddenly became "severe and created a heavy smoke and heat, which made it difficult to extinguish" using the fire extinguishers (Chaoke, 2019, p. 6). The report also claimed that there were acetylene bottles which were stored along the conveyor belts which also exploded due to the fire escalation (Chaoke, 2019).

According to PMC (2018), there were two hundred and twenty six (226) employees who were working underground during the shift in which the incident happened. During the incident, two hundred and twenty (220) employees were evacuated from the mine, and six employees were found deceased underground. Of the rescued, eighty eight (88) sustained injuries and one hundred and thirty two (132) were not harmed. Of the deceased three were found in the Refuge bay provided for conveyor belt employees and the other three employees were found lying along the conveyor belt. The DMRE report states that the conveyor belt which was installed at the mine was non-fire retardant. However, it is also important to note that, although there were six fatalities due to the fire, there were a number of controls which were in place in the mine for managing fire risks (Chaoke, 2019). Chaoke (2019) mentions the following as the controls, which were in place prior to the incident:

- Fire suppression system which had both automated and manual operation options;
- Fire detection system for environmental monitoring;
- Gas Detection Instruments (GDI);
- Escape routes for Emergency Preparedness and Response;
- Refuge bays;
- Self-contained Self Rescuers (Rescue Packs).

Furthermore, Chaoke (2019) stated that the cause of the fire was still not yet known at the time of the publication of the DMRE report.

4.4.1 Lessons from Palabora Mining Company Fire Incident

From the above-mentioned discussion, the details of the fire disaster, which claimed six lives are put forward and there a number of lessons from the incident and this research will put forward recommendations on how the incident could have been avoided and how future incidents may be avoided. The investigations showed that although there was a fire detection system at the mine, in reality the miners had to detect the presence of a fire through the smelling of smoke. It is clear from this finding that the fire detection system at the mine was not functional or did not offer real-time atmospheric monitoring because if one was present, it would have alarmed and alerted the miners and control room. The incident emphasises the need for an effective real-time AMS.

Another lesson from the incident is that although the mine had a fire suppression system in place, the system was compromised and did not have sufficient water to extinguish the fire. The report further states that the fire suppression system had an option of being automated or manually controlled. However, from the incident it can be suspected that it was on manual operation mode. If the fire suppression system was automated and functional, as the first line of defence it would have stopped the fire from escalating and extinguished it at the point of ignition. A lesson from this incident is that it is important to make sure that most of the critical risk controls like the fire suppression system and gas evacuation systems are automated such that the human error component in accident preventions and control is eliminated or minimised.

When a system is automated and controlled by artificially intelligent systems, it is easy to check on a daily basis or even in real-time if it is compromised. This will help mine management to make real-time decisions regarding safety. For instance in this scenario, if the system was monitored remotely and operated automatically, control room operators could have stopped the operation of conveyor belts and miners would not have been sent to the areas or in the case that the fault was found during normal operations, immediate evacuations could have been initiated. Remote and real-time monitoring would also have alarmed on the low water levels in the system.

Environmental monitoring systems, in this case fire detection systems are used for early warning, so it is important that the installed systems are effective and adequate to detect any risky situations from fire, toxic gases and directly pin-point the affected areas so that miners can be informed of the safe escape routes. It is clear from this incident that early warning systems are not helpful when they are not continuously checked to ensure they are not compromised. It is also imperative to note that having an early warning system which is not functional may instil a false sense of security in mine workers, as they will confidently believe they are protected. Therefore, it is important that mines emphasise a proper emergency preparedness plan which will train miners to know that after everything has failed they are the last line of defence for the preservation of their lives. Hence in severe cases they must run for their lives.

The case study also showed the importance of using fire resistant conveyor belts. This is important because from the incident it is clear that non-fire retardant conveyor belts are a serious fire hazard. The other lesson is the location of refuge bays. In any accident situation refuge bays must be very safe in order to save the lives of miners during incidents similar to this. However, from this study it is apparent that the refuge bays did not manage to provide life support. Refuge bays must be life supportive and be equipped with air supply systems that have designed in redundancy and are rugged enough to resist being destroyed by fire or any other hazards. The latter addresses the issue of mining companies not only being supposed to aim for compliance in terms of risk assessments and management, but to aim for proper site specific risk assessments for fire preventions.

The case study emphasises the importance of not only putting in place risk controls concerning fire suppression and fire detection but also to ensure that these systems are automated and provide continuous real-time monitoring and control. It is also important to note that it is clear that there is a need to put in place systems which do not depend on continuous human intervention to pin point when a system is compromised or is not working according to specifications. There is a need to introduce artificially intelligent systems to inform on risks in real-time. If all these systems had been functional the lives of the 6 miners would have been saved.

4.5 Conclusions from the Cases Studies

From the case studies, there are a number of overlapping solutions and findings. Looking at all the case studies, it is undeniable that there is a dire need for real-time location monitoring of miners and pieces of equipment in underground environments. With real-time monitoring systems, it is possible to monitor compliance of PPE, state of miners as well as their exact positions in both normal working conditions and emergency situations. The systems should also allow for well-informed and timely evacuations. The lessons also emphasise the importance of real-time atmospheric monitoring, and control systems for the underground environment. When combined together, knowing the miners' and equipment location and the state of the underground environment can help in eliminating underground fatalities through early warning systems and countermeasures to ventilation risks such as VOD. The monitoring and control systems can also help in the tracking of compliance with codes of conduct in the underground environment.

Furthermore, another key take from the case studies is that the control room must be manned with someone of higher authority than the mining personnel working underground to minimise the risks of intimidation and bribes because if the roles and duties of these operators are compromised, the benefit of using the real-time monitoring and control systems may not be fully realised. It is also important to note that in order to realise the full benefits of real-time monitoring and control systems, some critical health and safety (life and death) decisions must also not be left to the control room operator but to artificially intelligent systems. This must be put in place to minimise human errors as well as over-reliance on human behaviour. The effectiveness of such systems has already been proved to be high with examples being personnel/machinery warning and anti-collisions systems which have been used to bring pieces of equipment to halt before interaction occurs without involving any human intervention.

However, it is also important to note that with the way the underground environment is dynamic, it is not possible as yet to programme AI systems for all possibilities. Due to this shortcoming, AI systems will be programmed to make the decisions for control operators, but an emergency alert must be sent to the manager, who can over-rule or accept the decision through a password-protected intervention after evaluating the information. This way the system takes into account some of the risks such as sensor imperfections, cyber security (hacking to tamper with algorithms) and viruses affecting decisions. It also gives allowance for a 'human touch' in the decision making process which is important in cases of false alarms and to avoid panic evacuations.

The case studies also showed that it is possible to implement Section 23 of the MHSA using technology, especially when looking at ventilation risks because it is possible to remotely and continuously monitor and control most of the ventilation properties of the underground environment using available sensors and devices. Realising this potential will solve the issue of the 'blame game' between mine management and mining personnel on the incidents of working and/or withdrawing from dangerous working areas. The final opportunity to avoid danger is the realisation by miners that they have an important role to play as decentralised decision makers in times of emergencies. Miners must be trained to understand the importance of them acting as the final line of defence in achieving zero harm. This is because, even when technologies are used to help miners in pin pointing and identifying risks, it is still dependant on the miners' reactions to these warnings, to either withdraw or ignore. Ultimately, it is important to train miners to be risk averse and maintain a solid safety culture if the industry is to realise how technology can help in eliminating fatalities.

5 TESTING AVAILABLE SYSTEMS FOR SYSTEMS INTEGRATION

In order to ascertain the effectiveness and functionalities of some of the leading practices recommended in the aforementioned discussions, the researcher will discuss the results and findings obtained from testing various available technologies in the mining industry. There are a number of companies offering products that support underground mining real-time monitoring for gases, dust, diesel particulate matter, mining personnel, mining equipment and assets. Examples of these companies include (but are not limited to), Schauenburg Systems, Northern Light Technologies (NLT), Newtrax Technologies, Mine Site Technologies (MST) and Minetec. This section will discuss and test various systems installed in the Wits DigiMine Mock Mine. The Mock Mine is a component of the Wits Sibanye Stillwater Digital Mining laboratory (DigiMine), a research group part of the Wits Mining Institute. The section will also discuss several systems that are installed at Gold One Mine.

5.1 Overview of the Wits Mining Institute DigiMine Laboratory

The DigiMine laboratory is a "21st century state of the art mining laboratory which is aimed at finding solutions through applied research, to make mines safer and sustainable through the use of digital mining technologies (Wits Mining Institute, 2019). According to Cawood (2017, 2019) the research carried out at DigiMine is classified under four themes, namely:

- Wireless Communication – the mission of the laboratory is to establish what Cawood (2019) describes as "reliable, multipurpose underground communication systems". The research carried out under this theme tries to address the challenges that mines are facing in terms of getting Wireless Sensor Networks (WSNs) to work in establishing communication to and from complex underground environments in real-time. This theme also forms one of the areas of interest in this particular research, with one of the objectives of the research determining whether it is possible to send health and safety messages to and from the control room from and to the production zones in underground mines and in the process enforcing the adherence of miners to Section 23 of the MHSA which empowers them to withdraw from dangerous workings.

- Surveying, Mapping and Navigation- the research under this theme shows that it is important to know the exact positions of miners, assets and equipment in an underground environment. Determining these positions, makes it possible to estimate the equipment and mining personnel's proximity to risk in real-time. In this research this theme was addressed through analysing the different incidents that could have been avoided through the use of real-time location monitoring of mining personnel and mining assets.
- Health, Safety and Security- this theme emphasises the need for real-time intelligent risk management through remote monitoring, visuals as well as inspections. This theme encompasses almost all of the other themes, however, it mainly addresses PPE monitoring and, enforcements of Codes of Practice through the lamproom and control room. The security aspect of the theme mainly addresses the issues of theft through mine access control systems. This also ensures that miners do not enter abandoned or unauthorised working areas. Lamproom asset management is one of the fundamentals in this theme. In the South African context, the security issues posed by illegal miners (Zama-Zamas) is considered under this theme.
- System Integration for Smart Mining – the integration of various digital mining is the final research theme being pursued at WMI. The research area encompasses all the aforementioned themes. System integration allows for communication between all the systems and show results on one platform, not as presently happening where systems work as standalone platforms, sending information to different databases. By integrating systems, it is possible to realise the full benefits of systems. The realisation of the systems integration enables mines to reap the

full benefits of the adoption of different technologies and ultimately achieve the goal of zero harm.

To fulfil the research in the four aforementioned research themes, the Wits DigiMine designed and created a mock mine with a control room all located in the basement floor of the Chamber of Mines building on West Campus of the University of the Witwatersrand (Wits Mining Institute, 2019). The mock mine is equipped with various digital systems that were specifically selected to fit under one or more of the four themes aforementioned. The mock mine also has “a life size tunnel, stope, lamproom and other features shown in Figures (5.1, 5.2, 5.3, and 5.4).

Figure 5.1 Overview of Wits DigiMine Mock Mine (1) Nick’s tunnel (2) Lamproom (3) Ventilation duct and velocity meter (4) Narrow-Reef Stope

Figure 5.2 (1) DetNet Blasting Unit (2) Timed Development End Face

Figure 5.3 (1) Schauenburg MIMACS Communication device (2) Fixed gas detectors & Minetec tracking Node (3& 4) Minetec tracking Nodes and ventilation duct

Figure 5.4 Overview of the Wits DigiMine Control Room

5.2 Testing the Schauenburg MIMACS System

One of the digital systems installed in the DigiMine mock is the Schauenburg Mine Wide Integrated Monitoring and Control System (MIMACS). The Schauenburg MIMACS is one of the leading systems believed to be a solution for the South African mining industry in achieving the goal of zero harm (Rungani, 2016). The system is a product of a South African based Schauenburg Systems Private limited. The company is a leading producer of safety products and systems for the South African mining industry and other mining countries (Schauenburg Systems, 2015; Schauenburg Systems 2016). As a research institute established to facilitate the adoption of digital technologies in underground mining environments, WMI's vision is to inform the emergence of a model of mining that promotes sustainability and competitiveness through focused research and development of skills and technology (Cawood, 2019). Currently, the DigiMine laboratory houses a variety of advanced technological systems that are currently under research for their application in South African underground mines, particularly in hard-rock environments.

For the purpose of this research, the testing of the Schauenburg system that is installed in the mock mine was to ascertain if it is possible to monitor the atmospheric environment in underground mines in real-time from the control room; if it is possible to monitor and pin-point underground miners' locations in real-time; if it is possible to monitor and enforce PPE compliance of underground personnel in the lamproom; if it is possible to integrate the Schauenburg system with other leading practice technologies and also determine the requirements of the systems' integration.

The Schauenburg MIMACS system falls mainly in three of the four research themes of WMI that were discussed earlier in section 5.1 above. The three being communication; health, safety and security and navigation. Under the communication theme, the research mainly focused on the communication between the sensors in the mock mine and the server in the control room through wireless and wired communication nodes. Under the health, safety and security, and navigation themes, the research tested for the effectiveness of environmental monitoring, location monitoring and the lamproom personnel and asset management systems components of the Schauenburg MIMACS system.

5.2.1 Components of the Schauenburg System

The Schauenburg System installed at Wits DigiMine is made up of different hardware and software components to fulfil its purposes. The different hardware components are shown in Figure 5.5. The components range from handheld and fixed gas sensors, communication devices, network switches, access control frames and turnstiles, control room and servers. The handheld and fixed gas detectors shown in Figure 5.1 are the ones used for real-time environmental monitoring in the mock mine. The devices communicate to the control via both wired and wireless communication.

5.2.1.1 S-link

The S-link (also shown in Figure 5.5) is the backbone of the communication of all the sensors for the Schauenburg system (Schauenburg Systems, 2015; Rungani, 2016). The S-link works both as a tag reader and communications hardware. The device is connected to a radio frequency (RF) wave antenna. The RF antenna acts both as a receiver and transmitter of radio signals between active Radio Frequency Identification (RFID) tags. Different mining assets and equipment are assigned unique RFID tags. It is through the communication between the tags and the S-link antenna that the location of assets, equipment and mining personnel is achieved. The S-link is connected to the control room and lamproom via internet cables and fibre optics. The S-link is capable of communicating with the Communications Cap lamps (PTC lamps) wirelessly using wireless RFID (shown in Figure 5.5). Schauenburg Systems (2015, 2016) claim that the radius of communication of the S-link can go up to 200 metres. It is through the PTC lamps that continuous tracking of assets and mining personnel is achieved in the underground environment. Whenever a PTC lamp is in the range of the S-link, the S-link combined with the software associated with it, downloads data from the active PTC lamp and conveys the information to the control room. In the Wits DigiMine Mock Mine there are two S-links, one in the lamproom and the other in the tunnel. However, considering the length of the tunnel and close proximity of the S-links in the Wits DigiMine Mock mine, the range of the S-links was reduced to 3m in order to enable and ensure that the S-link readings would not overlap. Figure 5.5 shows the Wits DigiMine Mock mine tunnel S-Link and lamproom S-link.

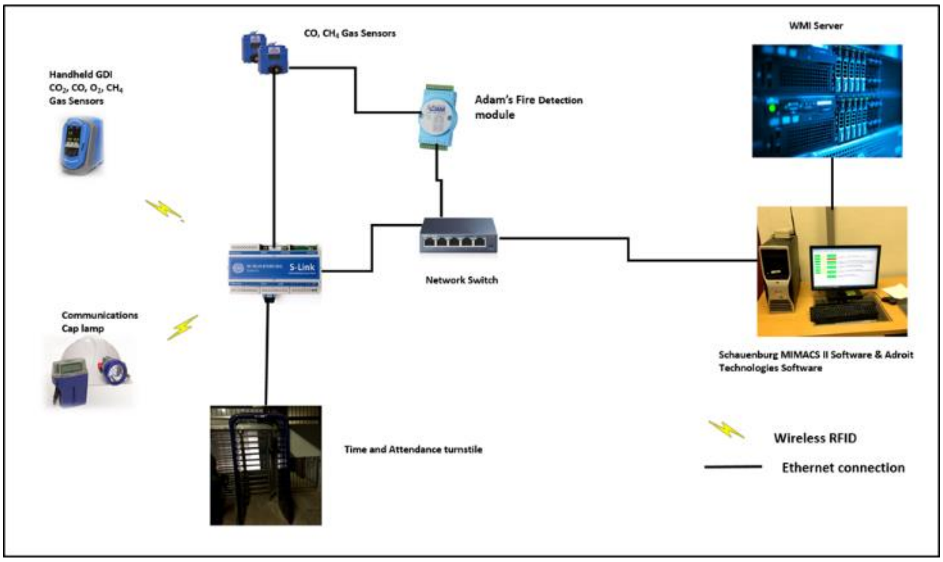


Figure 5.5 Wits DigiMine Schauenburg System Architecture Diagram

5.2.2 Location Monitoring using the MIMACS System

The tracking of the mining personnel location at any given time in the underground environment is very critical, it becomes more important in cases of emergences. The Schauenburg MIMACS offers a tracking capability of mining personnel and assets. Part of the objectives of this research is to determine whether or not it is possible to track miners and assets locations in real-time and relay important health and safety decisions in real-time, thereby putting a distance between mining personnel and hazards.

The Schauenburg MIMACS system is equipped with different software agents that allow it to track the location of both mining personnel and mining assets. There are two agents, namely the tracking agent and the communication agent. According to Schauenburg Systems (2015), the tracking agent is the one responsible for communicating with the S-link via a Local Area Network (LAN). It is through this agent that the tracking events of both assets and mining personnel are gathered and conveyed to the tracking Graphical User Interface (GUI). Another important agent is the communication agent, this agent communicates and controls the S-links. It is through the communication agent that paging and tracking events are handled. Paging involves the sending of pre-coded messages to and from the control room. The communication agent also generates timestamps for all tracking events. The communication agent is also responsible for downloading information from all downloadable RFID devices, in this case the PTC lamps and the Sentinel gas detection instruments.

5.2.2.1 Location monitoring principles

The tracking event of mining personnel or mining asset is initiated immediately after the miner or asset has left the lamproom. The S-link in the lamproom registers the miner or asset through RFID active tags. After the registration of the active tags, the S-link transfers the information to the communication agent. After receiving the information, the communication agent transfers it to the tracking agent. The tracking agent decodes the tag information, and identifies all the personnel and assets in the range of the S-link. The tracking agent updates information from the S-link in every ten to twenty seconds. After identifying the personnel and assets in the range, the tracking agent transfers the information to the tracking GUI. The tracking GUI shows a graphical representation of the location of miners and assets through the tracking zones.

Figure 5.5 and 5.6 show how the tracking GUI displays the tracking event on the Schauenburg MIMACS system. In order to be tracked, an employee must be in the tracking zones. Tracking zones can be referred to as radio frequency zones in which an employee or asset can be tracked using an S-link and the MIMACS software. For the MIMACS software, tracking zones can have a radius of up to 100 metres, but in the case of the Wits DigiMine mock mine the radius was reduced to 4 metres. This was done to ensure that the radius of the two S-links in the Mock mine do not overlap since the separation distance between the two S-links is less than 100m. During a tracking event, when a miner enters the tracking zone, the S-link creates a First seen log. This log indicates the exact time a miner’s PTC lamp or asset as picked up by the RFID reader.

The S-link is set up in such a way that it continuously searches for an asset or miner within its radius after every few seconds. Once an asset or worker cannot be located by the S-link, this then serves as an indication that the asset or the miner is out of range. At this point the S-link creates a last seen log that shows the time in which a certain asset or miner was last seen within the radius of the specific S-link. All this information is continuously relayed to the MIMACS database located in the control room. The information that is relayed to the database allows for the MIMACS software to generate location and asset movement reports. The reports include the following (Schauenburg 2015; Rungani, 2016):

- Person Tracking History Report;
- Last Person Location Report;
- No Person Movement Report;
- Asset Movement History Report;
- Last Asset Location Report;
- No Asset Movement Report.

The aforementioned reports are useful in cases of emergencies and accidents, because they can assist management and rescue teams to locate miners. With regard to the assets knowing their exact locations at any specific given time can increase their utilisation and ultimately increase production.

5.2.3 Testing the Location monitoring functionality of the MIMACS System

In order to test the real-time location monitoring functionality of the MIMACS system, the researcher selected four PTC Lamps for the exercise. The test was conducted in the Wits DigiMine Mock Mine. The results were displayed in the DigiMine control room on a dedicated personal computer (PC) that has the MIMACS software installed in it.

5.2.3.1 Location Monitoring Fundamentals

The tracking of personnel was done through using the active RFID tags embedded in the PTC Lamps. The results of the tracking event are shown on a tracking application software (Figure 5.6 and Figure 5.7) that is installed on a computer in the control room.

The top left corner in Figure 5.6 shows the number 10 enclosed right above the Wits University information bar, it represents the total number of the trackable assets which are registered under the Wits DigiMine. The MIMACS system updates this number after seven days (varies depending on mine preference). The seven day allowance is given to cater for absence of trackable assets due maintenance. The reduction in number of assets from 10 signifies that an asset or assets have not been in the vicinity of the mock mine for seven days. The number 10 right above the Wits Lamproom information bar (Figure 5.6), represents the number of trackable assets or miners in the Wits Mock mine lamproom. The number was set to update after three days. The change in the number signifies missing assets in the lamproom. The reasons for the change in the number can range from (but not limited to) maintenance, repairs and theft. The number 4 right above the Wits Tunnel information bar (Figure 5.6) represents the number of miners or assets which are underground or in the tunnel at any given time. The number was set to update at the beginning and at the end of shifts. Control room operators were the ones who set the different times in which each information bar would be updated.

5.2.3.2 Location of Personnel and Assets Scenario One Results

The S-Links are the major components of the tracking system that aid in locating personnel. There are two S-links in the Wits DigiMine Mock Mine, one located in the lamproom and another in the tunnel (Figure 5.8). On the tracking application, the two S-links are the lamproom S-Link and tunnel S-Link (Figure 5.6 and Figure 5.7)**.** Figure 5.6 shows the results from the tracking of the four PTC Lamps from the lamproom into the tunnel area of the Mock Mine. The tracking location symbol used either a green or blue colour codes to indicate the absence or presence of miners or assets in the tracking zones. Whenever there were people (PTC Lamps) in the radius of a specific S-link, the green code would indicate their presence. If there were no miners or assets in the radius of a specific S-link, the blue code would indicate this. From Figure 5.6, the lamproom S-link tracking symbol shows a number 4 and the tunnel S-link is shows a zero. The number 4 on the lamproom S-link tracking symbol shows that there four PTC Lamps in the proximity of the lamproom S-link. The zero on the tunnel S-link tracking symbol shows that there are no PTC Lamps in the tracking radius of the tunnel S-link. As the miners (PTC Lamps) moved towards and away from the lamproom, the number would change. The S-Links updated the number of miners or assets within their tracking radii after every ten seconds.

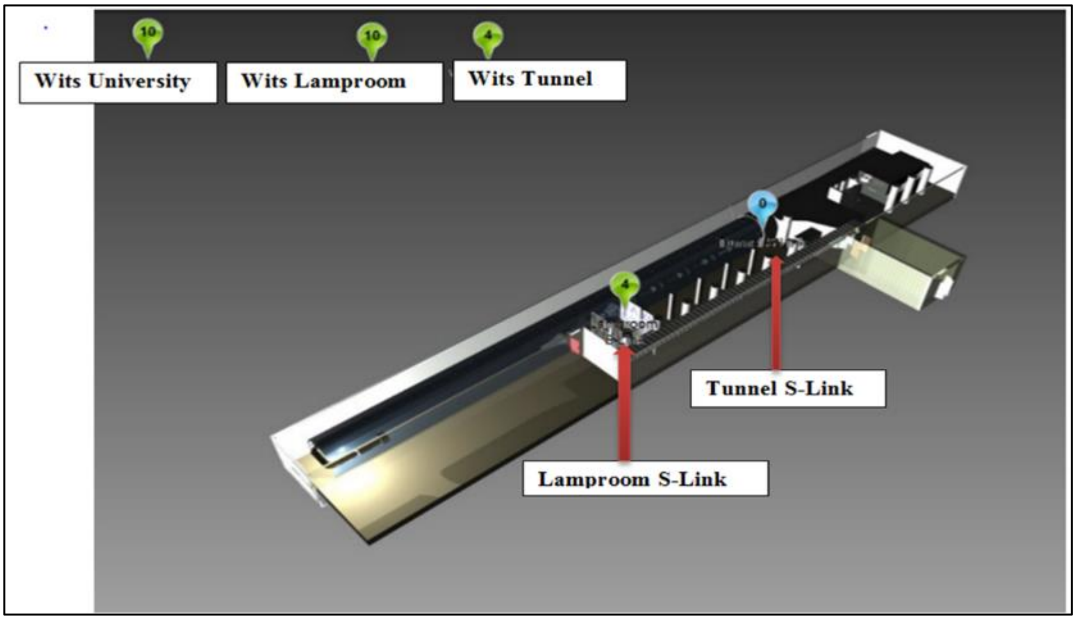


Figure 5.6 Tracking Incident in the Wits DigiMine Mock Mine

The MIMACS database created time logs for the last seen of the PTC Lamps during their movements in the tunnel. Table 5.1 shows the names of the Four PTC Lamps in the proximity of the lamproom S-link. The location report generated from the MIMACS software shows that PTC Lamps, namely 002S, 004S, 008S and 009S were in the proximity of the lamproom S-link during the tracking event. The report also shows the employee numbers allocated to each particular PTC Lamp. The first column of Table 5.1 shows the timestamp for each of the PTC Lamps in the radius of the lamproom S-link.

Table 5.1 Showing the Timestamps, Employee Numbers, Names and Specific Locations

MIMACS-II **Location Report** **Wits University**

Start Time = 2019-09-22 09:18:17 End Time = 2019-09-22 10:04:11 Location = lamproom-slink

Enter Time	Employee Number	Name	Section	Shift
2019-09-22 10:04	208282417713	009 S.	2	Default Access Time Pattern
2019-09-22 10:04	208282419037	008 S.	2	Default Access Time Pattern
2019-09-22 10:04	208282418412	002 S.	2	Default Access Time Pattern
2019-09-22 10:04	208282366548	004 S.	2	Default Access Time Pattern

5.2.3.3 Location of Personnel and Assets Scenario 2 Results

In order to check the effectiveness of the system in showing the number of assets at a specific given time, seven trackable assets were removed from the lamproom for a period of seven days. After seven days the number of assets on the tracking application reduced from ten to three **(**Figure 5.7). Figure 5.7 shows that the lamproom assets are the same as the total Wits assets, this is because all the Wits DigiMine trackable assets are stored in the lamproom hence the Wits University and the lamproom information bars in the tracking application always show the same value after seven days. However, the difference between Wits University and lamproom information bars is that, the lamproom information bar updated from ten assets to three after three days whereas the Wits University one updated after seven days.

Another important aspect of the Schauenburg tracking system that was tested, was finding the location of a trackable asset that was not in the radius of either of the lamproom S-link or the tunnel S-link. This scenario is shown on the tracking application (Figure 5.7). From Figure 5.7 it can be seen from the information bar that there is one trackable asset or miner in the tunnel. However, neither the lamproom S-link nor the tunnel S-link is showing that the asset is in their vicinity. Both the lamproom and tunnel S-Links are recording a zero (0) on their tracking symbols. However, in-between the two S-links there is **1** encompassed in a green square tracking symbol (Figure 5.7). This results shows that the DigiMiner is directly in the middle of the two S-links hence they cannot be identified to be closer to any of the two S-links. This is so because the S-links do not necessarily pin-point the actual position of an asset or miner but only shows that the miner or asset is within the RF tracking zone of a specific S-link.

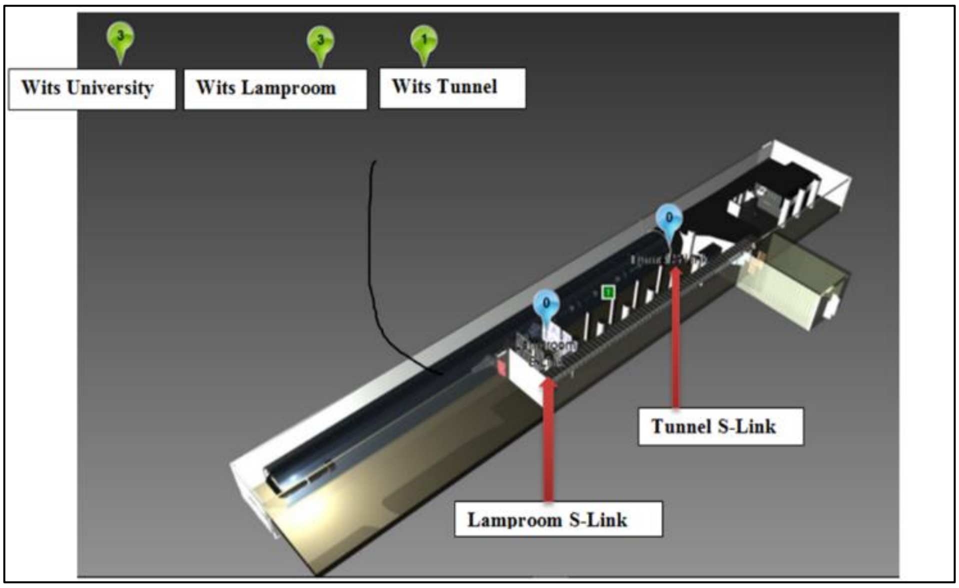


Figure 5.7 Tracking event 2 in the Wits DigiMine Mock Mine

Figure 5.8 showing the Schauenburg Lamproom S-link (1and 2) and Tunnel S-link (3 and 4)

5.2.4 Conclusions on the Schauenburg Location Monitoring

The testing of the real-time location monitoring functionality of miners and assets in the Mock Mine showed that the system is functional. This is a great stride towards achieving zero harm. However, the downside of the Schauenburg MIMACS system found during the tests is that it does not give the exact location of the miner but instead gives a radius in which the miner is located. To solve this problem, integrating the system with a GIS system or any other system which gives co-ordinates, will enable the exact location with co-ordinates for the miner or asset. This will go far in putting an exact distance between miners and risks particularly in times of accidents or emergencies. However, regardless of its limitations, the Schauenburg System could have helped in locating the miners who lost their lives in the incident discussed in Case Study 3 elaborated in Section 4.3 of this dissertation. Using a system like the Schauenburg MIMACS can also help mine management and control room operators to track and warn mining personnel whenever they approach or are in proximity of restricted or abandoned working areas.

Combining the system with a real-time atmospheric monitoring system can also enable control room operators to warn and order miners to withdraw from dangerous workings. If the Section 23 incidents have a trace record in the form of a report in the system, it can help both mine management and miners in investigations. Conflict can be minimised between the different parties. The abandoned or restricted areas can also be geofenced to ensure that clear warning signals are sent to the miners before they enter or are approaching these areas and this can go a long way to prevent avoidable accidents.

5.3 Testing for Real-time Gas Monitoring Functionality of the MIMACS System

Real-time gas monitoring is another important functionality of the Schauenburg MIMACS system. Testing for this functionality was critical for this research in order to ascertain the effectiveness of this particular system in helping to improve health and safety in underground mines. There are various components installed in the Wits DigiMine Mock mine for testing the effectiveness of ventilation systems in typical underground environments, in cases of a gas event. Figure 5.8 shows a brief overview of some of the systems installed. An effective real-time gas monitoring system allows for the easy and safe withdrawal of miners from areas where harmful gas build-ups are detected. There are a number of components that make up the Schauenburg real-time gas monitoring system (Figure 5.9).

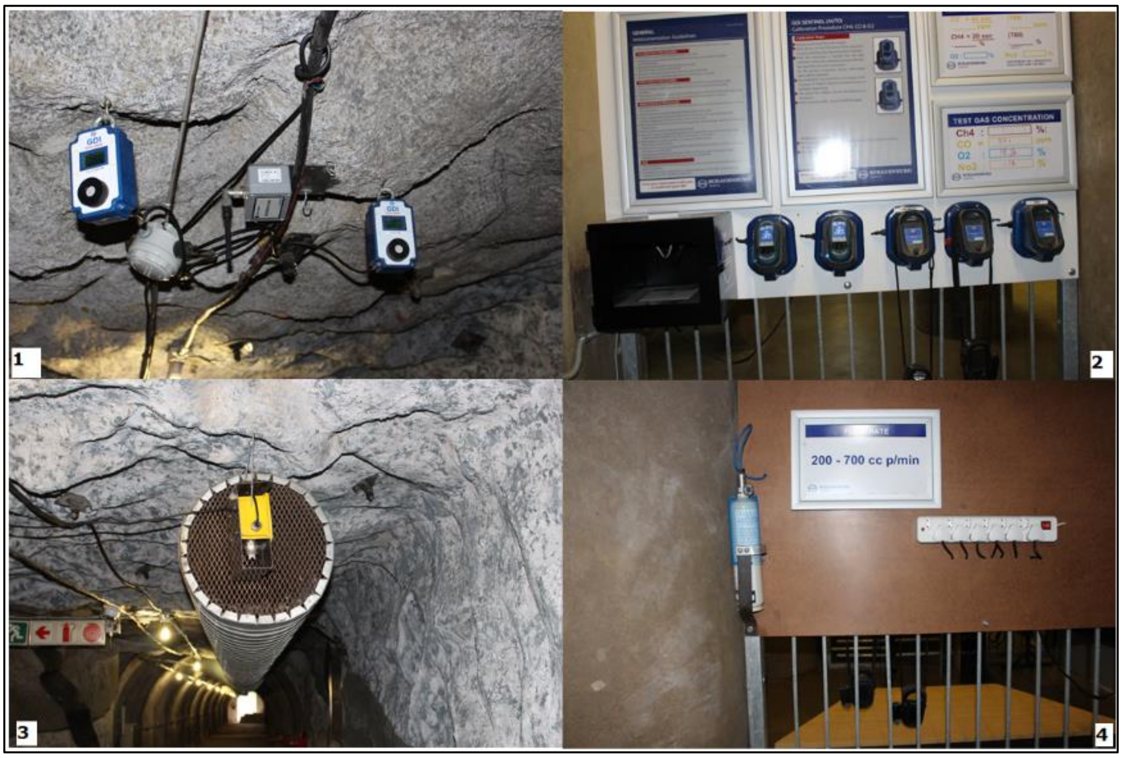


Figure 5.9 Mine Ventilation Systems installed in the Wits DigiMine Mock mine (1) Fixed Gas Detectors (2) Sentinel Handheld GDI (3) Velocity Meter on an ventilation duct (4) Methane Calibration Gas Canister

However, the main components for real-time gas monitoring using the Schauenburg MIMACS system are, the Handheld Sentinel GDIs (Figure 5.10), the PTC lamps (5.11) and the S-links. The GDIs are the ones that detect the gas build-ups and both the S-links and PTC lamps work as the communication platforms. The GDIs are equipped with three gas sensors namely methane, carbon monoxide and oxygen. These sensors are programmed to set out alarms when certain threshold limits for gas concentrations are reached. The threshold limits for each gas are set according to the Department of Mineral Resources and Energy regulations. The alarms come in threefold, namely audio, visual and vibrations. Each gas is assigned a different colour code for the visual alarms (Schauenburg Systems, 2015).

Figure 5.10 Sentinel Handheld GDI (1) on a table, (2) charging

Figure 5.11 PTC Lamp

Similar to location monitoring, the real-time gas monitoring for the MIMACS system is facilitated through the use of RFID active tags. The communication pathway of the gas monitoring is also done via the S-link to the control room MIMACS database. The real-time gas data is downloaded from the GDI. When the GDI raises an alarm, the alarm gas interception message can be transferred to all the nearby PTC lamps. This feature only works when both the GDI and the PTC lamp are in the same radio frequency range or S-link radius.

Before using a Sentinel GDI, it is important to ensure that the device is tested and calibrated. The Sentinel GDI testing and calibration process is fully automated and it is directly linked to the radio frequency communication line. This means that, during the testing and calibration processes, data is directly conveyed in real-time to the control room through the S-link. In addition to the RFID active tags used for real-time gas monitoring, the GDIs are also equipped with RFID passive tags, and these tags are mainly used for asset management and real-time fire patrols. The real-time fire patrol functionality of the Sentinel also uses the S-link channel to send warning alarms to the control room.

The threshold limits for the gas alarming are set according to the mandatory Codes of Practices (COPs). The COPs state that underground mining personnel must be withdrawn from any section where 1% of methane gas is detected. The COPs also state that, 100ppm of carbon monoxide is the maximum concentration (threshold limit) when encountered, miners must evacuate to a safe place. For oxygen, the threshold limit was set to a minimum of 18%, below which, miners must be evacuated from their workings to a safe place (Schauenburg Systems, 2016).

The Sentinel GDIs are set such that, for every threshold limit, an alarm is set. Each of the gases is assigned a colour code using different coloured light emitting diodes (LEDs) installed on the GDI. The colour code for methane alarms for concentrations above 1% is red. The alarming threshold limits for carbon monoxide and oxygen were altered from the COP guidelines to 50ppm and 21% respectively. For oxygen concentrations below 21%, blue LEDs are used as alarms and for carbon monoxide concentrations from 50ppm going upwards, yellow LEDs are used. The alarms for these gases are set, such that the GDI will only stop the alarm when the gas levels go back to concentrations within the set threshold limits. For methane concentrations above 1%, the red LEDs visuals are accompanied with loud alarming sounds and GDI vibrations (Schauenburg Systems, 2015).

The MIMACS database also records a number of reports for the real-time monitoring system. The reports come along with timestamps for every gas event, from testing and calibration of the equipment to the different gas measurements. The reports are downloaded in the control room where the MIMACS server database is located. This system does not only allow the monitoring of gas levels and trends in different sections of the mine, but also allows for the easy regulatory inspections from the DMRE for compliance in gas monitoring and reporting. This is most helpful in cases of investigations of gas incidents or accidents. The server allows for searching and downloading of reports from any day and time, to as long as years before. The gas concentrations in the reports are represented as graphs (Schauenburg Systems, 2015).

5.3.1 GDI Calibration

Prior to the testing of the system, the GDI calibration was carried out. Figure 5.12 (1) shows an uncalibrated and untested GDI with a blinking red LED. Figure 5.12 (2) shows the GDI after testing and calibration. On the display screen of the calibrated GDI (Figure 5.12 (2)) there are messages showing that the calibration for both methane and carbon monoxide was successful. The testing of the GDIs was done using the gas canister (Figure 5.12 (3)). The calibration results were recorded in the MIMACS database as shown in Table 5.2. From the results the name of the equipment, the date and time on which the equipment was calibrated is shown. The report allows for checking for calibration compliance of every piece of equipment used underground. It was also possible to get a history of the equipment calibration as shown in Appendix A.

Figure 5.12 showing an uncalibrated GDI (1); calibrated (2) GDI; calibration gas canister (3)

Table 5.2 GDI Calibration report

MIMACS-II — **Sentinel GDI Calibration Report** — **Wits University**

Start Time = 2019-09-01 14:23:49 | End Time = 2019-09-30 14:23:49 | Selection = [Summary] | Lamproom = [No Filter]

Equipment Id	Serial	Equipment Type	Last Calibrated	Outcome
SEN001		Sentinel GDI	2019-09-26 11:48	pass
SEN002	15215	Sentinel GDI		
SEN200000336F		Sentinel GDI		

5.3.2 Testing the gas monitoring system

To test for the real-time gas monitoring component of the MIMACS system, a butane gas source was used in the place of methane. The researcher did not use methane because of the danger posed by the explosive nature of the gas. The reason of choosing butane was that the sensors used for detecting methane gas are exactly the same as that of butane. A cigarette lighter was used as the gas source. The lighter was placed close to the GDI and was allowed to disperse butane gas into the air until the gas concentration readings on the

GDI were above 1%. The test was carried out in the Mock Mine Tunnel, a few metres from the lamproom. Immediately after getting a gas reading above 1%, the GDI alarmed. The GDI vibrated, rang an alarm very loudly and also showed a flashing red LED (Figure 5.13).

The PTC lamp which the DigiMiner was carrying during the test also made an alarming sound, accompanied with a red flashing LED on the lamp. Figure 5.13 (1) shows the flashing red LEDs. Since the GDI which detected the high gas (butane/ methane) concentrations was in the proximity of the lamproom S-link, all the PTC Lamps in the RF zone of the lamproom S-link received the high methane gas concentration signals and triggered their alarms (Figure 5.13 (3)). On each and every display screen of the PTC lamp which was in the S-link range, a message which read '*Methane (CH4) Evacuate'* appeared (Figure 5.13 (2)).

The high gas concentration warnings and values were sent directly to the MIMACS database in the control room via the S-link. The GDI and the other corresponding alarms on the nearby PTC lamps only stopped when the miner evacuates to an area where there was clean air within the allowable safe gas concentrations. The red LEDs on the PTC Lamp pager only stop flashing when the miner sends the methane evacuation message to the control room. Figure 5.14 summarises how the Sentinel GDI, S-link, PTC lamps and the MIMACS database in the control room communicate.

Figure 5.13 Methane gas alarm (1), 'Methane (Ch4) Evacuate' message on PTC Lamp (2), Nearby PTC Camp alarming (3)

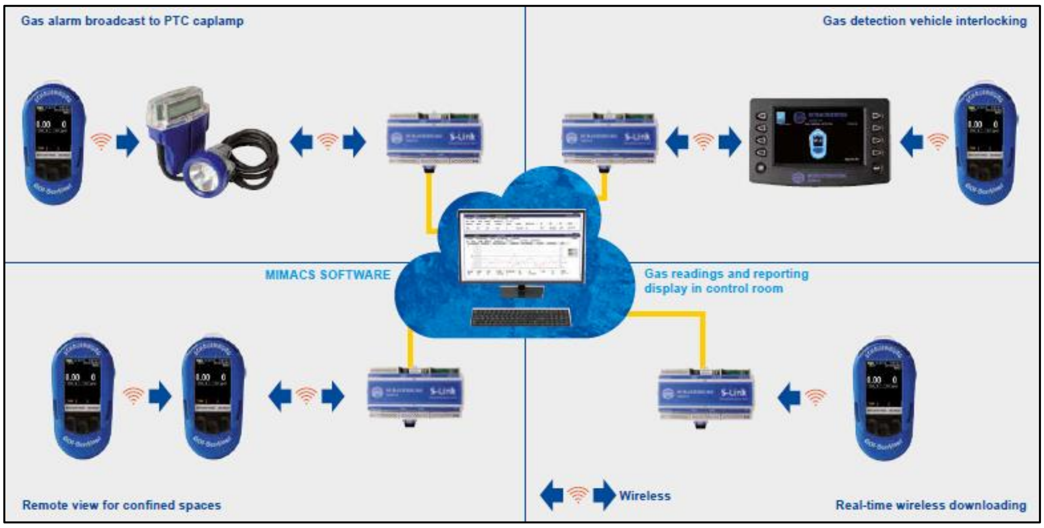


Figure 5.14 Summary of how the Schauenburg Handheld Gas Detection works (Pretorius & Blaauw, 2018)

5.3.3 Conclusions on the Real-Time Gas Monitoring

From testing the real-time gas monitoring functionality of the Schauenburg MIMACS, the system showed that it is capable of monitoring gas in in real-time. The Schauenburg MIMACS system also showed that it is capable of warning all the miners with communications devices in the proximity of the gas event. Using such a system could have prevented some of the fatalities discussed in the case studies in chapter 4 of this dissertation.

The system can also be integrated to other environmental and atmospheric (e.g. temperature, humidity and dust) monitoring systems, such that miners underground can be more informed on the risks they face underground. This can help in implementing Section 23 of the MHSA. In this case, in the event of dangerous gas build-ups, miners can easily withdraw from dangerous workings and there will be evidence to back up the reason to their withdrawals and actions. Fixed real-time gas and environmental monitoring can also inform production supervisors and management if it is safe to send miners to some areas by remotely checking the environmental and atmospheric conditions remotely.

5.4 Testing the Minetec Location Monitoring System

The Minetec system is one of the leading systems in mine asset and personnel tracking in underground mines. The system is a product of Minetec a division of Codan Limited. The company's headquarters is in Australia but opened a subsidiary (Minetec RSA Private Limited) in South Africa in 2015 (Minetec, 2015). The Minetec system being a leading practice, it forms to be part of the systems installed in the Wits DigiMine mock mine. The Minetec system installed in the mock mine encompasses three of the four themes currently being researched at DigiMine. These themes are, wireless communication; health, safety and security; and system integration for smart mining.

Under wireless communication, the DigiMine research group tries to understand how the communication devices and the reference nodes installed in the mock mine communicate, and how the information is presented in the control. Under the second theme for health, safety and security, the research focuses on the real-time and intelligent asset and personnel monitoring and control system functionalities of Minetec. The research under the third theme deals with the Minetec system capabilities of being integrated with other systems available in the DigiMine mock mine.

5.4.1 Technology behind the Minetec System

Like any other systems, the Minetec system is made up various components. The main system installed at Wits DigiMine is the Minetec TRAX. The Minetec TRAX is the system responsible for real-time personnel and asset tracking in underground mines. The Minetec TRAX is unique compared to the other available underground real-time tracking systems in the sense that it does not use RFID as the underlying technology for both tracking and communication. It uses a technology called Wireless Ad-hoc System for Positioning (WASP). The WASP technology was developed by Australia's national science research agency called the Commonwealth Scientific and Industrial Research Organisation (CSIRO).The WASP technology integrated into the Minetec TRAX allows for wireless data communication and high-precision tracking**.** The high-precision tracking offered by the WASP technology allows for the pin-pointing of an asset or mining personnel location within about half a metre accuracy in an underground environment (Commonwealth Scientific and Industrial Research Organisation, n.d.; Sathyan, et al., 2011). Combining the tracking with a real-time data communication capability makes the system capable of improving safety in underground mines and ultimately makes the goal to zero harm achievable.

In order to achieve its system functionality the Trax tracking system uses mobile tags (mobile nodes) attached to vehicles or mining personnel together with a series of reference nodes placed at known locations around the area being monitored (Gardiner & Fenelon, 2018). The Trax reference nodes communicate wirelessly, calculating the arrival time of signals, allowing the system to accurately track the location and speed of objects as they move through an underground mine. The technology is also useful in emergency evacuations, were it can be used to locate miners and help in directing them to safe areas. Using the reference nodes positions, the mine can be demarcated into different occupancy zones, which allow for it to classify the locations of every mining personnel or asset (Gardiner & Fenelon, 2018).

According to Minetec (2017), the WASP sensors' software run on both Wi-Fi (2.4GHz) and WASP (5.8GHz) frequencies which allow these sensors to work as digital processors and as well as an Inertial navigation system (INS). An INS is "an autonomous system with good concealment, which is not dependent on any external information, nor radiates energy to external space, making it applicable in airspace, sea, or underground" (You, 2018, p233). These navigational systems are capable of calculating positions, either relative to some reference system/point or to absolute coordinates (You, 2018). The WASP algorithms that run on the Minetec system use the Time of Arrival (TOA) technique to measure the accurate distance measures between mobile assets or miners and reference nodes (Minetec, 2017).

The TOA technique is based on calculating the exact time a radio signal is sent from a target (miner or asset), the exact time the radio signal arrives at the reference point, and also the speed at which the signal travels between the two points. Using the time (usually to a fraction of a nanosecond) and speed (usually the speed of light) the distance between the reference point and the target (asset or miner) can be calculated (O'Keefe, 2017). The reference points are surveyed using conventional underground survey techniques to establish the co-ordinates, and during the tracking of the mobile assets or miners, their co-ordinates are then calculated using the ones of the known points through the application of the TOA technique (Sathyan, et al., 2011).

Using principles similar to the outdoor or surface positioning systems such the Global Positioning System (GPS), the Minetec Trax system allows for the tracking of assets and miners in real-time with options of displaying the results on either a two dimensional (2D) or three dimensional (3D) maps. The maps can be viewed from a control room computer or a rugged In-vehicle-Personal Computer (IVPC) or tablet which can be mounted on a mobile vehicle or carried by mining personnel (Minetec, 2017).

In order to visualise the tracking events, a number of softwares namely MineOffice, 3D MineView, Mobile Minetec Client and Mine Control, must be installed on a the Minetec Server in the control room or network. All reference nodes are connected to the Minetec server via a mesh gateway. The mesh gateway allows the individual nodes to communicate wirelessly with the Minetec server. It is through the mesh network gateways that data can be send back and forth the Minetec server and the nodes (Gardiner & Fenelon, 2018).

5.4.2 Components of the Wits DigiMine Minetec System

There are a number of hardware pieces installed in both the Wits DigiMine mock mine and the control room that enable the Minetec system to be able to track mining personnel and assets. The key components for the Minetec TRAX system are the, mobile nodes (tags), reference nodes, mesh gateway and the software installed on the Minetec server. There is only one mobile node in the mock mine (Figure 5.15).

Figure 5.15 Minetec Mobile Node

Along the length of the Mock mine tunnel, four reference nodes (Figure 5.16) are also installed. The reference nodes are mounted on the sidewalls and the roof of the tunnel (Figure 5.17). The four reference nodes were surveyed using a Total Station to establish the co-ordinates of each. The co-ordinates of the reference nodes form the basis on which the location of the assets and personnel during the tracking is established.

Figure 5.16 Minetec Reference Node mounted in the Mock Mine Tunnel Roof

Figure 5.17 Four Minetec Reference Nodes at Different locations in Mock Mine Tunnel

All the four reference nodes are linked to the Wits network and Minetec server in the control via a Minetec Meshing gateway (Figure 5.18). In cases of a power outage, the Minetec reference nodes and the mesh gateway are powered by an Uninterrupted Power Supply (UPS) (Figure 5.19 (2)) device installed directly outside the mock mine lamproom and stored in a secured Minetec box (Figure 5.19(1)). The Minetec box also houses a rugged In-vehicle-Personal Computer (IVPC) shown in Figure 5.19 (3).

Figure 5.18 Minetec Mesh MineGateway

Figure 5.19 Minetec box (1) housing an Uninterrupted Power Supply (UPS) (2) and Rugged In-vehicle-PC (3)

In addition to the devices installed in the tunnel, there is also a dedicated computer (Figure 5.20) in the DigiMine control room which houses the Minetec TRAX tracking server and the tagboard server. The two servers housed in the computer are supported by Minetec software namely the MineOffice, 3D MineView and Minetec Mobile Client (MMC) and Mine Control-ALF to achieve the system functionalities. The MineOffice software acts as database for the Minetec system. The MMC application software allows for a continuous real-time tracking for the assets and personnel.

The 3D MineView Software enables the tracking event to be displayed on a map overlay of the DigiMine mock mine tunnel. The software supports both 2D and 3D map visualisation of all the assets showing the (X, Y) or (X, Y, Z) coordinates of each asset in every selected area. The tagboard server can also subdivide the mine into different tracking zones and allows to visualise each asset in every area. Assets or mining personnel can be assigned to different tracking zones such that when an asset or mining personnel is in an unauthorised zone it will be shown on the map.

Figure (5.21) is showing a tagboard on the tracking application with different predefined signs allocated for certain zones and zone violations. This functionality makes it easier to know if the asset or miner's location is authorised and the mine can also demarcate safe and unsafe areas using this functionality.

Figure 5.22 summarises the way the DigiMine Minetec system is connected and how data is transmitted between the sensors in the DigiMine tunnel and the Control room

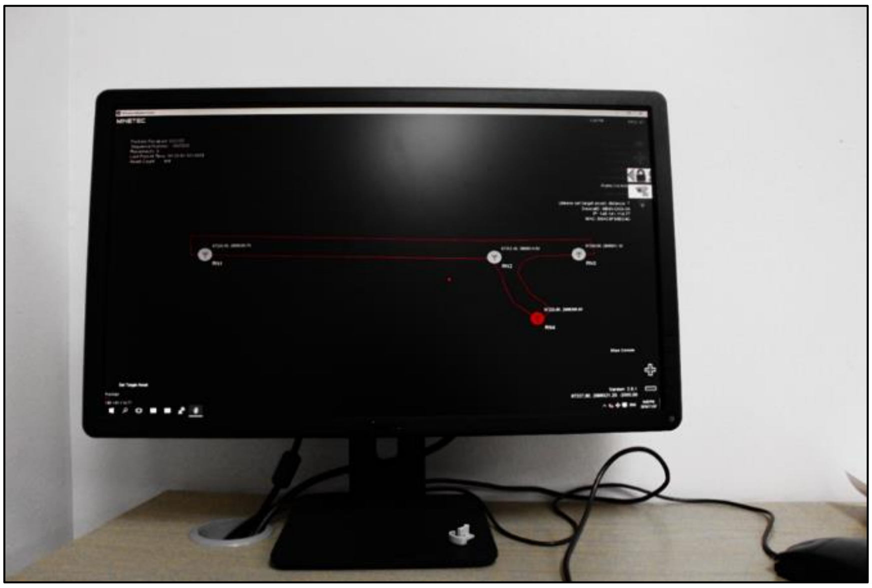


Figure 5.20 DigiMine Control Computer housing the Minetec Server

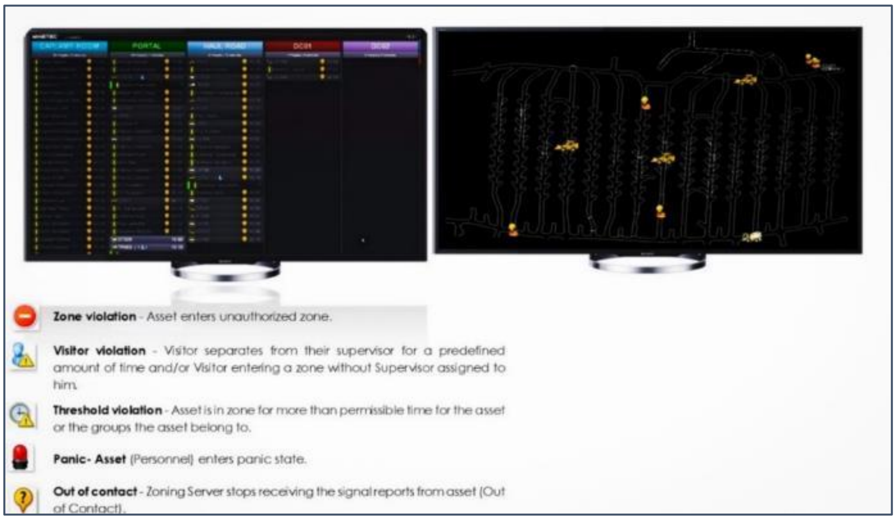


Figure 5.21 Minetec Tagboard Tracking Zones (Gardiner & Fenelon, 2018)

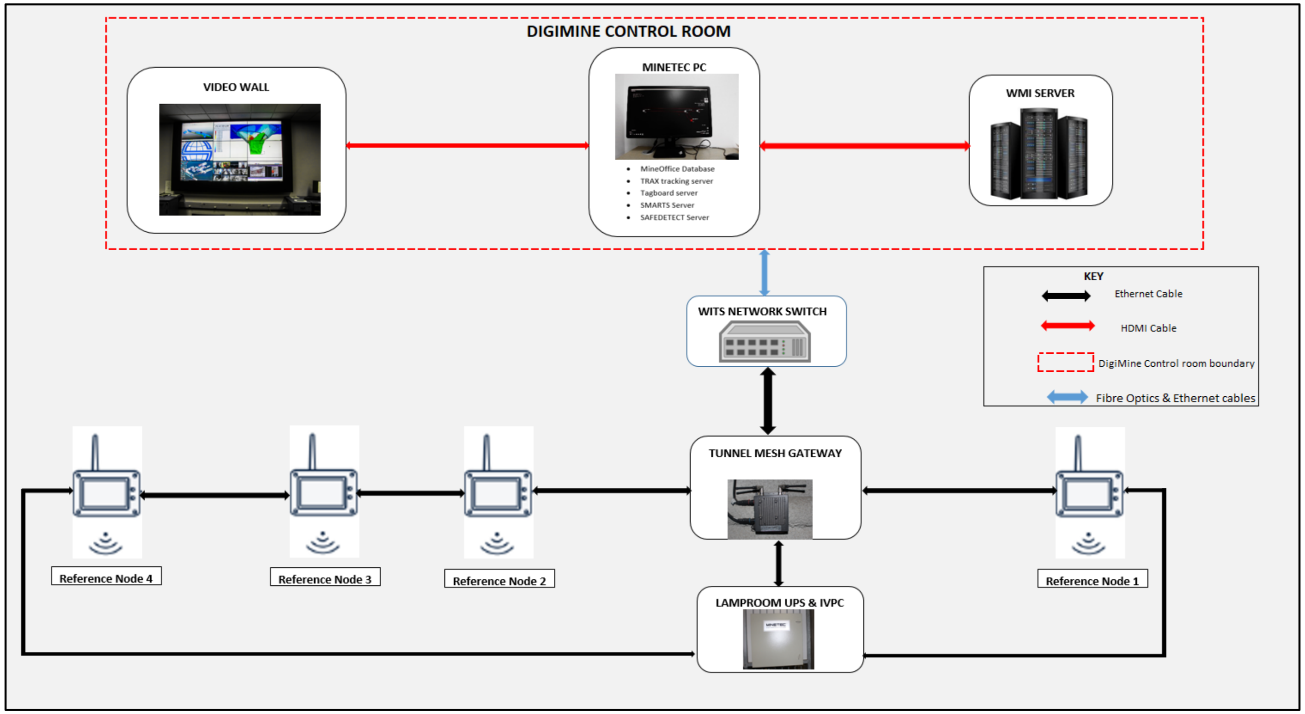


Figure 5.22 DigiMine Minetec System Architecture Diagram

5.4.3 Findings from Testing the Wits DigiMine Minetec TRAX System

To be able to track using Minetec, a trolley (Figure 5.23 (1)) was used as the mobile asset. The mobile node and the IVPC (Figure 5.23 (2)) were placed in the trolley. The Researcher (Figure 5.24) pushed the trolley across the length of the tunnel during the tracking. In order to record the continuous real-time movement of the trolley during the tracking event, a video camera was setup to record the screen of the MineView tracking application in the control room.

The MineView 2D map (Figure 5.25) shows the DigiMine mock mine map and the location of all the four reference nodes. The four reference nodes are labelled RN1, RN2, RN3 and RN4 as shown in Figure 5.25. Right above each reference node their x and y co-ordinates are shown. The screenshot shown in Figure 5.26 shows the 2D map before commencing the tracking of the trolley. The tracking event was initiated close to RN3. For the test the Mobile node was assigned a name WITS001. Figure 5.26 shows the symbol of a yellow truck named WITS001 just activating the mobile node. From the screenshot, the (X, Y) co-ordinates of the node with reference to its position in the tunnel is clearly shown. As the trolley (WITS001) starts moving towards RN2, it can be seen in Figure 5.27 that the (X, Y) co-ordinates of WITS001 are also changing and also the position of the trolley on the map. Figure 5.28 further shows the trolley's location as it passes RN2 moving towards RN1 at the other end of the tunnel. Figure 5.29 also shows WITS001's position as it approaches RN1. The screenshots show that using the Minetec TRAX software it is possible to pinpoint the exact location and position of an asset or mining personnel. It is also easy to relate this location with the reference nodes position in the mock mine.

Figure 5.23 Trolley (1) used to carry the In-Vehicle-Personal Computer (IVPC) (2)

Figure 5.24 Researcher pushing the trolley during the tracking

The Minetec system offers a number of health and safety solutions for underground mines. With the Minetec TRAX system it is possible to continuously pinpoint a miner or an asset exact location with high precision in real-time. It is also possible to subdivide a mine into tracking zones. These functionalities can help a long way in solving the problem of miners going into unauthorised areas as well in emergency rescue operations, as the exact location of the miners can be found. The implementation of Section 23 of the

MHSA is also made easy, and this can save a considerable number of lives as well as eliminate the blame game between management and miners, as it will be very clear on the tagboard reader, where every miner and piece of equipment is allocated to go and work in a specific shift. As previously shown in Figure 5.22, the tagboard reader is capable of showing any piece of equipment or mining personnel violating the rules and going into any unauthorised area. The tagboard reader is also capable of alarming when someone or an asset has overstayed in a certain zone signifying any danger. However, the Minetec system does not offer atmospheric monitoring and this brings back the importance of how it is important to integrate it with other systems for example the Schauenburg System. Integrating different systems allows for the systems to capitalise on the different synergies brought about by the overall systems together covering over of each's weaknesses.

Figure 5.25 DigiMine tunnel 2D Map View on the Minetec MineView Application before a tracking event

Figure 5.26 showing the location of the Trolley (WITS001) moving from Reference node RN3 towards reference node RN2

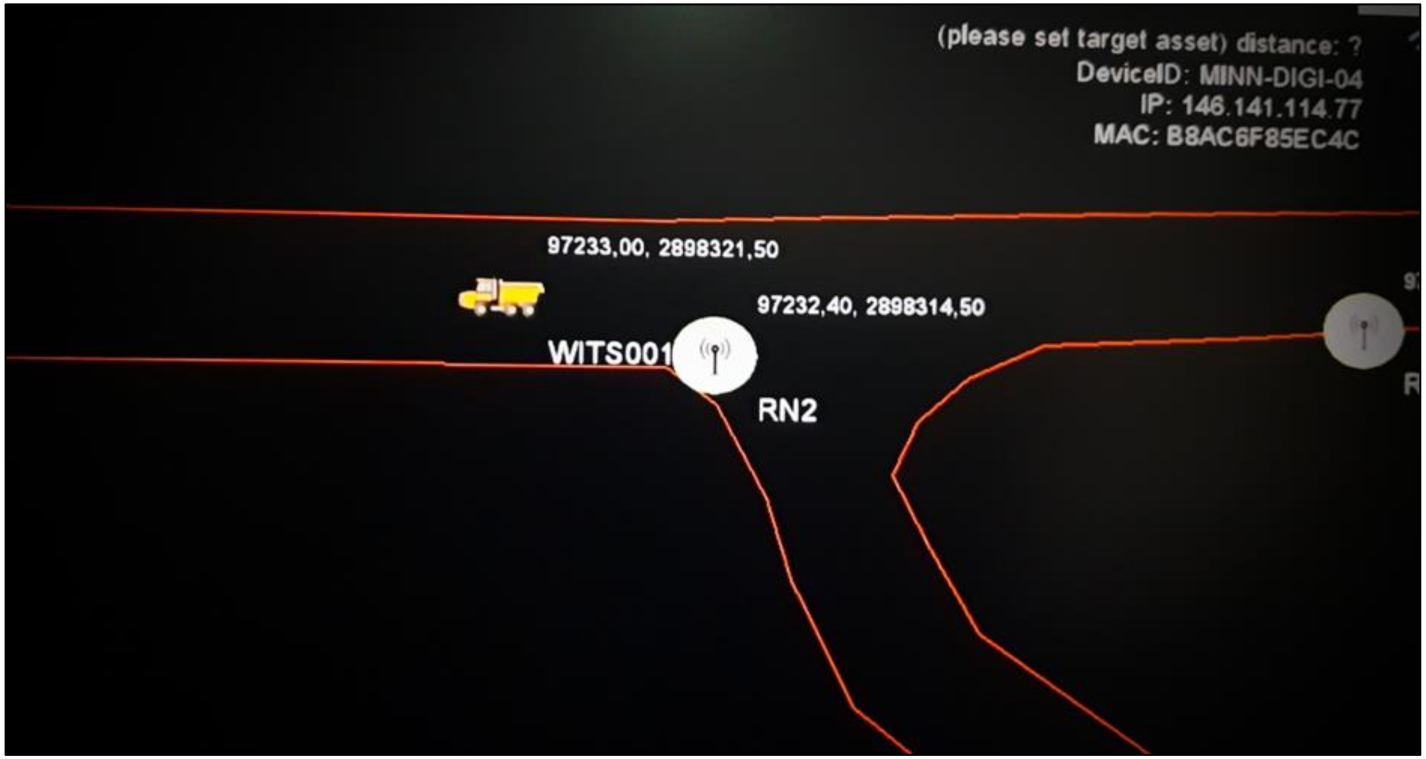


Figure 5.27 showing the location of the Trolley (WITS001) just after passing Reference node RN2

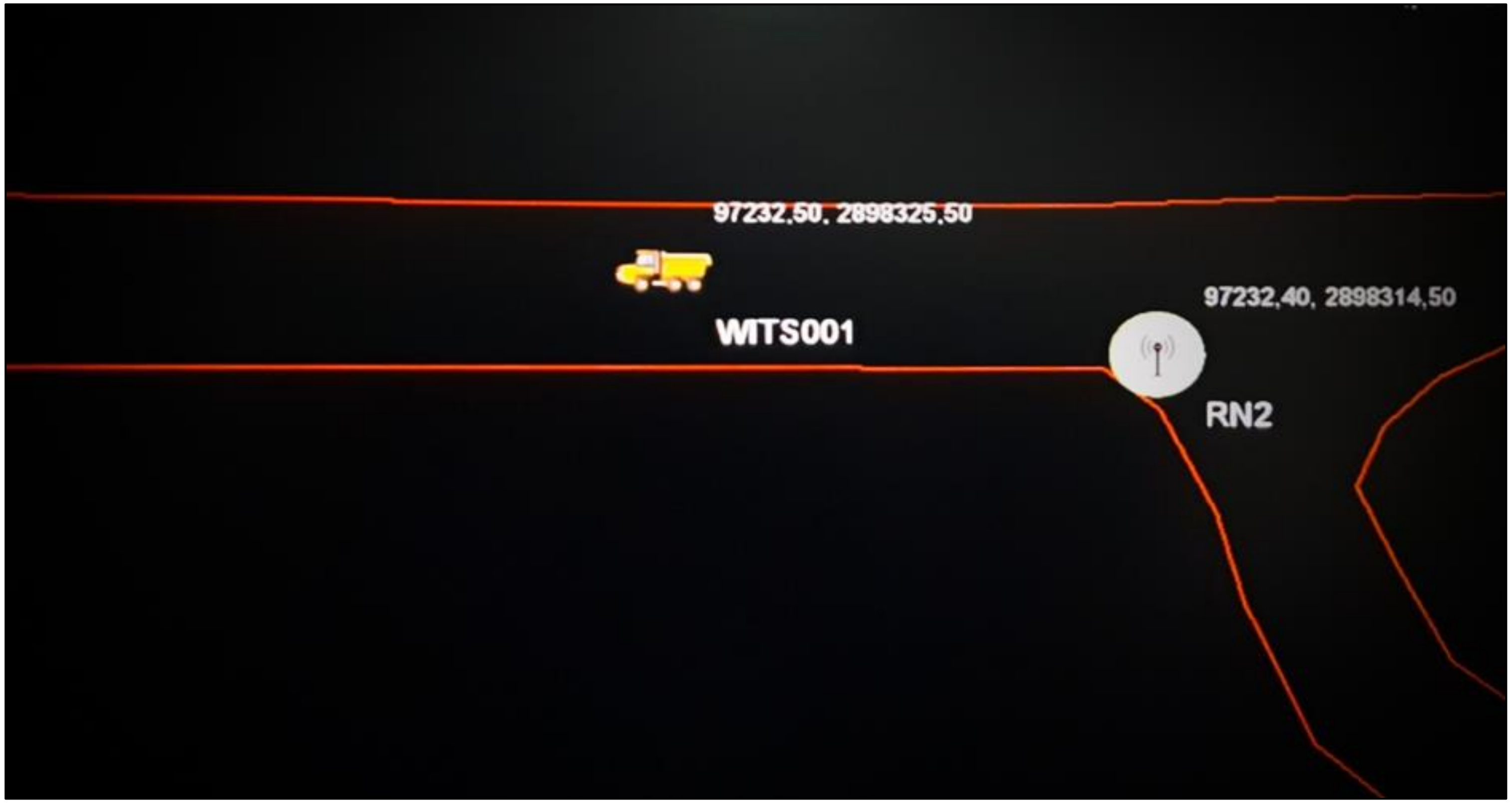


Figure 5.28 showing the location of the Trolley (WITS001) moving away Reference node RN2 towards reference node RN1

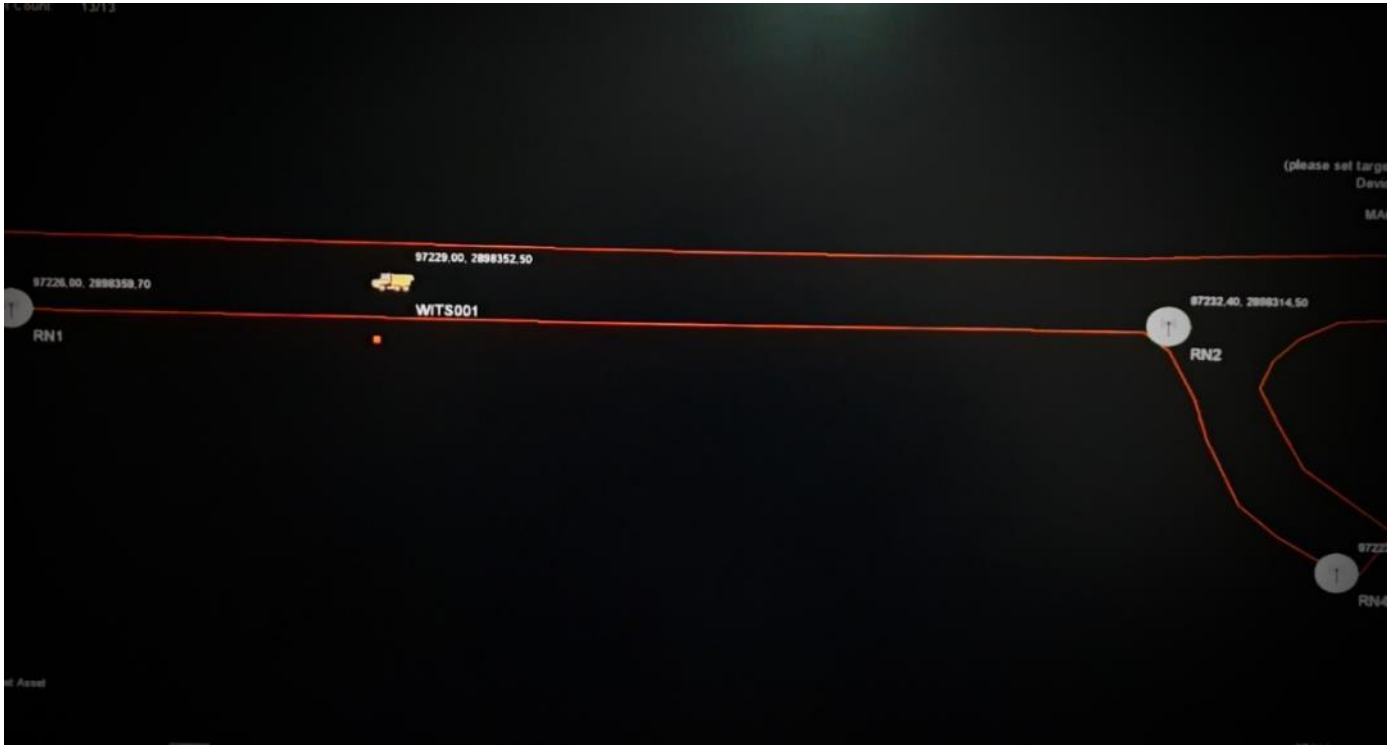


Figure 5.29 showing the location of the Trolley (WITS001) as it moves closer to Reference node RN1

5.5 Testing the Schauenburg Lamp Room and Asset Management System (LMS/AMS) at Gold One Mine

The LMS/AMS is a comprehensive database and software suite that offers a total management solution, ensuring compliance with DMRE regulations regarding all Lamp Room operations. The system is integrated with the mine's existing Time and Attendance (T&A) database and a passive RFID solution. This allows for the implementation of business rules that can block a person from going underground if he or she does not have all his or her safety critical equipment with. The system can also verify that all safety critical equipment that is subjected to functional testing is in good working order before allowing access to the underground environment. Furthermore, a person can be detained in the Lamp room if he does not return all his equipment after shift. The system therefore enhances both safety and security of the daily operations. An extensive variety of reports are available that include amongst many a daily exception report and a backup shaft clearance report. The system configuration also offers remote client access which allows management staff to generate these reports from the comfort of their office (Schauenburg Systems, 2019).

The LMS allows mines to achieve accurate electronic records which can be used for DMRE audits, the records can also be remotely accessed and this can also help in accident investigations and inspections. The LMS/AMS controls access and movement of assets, workers, safety equipment and procedures. This universal system adds value to safety, security, production and realises cost savings. The LMS/AMS is designed such that it can interface with T&A and access control systems. This system can help track human resources rules from training records, medical information, and attendance reports (Schauenburg Systems, 2019). The other important use of the LMS/AMS is for tracking safety equipment. All assets in the lamproom are entered into the LMS and are able to be tracked and monitored. Assets are equipped with passive tags and, passive readers are placed at strategic positions in the lamproom, allowing accurate monitoring of assets as they pass through the lamproom. Each asset is installed with passive RFID Tag that does not require an external power source. As the assets are moved through the lamproom they are identified by the readers which are mounted on the turnstiles. The information is then sent to the database where it is linked to the employee's details and the system makes a decision regarding the access if the information matches. If mining personnel's details do not match, the Time and Attendance (T&A) blocks the miner from proceeding through the turnstiles (Schauenburg Systems, 2015; Schauenburg Systems, 2016; Schauenburg Systems, 2019).

Failure to allocate the correct combination of equipment to the miner results in the miner being blocked from going underground. However, every person going underground may require different entry requirements and this depends on the information inputted in the system. The combination of the various hardware and software described previously allow for personnel and asset to be controlled in the lamproom by means of passive RFID tags. The system is synchronised so that gate rules, asset clearance, asset control, movement reports, and passive tag tracking reports can be generated and implemented through the LMS (Schauenburg Systems, 2015). Every asset is allocated a unique passive tag. The system is programmed so that when a miner does not comply with the gate rules, asset clearance, and asset control requirements he or she will not be allowed to pass through the time and attendance controlled turnstiles (Schauenburg Systems, 2015; Schauenburg, 2016, Schauenburg Systems, 2019). The active and passive tag tracking system for the LMS is summarised in Table 5.3.

Table 5.3 summaries the outcomes expected for four critical PPE for miners who go underground. These pieces of equipment are listed from a Sentinel GDI to a miner's emergency Rescue Pack. From the table, it is shown that for a miner assigned to carry a Sentinel GDI, the miner undergoes six stages of the LMS before being allowed to go underground. The first stage is for the GDI to go through the functionality test done via the S-link using a unique active RFID tag assigned to the equipment. The second stage is checking the GDI using a unique passive tag assigned to it via the RFID frame equipped with a passive tag reader. The miner then proceeds to the Time and Attendance clocking gate and it is at this point the MIMACS Gate rules are implemented. These rules check if the miner has the right GDI, if the GDI has passed the functionality test, the calibration test, and if the asset is operational. It is through checking the asset against the LMS database that a decision is made for the miner. When the miner is carrying the right GDI assigned to them, and it has passed all the test, an *Access Allowed* message shows on the T & A system and the miner can go underground. When the miner is carrying the wrong GDI or no GDI, the T&A shows an *Asset Missing* message and the miner will be denied access to go underground. When the miner's GDI did not pass the functionality test or calibration test, an *Asset Failed Test* pops up on the T&A and the miner is denied access to go underground. When the GDI is not operational, an *Asset Not Operational* message pops up on the T&A. The green ticks shown in Table 5.3 for steps 1 and 2 for the GDI, Virocap and PTC lamps mean that the three pieces of equipment must pass through both an active tag reader and passive reader to be able to be authenticated through the T&A, unlike the Rescue pack which must only pass through the passive tag reader to check if the miner has the one, correct Rescue Pack assigned to him or her. In the case where the miner must have more than one of the listed assets on them before going underground, the gate rule checks for assigned assets before making a decision for access.

Table 5.3 Summary of the Schauenburg LMS/AMS system (Pretorius & Blaauw, 2018; Schauenburg Systems, 2019)

ASSETS	LAMPROOM ASSET MANAGEMENT COMMUNICATION PATH					
	1	2	3	4	5	6
	Active RFID Tag Reader Functionality Test	Passive RFID Tag Reader Assets Present	Time and Attendance (T&A) Clocking Event	Gate Rules	Result of Gate Rules to T&A	Access Messages
Sentinel GDI	✓	✓	Mining Personnel ID & Assigned Gate ID	1. Assets Present 2. Functionality test Passed 3. Asset Operational 4. Calibrated at **x** time	→	Access Allowed Asset Missing Asset Failed Test Asset Not Operational
PTC Lamp	✓	✓		1. Assets Present 2. Functionality test Passed 3. Asset Operational		Access Allowed Asset Missing Asset Failed Test Asset Not Operational
Virocap Lamp	✓	✓		1. Assets Present 2. Functionality test Passed 3. Asset Operational		Access Allowed Asset Missing Asset Failed Test Asset Not Operational
RESCUE PACK	✗	✓		1. Assets Present		Access Allowed Asset Missing

5.5.1 The Gold One Mine Case study

In order to check the capabilities of the Schauenburg LMS/AMS, one of the mines where the system is installed was chosen. The mine has LMS system that manages about 5000 The LMS system at Gold One mine is linked to the Proximity Detection System (PDS) of the mine. The PDS is for collision avoidance between mining personnel and vehicles or between vehicles and vehicles. The system works in such a way that an early perimeter warning notification is sent to both vehicle operators and pedestrian miners. The system is programmed into three different perimeter warning zones. The first warning notification is sent within 30 metres between the vehicle and the hazard, and this zone is called the first warning zone. The second warning notification is send within 15 metres and this is called the critical zone. The third and last warning notification is send within 5 metres and this called the hazard zone. In the hazard zone the vehicle is programmed to automatically stop to avoid collision, and the pedestrian is warned by a flashing red LED and audible alarm from their assigned cap lamp. The communication between the vehicle and the pedestrian is done through a Ranging Unit installed on the vehicle. The Ranging

Unit uses Radio Frequency (RF) technology to communicate with PTC lamps or Virocap lamps assigned to pedestrians. However, before a miner goes underground their caplamps must undergo a functionality test, and if the miner's caplamp does not pass the functionality test, the LMS will deny them access to go through the Turnstile.

The system used at Gold One mine is such that every miner carries either a PTC lamp or a Virocap lamp. However, the Mine Overseers carry both a GDI and either a Virocap or PTC lamps The two caplamps work for both collision avoidance and early warning gas systems as they communicate wirelessly with GDIs and S-links when there is a gas outburst in the mine. So when the Mine Overseer's GDI encounters a gas outburst, it automatically and wirelessly sends the warning signal to all the miners carrying Virocap lamps and PTC lamps. So for a miner to go underground at Gold One mine, they must have all the equipment assigned to them, their caplamps must undergo a functionality test for both collision avoidance and gas detection. These tests are done for the miners' safety and to ensure that the miners PPE is in good working condition in case of encountering a gas outburst or collision avoidance scenario. If the functionality test is not carried out the miners will have a sense of false security when carrying these safety devices.

Figure 5.30 summarises the possible outcomes which a miner carrying either a Virocap lamp or PTC lamp can encounter. From the illustration, when the miner carrying one of these caplamps goes through the functionality test and passes the test, the gate rules in the MIMACS software allows the miner to go through the turnstiles allowing the T&A system to record the time and date of the event. The second scenario is when the miner's Virocap or PTC lamp fails the test. In this scenario the gate rules from the MIMACS software denies the miner access to go underground. The third scenario is when the miner carries a Virocap or PTC lamp which is not tested. In this scenario, the gate rules deny the miner access to go underground. In order to check the effectiveness of the LMS shown in Figure 5.30, the LMS at Gold One mine was used.

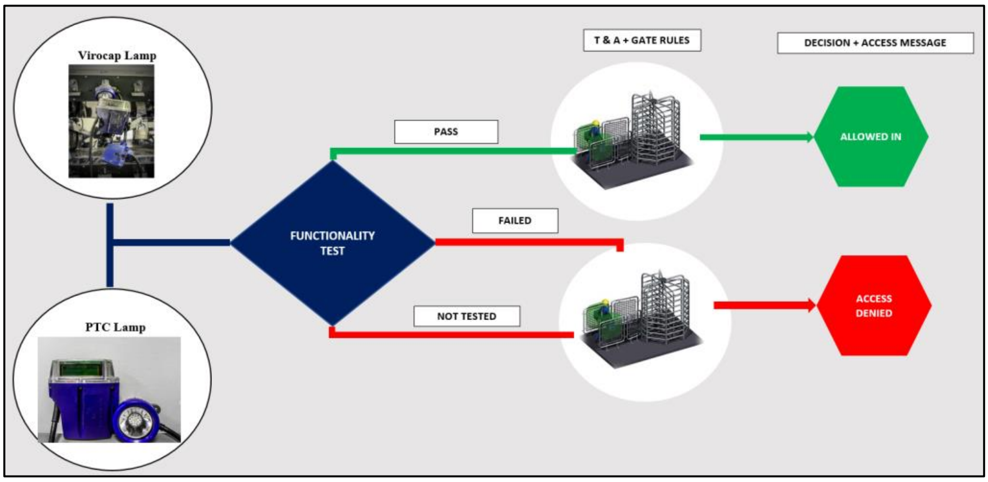


Figure 5.30 shows the procedure followed by a miner going underground through LMS system

5.5.2 Results from Testing Gold One Mine LMS

There are number of components that make the Gold One LMS system. Figure 5.31 gives an overview of the number of Virocap and PTC lamps housed in the Gold One Mine lamproom and all are managed by the Schauenburg LMS/AMS.

Figure 5.31 Gold One Mine Lamproom Overview

The assets in the Gold One lamproom are tracked by an S-link shown in Figure 5.32. The S-link's communication radius is set to 15m. This S-link works as the backbone of the LMS/AMS at the mine. To test the effectiveness of the LMS/AMS used at Gold One, one

Virocap (Figure 5.33) was picked from the lamproom rack. The Virocap was then assigned to one the miners from the mine before the test procedure. After assigning the Virocap to the miner, the miner proceeded to the Gold One mine underground entrance access gates ignoring the prerequisite procedure of undergoing the required Virocap gas detection functionality test and Virocap Proximity Detection System (PDS) functionality test carried out using the equipment shown in Figure 5.34.

Figure 5.32 Gold One Lamproom S-Link

Figure 5.33 Virocap Lamp 2450

Figure 5.34 Virocap Test points (1) Virocap PDS Functionality Test (2)

The access gates at Gold One mine are equipped with Schauenburg RFID Frames and swipe access points for the Time and Attendance (T&A) turnstiles (Figure 5.35). Upon arriving at the underground entrance, the miner allocated with the Virocap lamp passed the RFID Frame and proceeded to swipe his access card on the swipe access point shown in Figure 5.36 (1). After swiping his card, a message reading **Not tested** (Figure 5.36 (2), showed on the swipe access point. The miner was denied access to proceed through the T&A turnstiles. To try and trick the system, the miner exchanged the Virocap lamp with different one not assigned to him and repeated the procedure of trying to enter the underground access point. After going through the RFID Frame and trying to swipe again, a different access message reading **Asset Missing (**Figure 5.36 (3)), popped on the swipe access point. The miner was again denied access to proceed to underground.

Figure 5.35 Gold One RFID Frame and T&A Turnstiles

Figure 5.36 T&A Swipe Access Point Message: before miner swipes in (1), after miner swipes with a not tested Virocap Lamp (2), after miner swipes without the assigned Virocap lamp

After realising that it was not possible for the miner to proceed underground without both assigned assets and tested assets, the researcher decided to take the miner's Virocap through the complete testing procedure. The first test procedure carried out for the Virocap was the Virocap gas detection functionality test. The Virocap gas detection functionality test basically is testing to check if the caplamp is in a good working condition to be able to receive gas outburst warning signals. During this test the Virocap lamp's time readings are synchronised to that of the lamproom S-link.

This synchronisation of the time is important to ensure that the reports from underground events run at the same time with the lamproom database time, as this is important in tracing events and reporting of emergency situations. Figure 5.37 shows the Virocap lamp going through the gas detection functionality test procedure step by step. When the Virocap test point shows a green LED (Figure 5.37 (3)), it means the ViroCap has passed the gas detection functionality test. To the contrary, when there is a red LED it means the Virocap lamp has failed the test, but in this case the Virocap passed the functionality test.

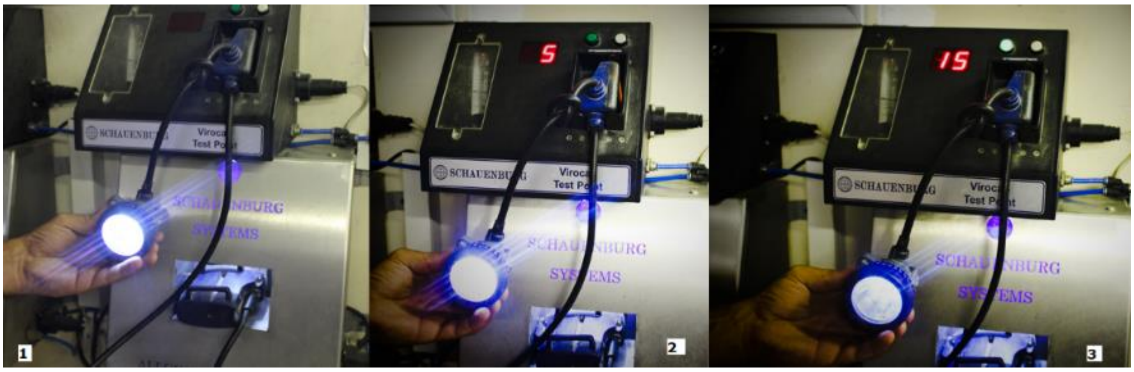


Figure 5.37 Initiation of Virocap testing (1) During the Virocap testing process (2) Green flashing LED showing a Virocap pass result for the test (3) at the Virocap Test Point

After passing the gas detection functionality test, the miner proceeded to test the Virocap for the Proximity Detection System (PDS) functionality test. During the PDS functionality test, the Virocap Lamp is tested to check if all the audio, visual LED alarms are working. It is also during this testing procedure, that the template rules for the warning zones for the collision awareness signals are loaded in the Virocap lamp. These zones as discussed earlier, are (1) the first warning zone, in which an alarm signal goes off when there is only 30 metres left in between a vehicle and a pedestrian, (2) the critical warning zone whereby there is only 15 metres left in between a vehicle and a pedestrian, and (3) the hazard zone whereby there is only 5 metres left between the vehicle and miner. The zones are automatically loaded on the Virocap lamp software during this test and are synchronised to all underground working vehicles' antennas in real-time.

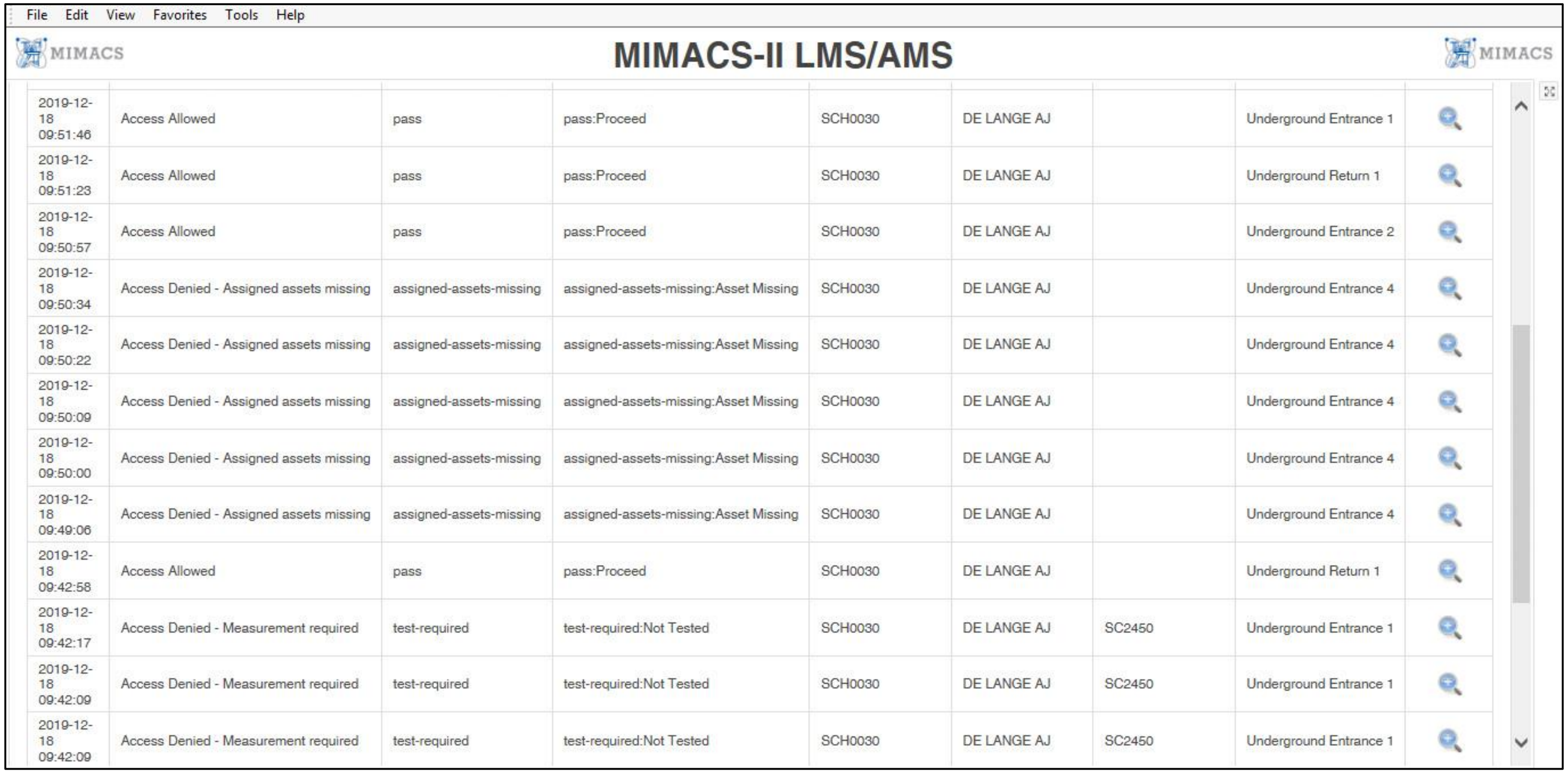
Figure 5.38 shows the procedure followed during the Virocap PDS functionality test. After placing the Virocap lamp close to the PDS test unit, a flashing blue LED (Figure 5.38 (1)) and a loud audible alarm are recorded, and this signifies that all the alarms (visual & audible) are functional. The flashing LED turns yellow (Figure 5.38 (2)) to show that the radio signals are working and the zones are being loaded to the Virocap lamp. The flashing LED turned green (Figure 5.38 (3)) and this signified that the Virocap lamp had passed the PDS functionality test. If the flashing LED had turned red the test would have failed. To guide miners on the testing procedure and expected outcomes during the test, charts illustrating the procedure are placed above each PDS testing unit. The procedure for the PDS functionality test and meaning of every outcome is shown in Appendix B of this research.

Figure 5.38 Virocap PDS Test: Blue Flashing LED (1); Yellow Flashing LED (2); Green Flashing LED

After completing both the required Virocap lamp functionality tests, the miner had headed back to the underground entrance access gates. The miner went through the RFID frames and proceeded to the T&A swipe access point. After swiping his card, a message reading **Allowed In (**Figure 5.39) popped up on the screen and the miner was allowed to through the T&A turnstiles.

Figure 5.39 T &A Swipe Access Point Message after miner complied with all Gate Rules

After completing the test in lamproom, the researcher proceeded to the control room office to check the reports generated by the MIMACS system for all the events created during the testing of the LMS/AMS installed at Gold One mine. The report (Figure 5.40) showed all the attempts by the miner to get access to go underground and all the corresponding messages which popped up during the swipe incidences. The report even showed the equipment number (2450) that was assigned to the miner and had not been tested when the miner was denied access. The report further shows the event in which the miner was denied access due to a missing asset. The report finally shows the time the miner was eventually allowed to gain access to go underground as well as the time the miner also swiped out from underground back to the lamproom. Another version of the report can be downloaded in a Microsoft Excel spreadsheet format as shown in Appendix C.



2019-12-18 09:51:46	Access Allowed	pass	pass:Proceed	SCH0030	DE LANGE AJ		Underground Entrance 1
2019-12-18 09:51:23	Access Allowed	pass	pass:Proceed	SCH0030	DE LANGE AJ		Underground Return 1
2019-12-18 09:50:57	Access Allowed	pass	pass:Proceed	SCH0030	DE LANGE AJ		Underground Entrance 2
2019-12-18 09:50:34	Access Denied - Assigned assets missing	assigned-assets-missing	assigned-assets-missing:Asset Missing	SCH0030	DE LANGE AJ		Underground Entrance 4
2019-12-18 09:50:22	Access Denied - Assigned assets missing	assigned-assets-missing	assigned-assets-missing:Asset Missing	SCH0030	DE LANGE AJ		Underground Entrance 4
2019-12-18 09:50:09	Access Denied - Assigned assets missing	assigned-assets-missing	assigned-assets-missing:Asset Missing	SCH0030	DE LANGE AJ		Underground Entrance 4
2019-12-18 09:50:00	Access Denied - Assigned assets missing	assigned-assets-missing	assigned-assets-missing:Asset Missing	SCH0030	DE LANGE AJ		Underground Entrance 4
2019-12-18 09:49:06	Access Denied - Assigned assets missing	assigned-assets-missing	assigned-assets-missing:Asset Missing	SCH0030	DE LANGE AJ		Underground Entrance 4
2019-12-18 09:42:58	Access Allowed	pass	pass:Proceed	SCH0030	DE LANGE AJ		Underground Return 1
2019-12-18 09:42:17	Access Denied - Measurement required	test-required	test-required:Not Tested	SCH0030	DE LANGE AJ	SC2450	Underground Entrance 1
2019-12-18 09:42:09	Access Denied - Measurement required	test-required	test-required:Not Tested	SCH0030	DE LANGE AJ	SC2450	Underground Entrance 1
2019-12-18 09:42:09	Access Denied - Measurement required	test-required	test-required:Not Tested	SCH0030	DE LANGE AJ	SC2450	Underground Entrance 1

Figure 5.40 MIMACS system generated report for the LMS testing events

5.5.3 Conclusions from testing the Schauenburg LMS/AMS at Gold One Mine

The results from testing the Schauenburg LMS/AMS installed at Gold One Mine showed that it is possible to ensure miners comply in having all the adequate PPE before going underground. The system also showed that it possible to check the exact reasons why a miner is denied access to go underground. Ensuring that mine workers have adequate PPE is the first step in avoiding preventable accidents in underground mines. Looking at some of the case studies discussed in Chapter 4 of this dissertation, it is evident that some of the fatalities which were caused due to human errors or not carrying adequate PPE such GDIs could have been avoided using a similar system to the LMS/AMS being used at Gold One mine. Investigations into these accidents could have been made easier especially in the incident in which the miner lied that he had carried his GDI underground yet he had left it on surface for calibration. With a similar system aforementioned, the miner would not have been capable of going underground without his GDI or with the GDI not it being calibrated. However, the full benefits of systems like the Schauenburg LMS/AMS can only be realised when the system is integrated with other systems such as location monitoring and atmospheric monitoring.

6 FRAMEWORK FOR INTEGRATED MONITORING AND CONTROL SYSTEMS IN UNDERGROUND MINES

Chapter 5 discussed some the systems readily available for real-time monitoring and control in underground environments. However, from the testing of these systems, it was evident that most of the available real-time monitoring and control systems are being used as standalone systems. Although these systems can work well to achieve their individual functionalities, the mining industry can benefit more if the systems are integrated. Opiti (2019) highlights that most of these standalone systems work as silo systems which make it difficult for these systems to share data with other systems used at the mines. The development of a systems' integration framework allows for comprehensive real-time data collection and analysis. Real-time data collection and analysis have a great potential to influence informed and effective decision-making especially in the management of environmental risks in underground mines.

When looking at ventilation related risks, the use of technology can contribute to proactive risk management. To effectively manage ventilation risks, a system must at a minimum be able to monitor and control; gas concentrations, respirable dust concentrations, wet and dry bulb temperatures, airflow speed, humidity and miners' locations. However, in most cases these aspects are monitored by different standalone systems. In order to achieve the goal of zero harm in areas of mine ventilation, all the aspects that affect and pose risks to the health and safety of mine workers must be monitored and analysed in real-time on an integrated platform.

The DigiMine Research group has been carrying out research on how to integrate different mining systems which encompass the whole mining value chain, with an aim of giving mine workers and mine management, "the right information to make the right decisions on mine health, safety and efficiency at the right time" (Cawood, 2019). Figure 6.1 shows an example of how different mining systems can be integrated to inform real-time decision-making. The systems shown in Figure 6.1 range from the Vibratech system for rock engineering monitoring, Minetec system for health and safety monitoring,, IBM research and EOH cameras for security and surveillance, laser scanning, Sterkfontein and Sibanye systems for seismicity monitoring and Schauenburg and BBE systems for mine ventilation control and monitoring. However, for this research only a framework of integrating ventilation related systems is discussed. Guided by the work being carried out by the DigiMine research group, the researcher proposes a framework on how the different ventilation systems available in the mining industry can be integrated to achieve zero harm.

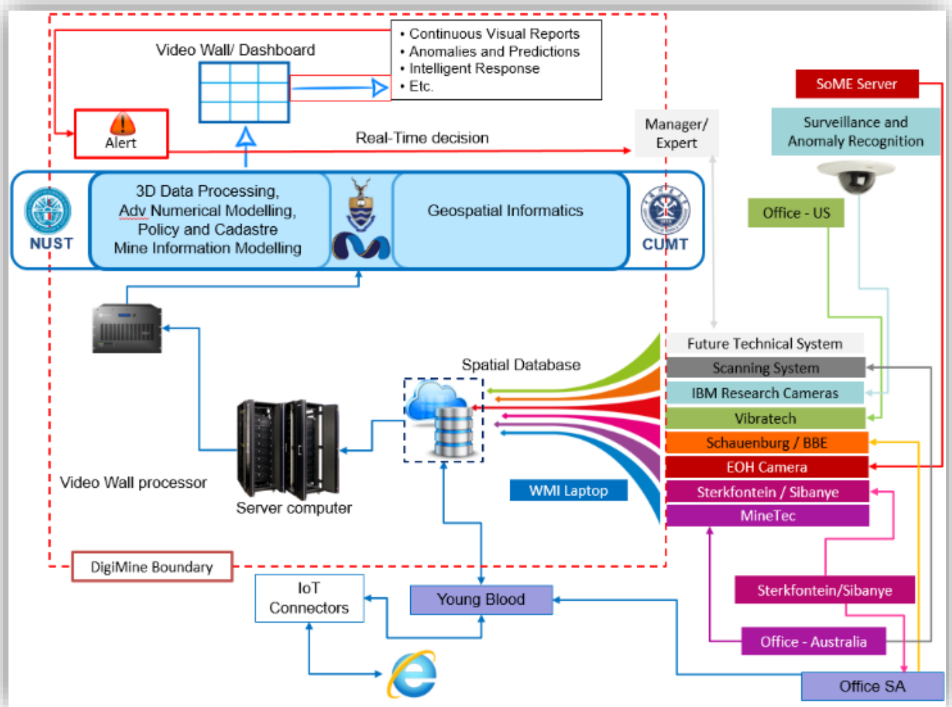


Figure 6.1 DigiMine Systems' Integration Research Flow diagram (Cawood, 2017; Kwiri, 2018; Cawood, 2019)

This chapter discusses how each independent system's functionalities can add to an overall typical defence-in-depth safety system. The proposed systems in the framework are the ones which were tested in Chapter 5 and some were adopted from the leading practices discussed in Chapter 3 of this dissertation. The proposed framework summarises the role played by the regulatory body, mine management, control room operators, lamproom operators and miners for the successful implementation integrated ventilation systems.

Figure 6.2 illustrates how the different mining systems can be integrated to give a holistic approach in achieving zero harm in the mining industry. The framework diagram shown in Figure 6.2 highlights how the different faculties of the mining industry can be integrated to form one system. The framework emphasises on how a collaborative system that include all the involved faculties of the mining industry are one of the ways the mining industry can achieve a solid defence-in-depth safety system. The diagram shows that the regulatory body which in the South African mining industry perspective is the DMRE, has the overall role of overseeing and regulating the mining operations at the national level.

The framework (Figure 6.2) shows that after the DMRE, comes the different individual mine management teams who play the executive and central decision-making for their mining operations guided by the mining regulations. From the mine management, the framework shows the control room and the different systems installed in the control room. The lamproom comes after the control room, and in the framework the recommended systems that can be used in the lamproom are highlighted. From the lamproom, the framework shows how the individual ventilation equipment installed in the mine are linked to the ventilation on demand (VOD) strategies. The framework further shows that all the monitoring systems from the location monitoring, gas monitoring, dust monitoring, fire detection systems and heat stress management systems must be linked to the VOD systems. In the framework, miners are shown as the final line of defence as they must exercise their decentralised decision-making roles. The role of each faculty highlighted in the framework is explicitly discussed later in this chapter.

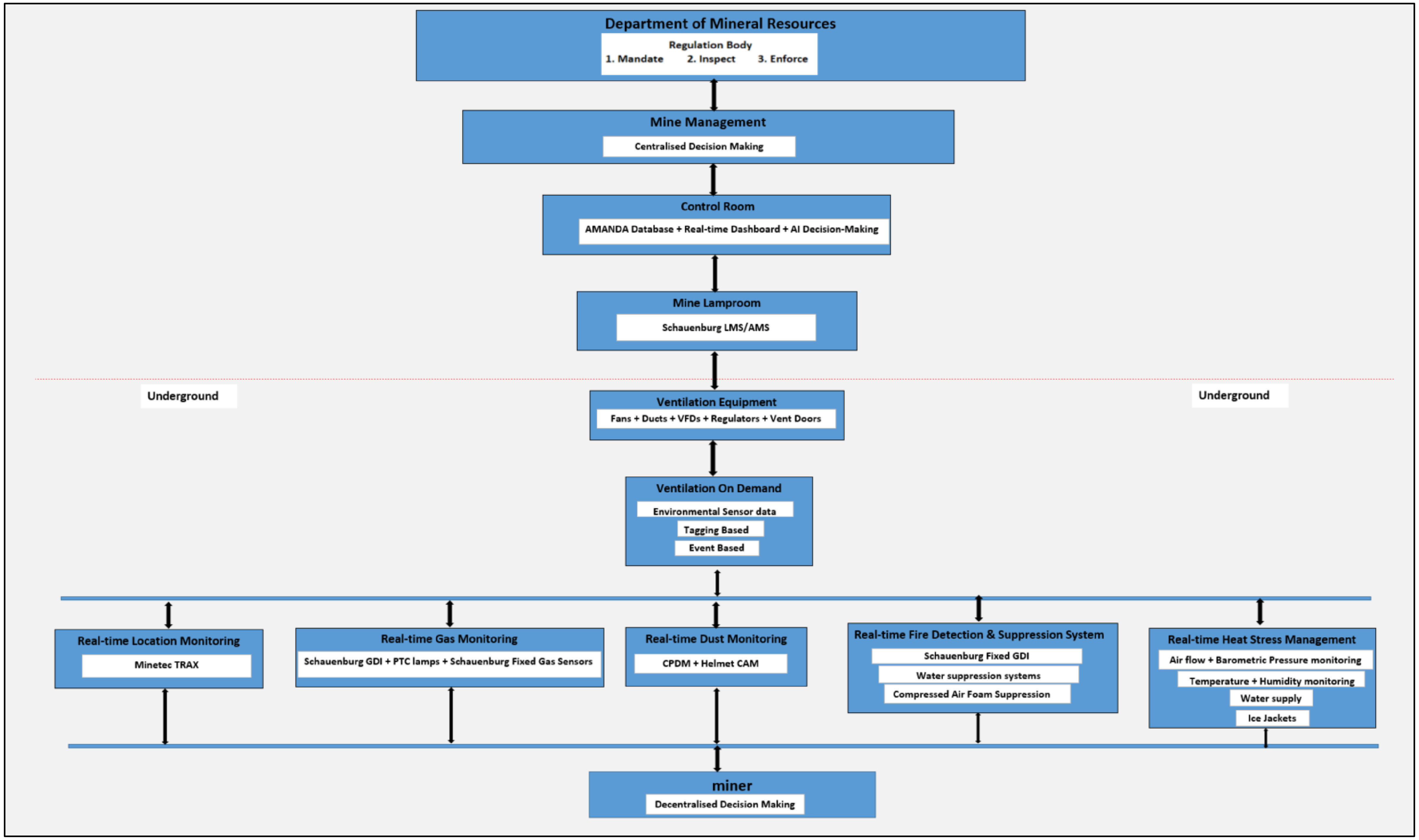


Figure 6.2 Proposed Integration Framework

6.1 The Role of Regulatory body and Government

From the foregoing discussion, the regulatory body plays the central role in the proposed framework. As discussed earlier in Chapter 3 of this dissertation, the government plays the crucial and main role in the defence-in-depth safety principle in order to achieve zero harm in underground mines. The government's regulatory body has three main arms, namely, the regulatory mandate, regulatory inspections, and regulatory enforcements. The three arms of the regulatory body must be set such that they fulfil their mandate of ensuring that they inspect and enforce the regulations, standard operating procedures (SOPs) that govern the health and safety of mining operations. The regulatory body must institute this by making sure there is proper education and training of Inspectors who carry out its mandate. It is also the duty of this arm of government to ensure that there is adequate research and funding into the development of technologies for improving health and safety in mines.

It is important that the government must play a leading role in funding research and development of mining technologies. Although most private companies are keen to make their operations safe, healthy and productive using different technologies, there is still underfunding of research and development (R&D) projects by mining companies (National Research Council, 2002). National Research Council (2002) adds to this by asserting that most private companies are not willing to invest in research and development projects especially in areas where the results and benefits usually take long periods of times. Mining companies regard these projects as very risky. Therefore, it is imperative for government to support R&D project funding especially for those ones that have potential to improve health and safety in the mining industry.

When R&D projects are funded by government, it can makes it much easier for the regulatory bodies to regulate the use of the products from these projects. The government will have a clear idea of the functionalities and limitations of the various systems which would have been developed. This can also help solve in the issues of intellectual property rights which are usually a major problem raised by vendor and equipment manufacturing companies when proposals of integrating systems are put forward. Most vendor companies are not willing to integrate their systems with their competitors because of fear of intellectual property infringements.

Another role of the regulatory body in the framework is accident investigations. Full facilitation of accident investigations is also another mandate of the regulatory body. The inspectorate arm of the regulatory body has a clear role to develop, issue and use up-to-date technical and safety standards of the proposed systems and the mining operations as a whole. The regulatory body must be able to carry out independent research on the various technology and best practices to improve health and safety. The research must include testing the functionalities of the different technologies before implementing them in the mines. It must only be after thorough research that mandatory adoption of different standards and technologies must be implemented in the industry. The latter makes sure that the regulatory body does not implement blanket regulations but rather proposes effective technologies which will not be a burden to the industry.

The government must also engage in collaborative research with vendor companies that design the technologies so that they can subsidise on costs for the research and development of some products to minimise the end costs of the products when they go to market (mining industry). These collaborations and subsidies allows for the regulatory body to effectively recommend best practices to the mining industry. The regulatory body will also be in good position to know if the vendors' products work according to their specifications and are not only a marketing tool to make more money from the mining companies. These aspects when considered have potential to make the regulatory body effective in carrying out its other mandates of inspecting and enforcing the law. The regulatory body cannot simply inspect or enforce systems and technologies they do not understand, hence it is imperative for them to take on investing in the R&D of the technologies. Their workforce must also be trained and competent with regards to the use of different technologies and systems implemented in mines such that they can confirm if the mines are not cheating or lying in complying with the law using technology.

The inspectorate arm of the regulatory body must be fully funded and given enough resources including manpower, to fulfil their duties of inspecting and auditing compliance of the regulations. As discussed in Chapter 3, the inspectorate must put emphasis on inspections on critical areas such as mine ventilation, gas monitoring, rock engineering and safety trainings. This arm of the regulatory body when poorly functioning, can lead to the rise of poor compliance or noncompliance which in some cases can lead to loss of lives due to accidents. Hence, understaffing of this arm of the regulatory body must be avoided. The inspectors must also be vigilant and make sure that heavy penalties and fines are put in place when intentional violations of the laws that affect the health and safety of miners are found. As also highlighted in Chapter 3 of this dissertation, a proper legal framework to support the enforcement arm of the regulatory body is critical in order for effective issuing of fines and penalties for violations.

6.2 The Role of Mine Management

Mine management plays an equally important role in the proposed framework. The management of a mine acts as the central decision-making body. Before implementing the whole proposed system, it is management’s role to understand the appropriateness of the whole system to both safety and their financial capacity to acquire it and maintain it. Mine management also plays an important role in the risk assessment and risk management programmes implemented at their mines. Management must properly address the miners, technology and processes for the implementation of the technology to be effective. Management must ensure that there is proper training on the benefits of different technologies and ultimately strive to get mine employees commitment

Junior and senior management must all be on the same page on the issue of implementing new technologies, if not top management must find ways to get all the management to buy in on the idea and technology. Communication must be effective and also follow a bottom to top strategy on all the planned changes. This is critical for the framework to work and ultimately to reap positive results. Management must also deal with the issue of miners not wanting to be tracked when performing their duties underground. Management must put in place good structures and resources to manage the change and also to convince miners the benefit of such systems specifically in areas of health and safety.

Getting miners' commitment must be prioritised before the implementation of these systems. The different systems installed must comply with all set standards. Mine management must ensure that all the systems they decide to install are fit for purpose and also that they are properly maintained such that when there is an incident, the system will not be found not working due to lack of maintenance or other issues which could have been avoidable. It is also the duty of mine management that they source a highly skilled workforce to monitor and maintain the systems installed at their mine. The mining companies must develop standards for the integration of systems which will support interoperability. Mine management plays a big role as it will be discussed further in the implementation plan in the next chapter.

6.3 Control Room and Control Room Operators

The surface control room and the control room operators are fundamental components of the proposed framework. The control room facility will house the data analysis, data visualisation software and all the other programs. The control room must act as the integrated control centre equipped with real-time dashboards displaying information from all the underground remote sensors. Control room operators are also the main human component of the control room system. It is important for the mine to make sure that the systems installed in the control room are capable of real-time monitoring and controlling of the underground environment.

The calibre of control room operators is also a major concern. For the control room operators to have full control of the underground environment and mining personnel, it is important that they are enshrined with higher authority than that of everyone working underground. This will ensure that there can be no fear or intimidation when carrying out their duties especially in incidents where they have to issue withdrawal signals such as in situations of emergencies or even entering of dangerous or abandoned areas. The control room operators must also be fully trained and highly skilled on the systems they operate. This include them being well versed with the systems they operate as well as being alert and quick to escalate actions which make sure that miners underground are protected from any danger. However, as it will be discussed later in this section, giving the sole role of making decisions to control room operators is not always the best solution.

The other main important components that must make up the control room are a database, and underlying software that support and power installed systems to fulfil their duties. One good example of such databases is the "Atmospheric Monitoring Analysis and Database mAnagement (AMANDA)" (Agioutantis, et al., 2014, p.1061). In their research paper, Agioutantis et al. (2014) state the AMANDA database is one of the available databases specifically designed to handle vast amounts of data from atmospheric monitoring systems installed in an underground environment. Agioutantis et al. (2014), further state that the AMANDA has a number of subsystems e.g. for data acquisition; data analysis; data validation, and data storage; data visualisation and report generation; alarm generation; and tools for statistical evaluation and cross-correlation.

The upside of using this database in the control room is its capability of importing and exporting data to and from different external sources including other independent databases. Figure 6.3 shows how the AMANDA can be linked to other databases and systems in the mining environment. Using a database such as the AMANDA, allows for the control room to have a storage system with all the historical atmospheric data from the underground environment (Agioutantis, et al., 2014). In his research, Griffin (2013) proved that the AMANDA is capable of fulfilling the aforementioned functionalities. Looking at the proposed framework, all the sensor data from the real-time gas monitoring, real-time dust monitoring, and heat stress management systems can be transferred to the AMANDA.

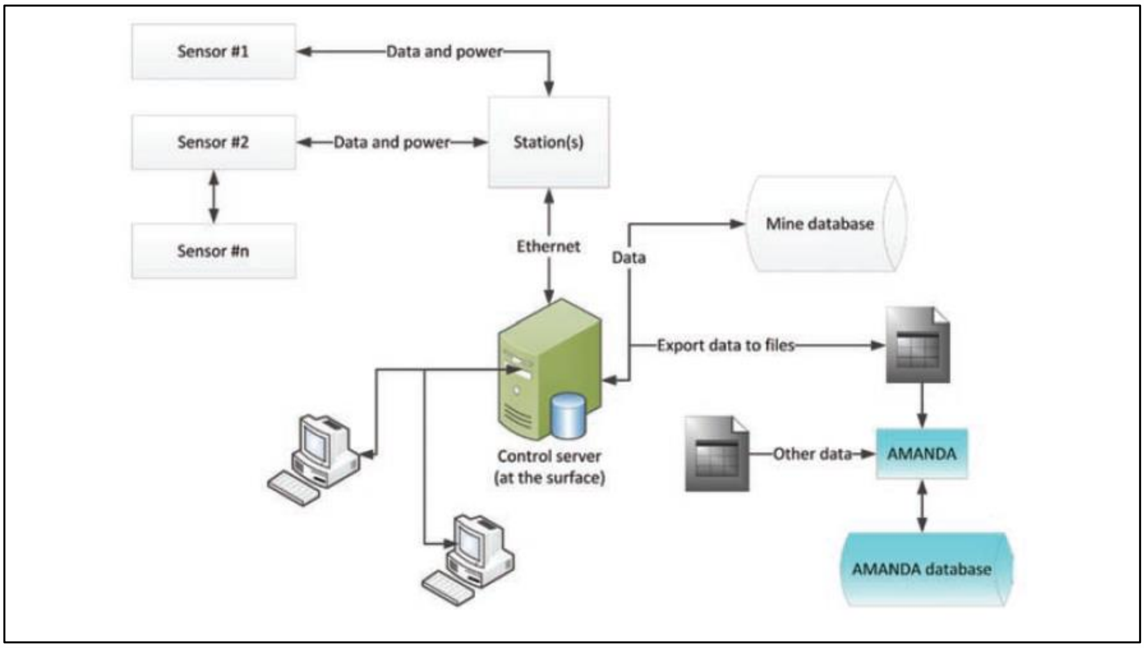


Figure 6.3 Data Flow Diagram for AMANDA Database (Agioutantis, et al., 2014)

Although there will be control room operators, the author recommends that the analysis of data stored and managed by the AMANDA be carried out by an artificial intelligent system. Linking the AMANDA to an Artificial intelligence (AI) system in the control room can allow the analysis of the live and historical sensor data to help in informed and real-time decision-making in the control room and beyond. There are scholarly arguments (Chou, 2018; Global Mining Guidelines Group, 2019; Kumar, 2019) that having humans to make critical decisions is not the best choice. Studies cite artificial intelligence (AI) as one of the best options in complementing humans in decision-making. Human decision-making is said to be sometimes affected by a number of external forces which may include (but are not limited to) emotions, fatigue and boredom (McKinsey & Company, 2018; Kumar, 2019). Actions due to these factors can endanger miners in cases of emergencies.

Unlike humans, AI systems can reduce human errors and have a high chance of reaching accuracies with greater degrees of precision. This enhances the decision-making processes. AI systems can also work without the need of taking breaks (24/7) and can also carry out repetitive tasks without losing focus or getting bored, and these are uncommon characteristics of humans (Kumar, 2019). The use of AI systems also allow for faster decision-making and quick reactions to situations when compared to humans.

To add to the shortcomings of human decision-making in the control room, Kwiri (2018) highlighted all the areas of concern. According to Kwiri (2018), when applying the traditional way of decision-making, computers are only used for collecting and storing data; and humans analyse, predict outcomes and in the end decide the actions they must take (Figure 6.4).

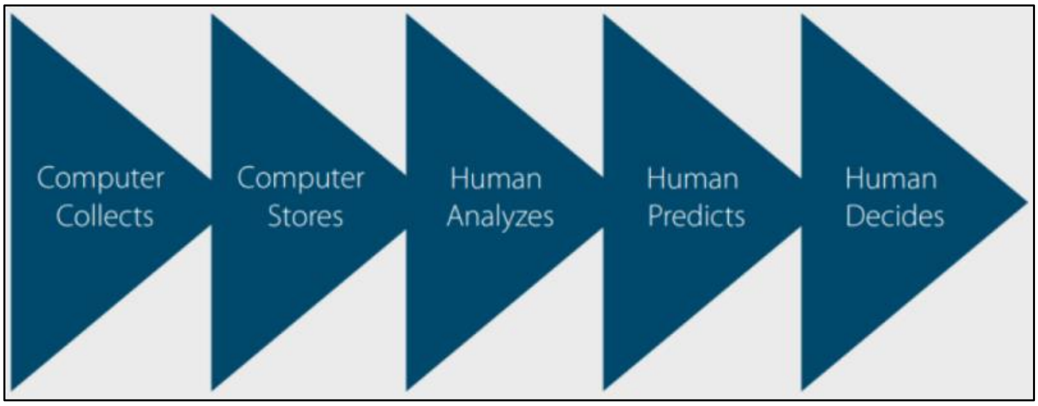


Figure 6.4 Traditional Decision-making Process for control rooms (Kwiri, 2018)

However, Kwiri (2018) argues that the main shortcoming of following the traditional decision-making process in the control is that there is usually communication breakdown between the human analysis and the human decision-making stages (Figure 6.5). The communication breakdown can be attributed to a number of factors, including emotions, fatigue, etc. This shortcoming is one of the main justifications of the recommendation of using AI in the control room decision-making process. Figure 6.6 highlights how replacing humans with AI systems in decision-making will look like. By introducing AI systems human interference is minimised in the decision-making process, however, humans will still have a role of overseeing and managing the systems.

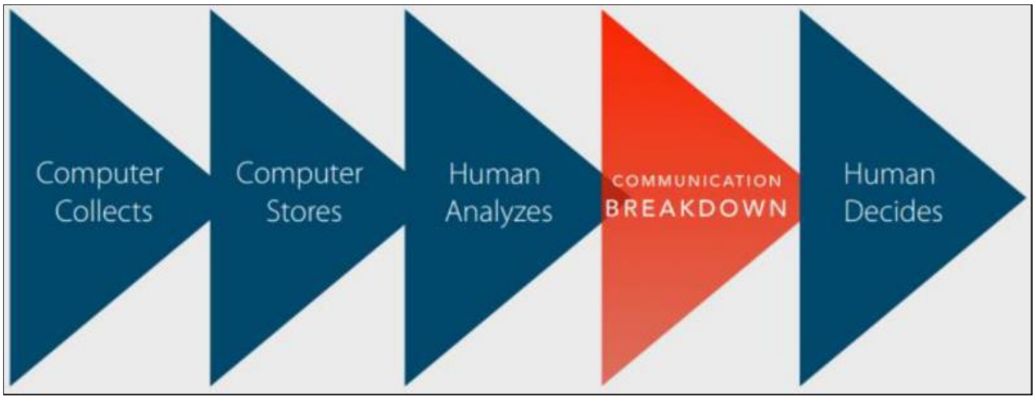


Figure 6.5 showing the Shortcomings in the traditional decision-making process (Kwiri, 2018)

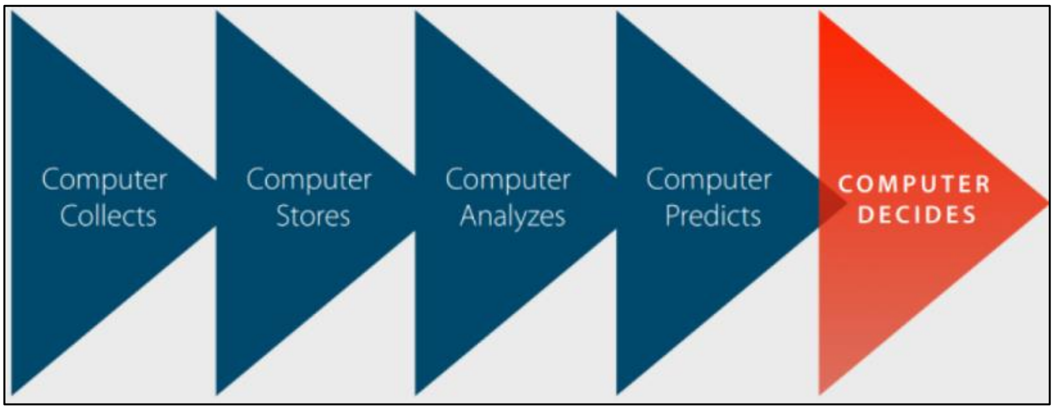


Figure 6.6 AI Based Decision-making process (Kwiri, 2018)

It is important to note that, although AI systems might be used for the data analysis, data predictions and decision-making processes, humans will still have an important role to interpret the results from the data driven decisions by the AI systems (Figure 6.7). According to the Global Mining Guidelines Group (2019), humans play an essential role in all AI systems, because for AI systems to be able to interpret all the input and output data there is need for human knowledge. The Global Mining Guidelines Group further states that for accurate and meaningful input data models into the AI systems to be built humans must be involved in carefully analysing the external environments. In relation to this research, there is need for consulting with ventilation specialists, health and safety specialists, MHSA regulations, mine management, maintenance engineers, electrical and control engineers, information technology specialists, control room operators and other support teams. Failure to consult with experts in the different domains of the mine can lead to the AI models missing valuable knowledge.

Additionally, consulting with a limited number of these experts can also increase the risk of biased decisions from the AI models. These models play a big role in life and death decision-making, hence it is important that there is no bias in the data (Global Mining Guidelines Group, 2019). In order to generate AI models which make sense of all the processes and systems involved in the mining environment, the necessity for an extensive human knowledge gathering exercise cannot be underestimated. Global Mining Guidelines Group (2019, p.7) emphasises on this by giving an example which highlighted that “to build a predictive maintenance algorithm, reliability engineers will be consulted to help determine which data are important for identifying certain categories of faults. Maintenance work orders may also need to be inspected and interpreted to determine which breakdown events can be attributed to which maintenance activities”.

Another example is that, to set the threshold limit values (TLVs) for atmospheric monitoring software that feed data into the AI models to trigger warnings and evacuation alarms, both ventilation specialists and health safety specialists must be consulted to define the TLVs for the gas concentrations, heat stress, dust concentrations and DPM. Similarly, the areas that are deemed abandoned or restricted must also be clearly defined by safety personnel before being fed into the AI models. The system must also be programmed to define the rules for the where and when employees must be withdrawn or withdraw from working areas for any reason as per Section 23 of the MHSA guidelines.

As shown in Figure 6.7, the results from an AI model built from human knowledge contributions can be presented in different visuals which can include graphs and charts.

It is the role of humans, mostly experts, to interact with these results and interpret and asses the meanings. The results must be interpreted by experts in the different fields.

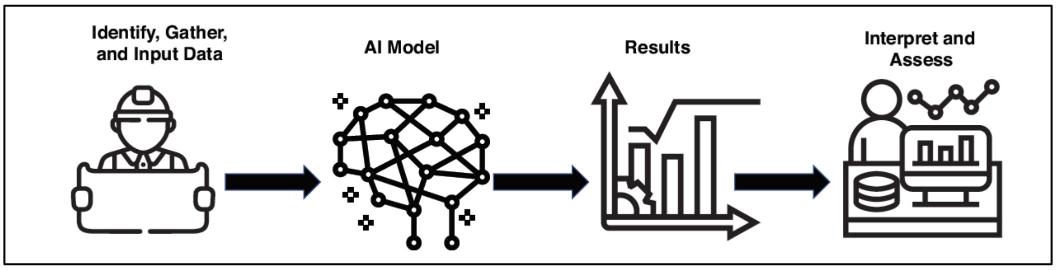


Figure 6.7 showing the Role played by Humans in AI input and output Interfaces (Global Mining Guidelines Group, 2019)

One of the recommended ways of representing the results from the AI models is in the form of a dashboard. In his research, Opiti (2017, 2019) designed and tested a prototype real-time dashboard (Figure 6.8), which is capable of showing different readings from sensors installed underground. The dashboard can show the exact locations and names of the sensors using colour-coded gauges to show if the sensor readings are within or beyond the threshold values (Opiti, 2017). From Figure 6.8, the green colour gauges represent sensor readings within the accepted range whereas the red gauges represent sensor readings that are beyond the threshold values. When the gauges are red, the system triggers alarms, and send messages to miners underground or mine management on surface (Opiti, 2017; Kwiri, 2018).

The colour gauges are designed to make it easy for the control room operators to interpret the results from the underground sensors. In order to manage these systems, there is need for clear set procedures in the control room that control room operators must follow for different alarms. The alarms must be set and ranked to have different priorities depending on the risks posed (Watkinson, et al., 2016).

In order to manage the health issues underground, the proposed framework requires the control room system to be programmed, to automatically update every worker's dust exposure records and other health records including acclimatisation after every shift from the lamproom system. The system must also ensure that it keeps records of all the workers who have breached health and safety rules. However, on dealing with these breaches and offences, mine management must put up measures that focus on more training of workers on the importance of good safety rather than punishment of the workers. The control room systems must be programmed such that they are auditable by both internal staff and external personnel (DMRE inspectors). Transparent measures must be put in place to make sure the systems cannot be breached by management to falsely alter the original reports especially for accident investigation purposes.

The database in the control room must work in synchrony with the lamproom database and all the other systems underground. Maintenance and fault finding for the installed systems underground must be monitored and controlled by intelligent systems using AI in the control room. This will ensure that when an incident occurs, the systems will be functional and running other than giving miners working underground a false sense of security. For example, a fire detection and fire suppression must always be remotely tested and checked if it is functional and have an adequate supply of suppressants (water or compressed air foam), in case of a fire break out.

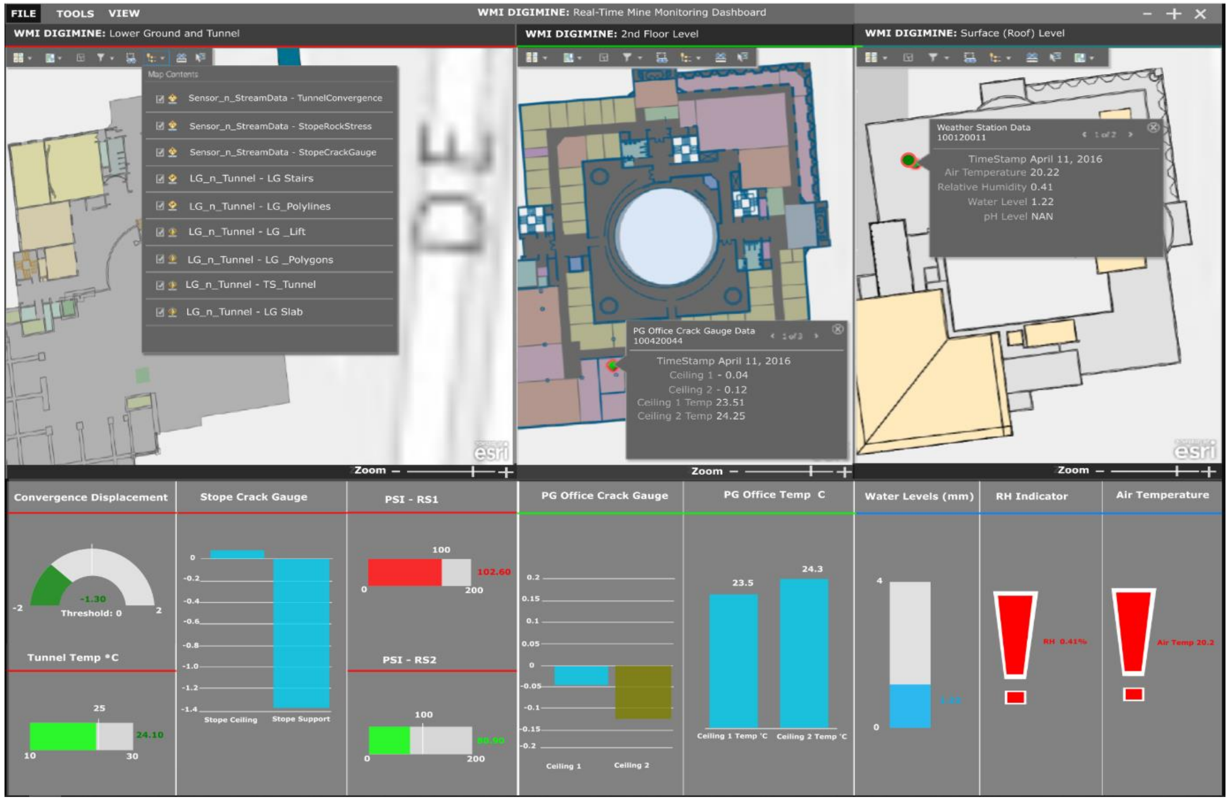


Figure 6.8 Typical Real-time Dashboard (Opiti, 2017; Kwiri, 2018; Opiti, 2019)

6.4 Lamproom and Lamproom operators

The lamproom plays an equally critical role in the proposed framework. It works as the connection and enforcer of rules between the surface control room and underground workings. From Chapter 5, the Schauenburg LMS was found to be capable of performing this kind of work. The system must be programmed to support not only the assigning of the right PPE to the right personnel but it must also ensure that the PPE issued is adequate for the assigned working area. The LMS must be set to check if every miner's medical records allow him or her to go underground. The LMS must also check if miner the worker is acclimatised to the conditions of the area they assigned to work in. Alcohol breathalyser tests must be made compulsory and automated in the lamproom. The lamproom must also implement proper checking for medical surveillance records for respirable dust exposures for every miner before going and coming from underground, the results from the daily check-ups must be used to make a decision if a miner is to be allowed to proceed and go to work underground. The synchronisation of the systems and decisions made in the lamproom and the control room is also critical for the proposed framework.

6.5 Ventilation Equipment and Ventilation on Demand

The proposed framework showed that there need for ventilation equipment supported with VOD. The ventilation equipment installed underground plays a critical role in maintaining the underground atmospheric environment by continuously controlling and supplying adequate fresh air. These pieces of equipment include main fans, auxiliary fans, ventilation ducts, regulators and ventilation doors. The main and auxiliary fans are supposed to be equipped with variable frequency drives (VFDs) also called variable speed drives (VSDs). The VFDs control the supply of air in the underground environment depending on the atmospheric conditions and demand. This supply of air for different conditions and demand is termed Ventilation on Demand (VOD) as discussed earlier in section 3.6 of this dissertation. The VOD system will work on data supplied by different sensors and subsystems installed in the underground environment (Acuña, et al., 2016; Dicks & Clausen, 2017). These subsystems which make up the VOD system depend on the information gathered from the sensors responsible for real-time gas monitoring, real-time location monitoring, real-time dust monitoring, real-time fire detection monitoring and real-time heat stress management. In Chapter 3 of this dissertation, the various pieces of equipment and sensors for monitoring atmospheric conditions were discussed in greater detail. The VOD system proposed work based on a number of different control strategies which are discussed later in this section.

The use of ventilation on demand can help manage underground occupational exposure limits of different pollutants such as gases, dust and DPM. Unlike using the mostly available ventilation systems which are static, the use of VOD systems allows for dynamic and intelligent supply of air and real-time control of the mining environment (Dicks & Clausen, 2017). The intelligent supply of air ensures that the air quality demands are met and a healthy and safe environment is maintained. In order to have an effective VOD system, the mine should ensure that there is complete and sufficient knowledge on the underground mine ventilation network and also all the tasks and operations taking place in the underground environment at any given time. The VOD system must also be designed to meet all the regulatory demands as far as mine ventilation is concerned.

To track all the tasks and processes taking place underground, location monitoring systems for both equipment and mining personnel must be installed in the underground environment. The tracking and location monitoring systems will ensure that, the positions for both the miners and machinery and properties of the pieces of equipment are known at any given point. Having the full knowledge of this information allows for the VOD system to precisely define the air demands in all the underground areas. Depending on the information gathered from the miners and equipment, the data is analysed by the software installed in the control room, and the control room then triggers a certain chain of commands to deal with the air demands.

The proposed VOD system must be remote controlled to minimise delays in the reaction times to certain demands as in some cases the conditions will be life threatening. In both cases, adequate infrastructure is required to transmit information. The proposed VOD system must be directly be linked to all the monitoring systems' sensors responsible for real-time gas monitoring, real-time dust monitoring, real-time fire detection and real-time heat stress management. Linking the VOD to these sensors will ensure the real-time analysis of the air quality and trigger quick reactions to any shortcomings in any regulatory demands.

According to Acuña et al. (2016) and Dicks & Clausen (2017), the VOD control strategies available in the market can be classified into five categories; namely manual control, time of day scheduling control, event based control, tagging and environmental control. The five control strategies vary in the levels of systems' intelligence. As shown in Table 6.1 these control strategies can be done in stages from level 1 to level 5. The manual control strategy is the easiest and cheapest to implement and maintain. However, its benefits are also minimal when compared to the other strategies. From Table 6.1, the environmental strategy that gives the most benefits for the VOD strategies, however it also has the greatest implementation and maintenance costs (Dicks & Clausen, 2017). These strategies can be used individually or in combination depending on the mine's need.

Table 6.1 Levels of VOD Control Strategies (Dicks & Clausen, 2017)

Level 1	User or Manual Control
Level 2	Time of day Scheduling
Level 3	Event Based
Level 4	Tagging
Level 5	Environmental

↓ Incremental Benefits

Incremental Implementation Cost

Incremental Maintenance Cost

6.5.1 Level 1 User control or manual control

This control strategy involves the manual control of different pieces of ventilation equipment. Ventilation officers can manually switch on and off both primary and secondary fans. The fans can also have set operational points. In addition, fans can be equipped with variable frequency drivers (VFDs) to adjust speeds during operations so that the fans can supply the required air quantities at different areas (Allen & Tran, 2011; Acuña, et al., 2016). For energy savings and extra safety for these fans, soft starters (SSs) can also be installed on the fans. As shown in Table 6.2, when using the manual control strategy auxiliary fans are usually manually put on the on and off control, and main fans are usually equipped with either VFDs or SSs or in some cases both (Acuña, et al., 2016).

The manual control strategy is also used to manually control regulators and ventilation doors. This is done by controlling the orifice openings for regulators to be able modulate and demodulate the air quantities across different working areas. The ventilation doors can also be controlled by setting them to open at certain highs from 0% to 100% (Dicks & Clausen, 2017). However, as shown in Table 6.2, the VOD manual control strategy is mainly based on expected vehicle and personnel distribution in different underground working areas as per mine plan and operations of a specific day and thus it does not have a real-time monitoring and control component.

6.5.2 Level 2 Time of day scheduling

The time of day scheduling control strategy unlike the manual control strategy, uses a button with a pre-set on or off pattern. In this strategy the system triggers different set points on the ventilation equipment (fans, regulators and ventilation doors) to follow a certain time schedule due to different time inputs by control room operators or ventilation officers (Allen & Tran, 2011; Acuña, et al., 2016). As shown in Table 6.2 this strategy is an extension of the manual control strategy with just an addition of a timer on the equipment to trigger certain semi-automatic actions on the ventilation equipment. This system also does not offer a real-time monitoring and control of the ventilation supply but just like the manual control strategy it is based on expected events and distribution of equipment and mining personnel at a certain given time in the underground environment.

6.5.3 Level 3 Event based

In this control strategy the ventilation system automatically triggers prescribed action depending on certain configured events in the mine. The software conveys a set of ventilation instructions for the ventilation equipment to react, for example when a blast is initiated, auxiliary fans are turned on so that the underground re-entry times are minimised. This strategy can also be useful in response to emergency underground fires and other unexpected events (Allen & Tran, 2011; Acuña, et al., 2016; Dicks & Clausen, 2017).

6.5.4 Level 4 Tagging Control Strategy

In this strategy, the ventilation system automatically is changed based on the real-time tracking and location of different mining equipment and mining personnel in the underground environment. The system is directly linked and integrated to the communication, location and tracking systems installed underground. In this strategy the use of VFDs plays a major role in the supply and distribution of air in the areas where the miners and pieces of equipment are located. Allen & Tran (2011) state that the tagging control system does not only respond to mining personnel or equipment locations but also to the environmental impact that the pieces of equipment or personnel introduce. The airflow distribution is also calculated according to the different rules and capacities assigned to each piece of equipment or type of task assigned to different mining personnel. The rules that control the system can include exhaust tests and dilution formulas supplied by equipment manufacturers. However, this strategy is more concerned with the air quantities not qualities in the location where the different tags are located (Acuña, et al., 2016).

6.5.5 Level 5 Environmental Control Strategy

The fifth control strategy uses real-time environmental data to control the ventilation systems underground. The environmental data is captured from different environmental sensors installed in the underground environment (Acuña, et al., 2016) including (but not limited to) gas, dust, heat stress, and DPM. These sensors trigger the automatic airflow distribution into the different areas identified by the environmental variables (Allen & Tran, 2011; Acuña, et al., 2016). The environmental control strategy is classified as both a quantity and quality control strategy. The air distribution will be set to achieve the mandatory regulatory requirements for each environmental condition. The control system ensures that all the recorded values from sensors are within the threshold limit values (TLVs) set in the regulations.

The environmental strategy generally can encompass all the other previously discussed strategies. Acuña, et al. (2016) state the environmental control strategy can be used as a failsafe system which triggers whenever any environmental parameter goes beyond the preset threshold values. The failsafe capability of the environmental control makes it suitable to work as the ultimate control strategy when compared to the other aforementioned strategies.

The use of VOD strategies does not only unlock health and safety benefits but significant energy savings. With energy especially electricity being a significant cost in underground deep-level mining, unlocking energy savings will reap considerable financial benefits for the mines. This will help the mine channel some of the finances into maintenance and implementation costs as well as labour. Hence the implementation of VOD strategies in in the integrated framework is critical. Table 6.2 summarises all the different VOD control strategies and their potentials to impact health and safety in the underground environment.

Table 6.2 VOD Control Strategies Implementation modified from (Acuña, et al., 2016)

						INFLUENCING MECHANISM IMPACTING HEALTH AND SAFETY			
						Fans (on/off, SS, VFD)		Environmental variable (quantity or quality approach)	
Level	**VOD**	**Personnel and vehicle information**	**Control Strategy**	**Sub control strategy**	**Description**	**Auxiliary**	**Main**	**Quantity (airflow volume)**	**Quality (Contaminants)**
1	VOD based on expected personnel and vehicle distribution	Expected distribution of personnel and vehicles	Manual	Manual or sensor loop set point	Local or remote manual start/stop, setting set points on devices	on/off	SS or VFD	Regulation	TLV
2			Time of day scheduling	Manual or sensor loop set point	Automatic execution of sequenced actions on devices at specific time	on/off	SS or VFD	Regulation	TLV
3			Event based	Manual or sensor loop set point	Automatic trigger of prescribed actions in reaction to configured events	on/off	SS or VFD	Regulation	TLV
4	VOD based on real-time personnel and vehicle distribution	Real-time Tagging data	Tagging	Auxiliary and/or Primary fans	Automatic adjustment in the ventilation system based on real-time personnel and vehicle tag data	on/off or VFD	SS or VFD	Regulation	Specified air quality based on equiment exhaust tests & dilution formulas
5		Real-time sensor data	Environmental	Auxiliary and/or Primary fans	Automatic adjustment in the ventilation system based on real-time environmental data	on/off or VFD	VFD	Failsafe	TLV

6.5.6 The Role of Miners and Monitoring Systems

The ventilation strategies discussed in this section play a major role when combined with the different available monitoring systems in the proposed integration framework. From the proposed framework, the recommended vehicle and personnel tracking system is the Minetec Trax. In Chapter 5.4 of this dissertation, it was shown that the Minetec Trax is capable of tracking the location of both mining personnel and mining equipment in real-time, showing the actual co-ordinates. Integrating the Minetec Trax with the aforementioned VOD strategies will ensure that miners and equipment are always safe and exposed to the healthy environments through the automatic adjustment of the ventilation using the tagging strategy. The other benefits of using the Minetec TRAX system is its capabilities to demarcate the areas miners and mining equipment must not enter. This functionality is very useful in the implementation and enforcement of Section 23 of the MHSA.

For gas monitoring, Chapter 5 of this dissertation proved that the Schauenburg GDIs, PTC lamps and fixed gas detectors are capable of monitoring gases in real-time. This makes the Schauenburg system useful in the integration with the environmental VOD strategy. The integration of the two systems allows for a safe and healthy working environment, as it is possible to maintain the gases within their mandatory TLVs. For dust monitoring, chapter 3.4 of this dissertation identified the continuous personal dust monitors (CPDMs) and the Helmet-CAM technology as leading practices which are available for real-time dust monitoring and can also track if a miner dust exposures are not beyond the regulatory respirable dust exposure limits. Integrating these two to the Environmental VOD strategy can also ensure that miners are not exposed to excessive respirable dust. If they do get exposed, these technologies will be able to pinpoint the exact areas where the miners were exposed and if a miner has been exposed beyond the exposure limits, the miner will be immediately withdrawn from working in areas which exposes them to respirable dust.

The Schauenburg fixed gas detectors are also recommended for a real-time fire detection system. When this system is integrated with both the environmental and event based control strategies, it will be easy to have early warning alarms for fires. The ventilation system will be controlled in such way that the fire is deprived of oxygen so that it does not spread and be contained in certain underground areas. The fire detection system suggested in the framework must also be equipped with either a water based fire suppression system or a compressed air foam fire suppression system. The fire suppression systems must be automated, and always be both maintained and remotely checked by an automated system for its full functionality, to avoid incidents such as that discussed in the Palabora fire incident in Chapter 4.4, where there was no water in the fire suppression system when a fire broke out and this ended up claiming lives underground.

The deployment of real-time heat stress management systems is also critical especially in deep level mining environments which are generally very hot and humid. As discussed in

Chapter 3.5, these systems must include real-time temperature, humidity, barometric pressure and airflow monitoring. The real-time systems must be integrated to the VOD system. However, when accessing abandoned or old working areas, there is usually no ventilation systems installed, and it is important for the people going into these areas to wear ice jackets and also undergo proper acclimatisation. These must be checked in the lamproom before deploying the miners to underground workings. There must also be adequate water supplies for the workers working in these environments, to ensure that they are well hydrated to combat heat stresses.

The integration framework shown in Figure 6.1 shows that all the real-time monitoring and control systems must also feed their data to the VOD system, and the systems all send data to the control room database. This must be done in a manner that ensures that when a health and safety decision is made, all the health and safety aspects of the underground environment will be considered. On the issue of miners entering dangerous working, the integrated framework can play an important role to ensure that miners are warned in real-time to withdraw. Dangerous workings can also be geofenced using the Minetec system and Schauenburg systems, such that when miners go beyond certain boundaries, their PTC lamps will alarm continuously and real-time messages will be sent to and from the control room. In the event that mine workers decide to withdraw due to any of the risks whether it be a gas outburst, respirable dust concentration beyond accepted limits, fire outburst and heat stress, the system will automatically record these events and location of both the miner and the event in real-time. This will help in eradicating the issue of the ‘blame game’ amongst mine workers and mine management.

Through the co-ordination with the lamproom monitoring system, the real-time monitoring systems can be programmed to set off alarms when miners try to go into sections they are not acclimatised to work in. However, the role of miners as front-line workers, to exercise decentralised decisions as discussed in Chapter 3.7, is paramount. Regardless of implementing all these monitoring systems, miners still carry the role of the ultimate line of defence when exposed to real-time risks in the underground environment. For instance, if an alarm rings to tell the miner to withdraw from a dangerous working, it is only the miner who can decide to obey or disobey to follow and react to the alarming signals, be it a gas outburst, respirable dust exposures beyond accepted limits, fire outburst, or a heat stress management system warning. Hence, the emphasis of training miners to know when to exercise their decentralised decision-making, is critical if the goal to zero harm is to be achieved.

As discussed in Chapter 3 of this dissertation, the miner plays a critical role of being a 'sensor' of their immediate underground environment. A strong culture of safety must be instilled in the frontline miners such that they can perform their 'sensor' role and become risk averse. The miners must reach a point where they are not afraid to exercise their Section 23 right of withdrawing from dangerous workings when they sense any kind of danger.

The use of an integrated system will ensure that there is also evidence to back up the decisions miners make when decide to withdraw from dangerous workings. It is important to note that the full benefits of the individual systems recommended in the proposed framework, are outweighed by the full benefits which come out when the systems are integrated. Through the use of the control room database, historic events from the monitoring systems can be stored and be used to predict some causes of some future events and they can also be used to determine or predict the environmental conditions in abandoned area. This information can be helpful in the acclimatisation of workers before sending them to these areas. Information such as the daily real-time respirable dust exposure data from the miners' CPDMs and Helmet-CAMs can also be used in making decisions on the areas a miner must work in every shift. By using these systems it is possible that no new cases of respirable diseases will be recorded.

The Internet of Things can also be used to provide a real-time communication platform for all the events and activities occurring at any given time underground and this can help in the real-time decision-making process from the highest management to lowest employee working underground. Accident investigations can also become transparent and quick as the information will be available to everyone in real-time. The communication backbone of the mine network can be run on fibre optics with a mesh network topology. As discussed in Chapter 3.3, the network infrastructure must be redundant and rugged to ensure that it can survive the harsh underground mine environments.

7 IMPLEMENTATION PLAN

The foregoing chapter put forward a framework on how to integrate different mining technology systems to improve health and safety in underground mines. However, it is important to discuss a roadmap in which successful implementation of the technologies can be achieved in the mining industry. Various researchers (Scott, 1998; Falmagne, et al., 2001; Mottola, et al., 2009; McCarthy, 2011; McCarthy, 2016; Pratt, 2017) have carried out case studies on the causes of both success and failure of implementation of mining technologies in the mining industry. The underlying findings from their studies showed that regardless of how promising and good a technology can be, a good implementation plan is paramount for the technology to be successful in the mining industry. Scott (1998) asserts that having poor implementation plans can lead to underutilisation of good existing technologies in the mining industry. To help solve these shortcomings, Scott (1998) proposed a criteria which can be followed for successful implementation of technologies. He suggested that for any technology or system to be successfully implemented it:

- must be needed;
- must work;
- must be simple and reliable;
- must be supported by management;
- must be understood by the people who have to make it work;
- must be economic and;
- must be compatible with the overall process.

This section discusses the aforementioned and other critical factors and how they affect the implementation of new technologies and systems in the mines.

7.1 Training

Before implementing any new technology system, it is imperative that everyone who will use the technology be adequately trained. Mines must properly train their workforce to be fully accustomed to the new systems or technologies. If needs be, the mine must even hire new skilled personnel to manage and maintain these systems. Training of personnel is critical and has a significant impact in the successful implementation of new systems and technologies in mines.

Bauer & Mantwill (2013) point out that there is need for mine management to invest in their workforce through improving worker motivation, behaviours as well as training for the technology implementations to be successful. Scott (1998) goes on to add that training requirements, industrial relations and management issues must be addressed before implementing new systems. Management and education have the greatest potential to impact performance of these systems. Development and sourcing of skilled people with the appropriate expertise which is usually scarce in the mining industry is also important in cases were the mines do not have the right skills for the technologies. For example for smooth control room operations and management, some of the new skills which need to be hired may include information and technology (IT) teams, server support teams, data scientists, software developers, and domain experts (Global Mining Guidelines Group, 2019).

The need for skilled workers and having a steady supply of these workers to operate, inspect, monitor, and interpret the data is also important. Mochubele (2014) found that the lack of skilled workers was one of the major drawbacks of implementing technologies in the mines. Any mine implementing new technologies must ensure that there is always a pool of these skilled workers readily available for most of the critical jobs other than relying on specific individuals. Relying on a few individuals is risky especially due to the usually high skill turnover in the mining industry. The mine must ensure that there is a proper plan to deal with high turnover in areas which involve the technology to be implemented. It is important to have a team trained and be made responsible for checking the systems integrity on a daily basis. The feasibility studies of implementing the new technologies must fully consider the costs and disruptions that may arise due to additional training needs. Failure to consider these can lead to big cost implications. Inadequate training can jeopardise operations due to unbearable breakdowns which can even lead to the need of hiring external labour which in many cases can be costly, even for simple problems. In the worst-case scenarios, the implications of the breakdowns can be fatal.

7.2 Reliability, Availability and Fit for Purpose

Before fully implementing any technology system, the technology must prove that it can be reliable and available at all times. Reliability of the proposed technology must be tested before being implemented. When it comes to systems that play a critical role in miners' health and safety, an unreliable technology can cause more catastrophe when it breaks down frequently. In the underground mining context, system reliability must not be compromised at any costs especially when health and safety is concerned. However, the unreliability of the systems and technologies implemented on the mines is in most cases, directly caused by the unavailability of skilled workers who can adequately and correctly maintain the systems. This highlights the importance of training and hiring skilled personnel as discussed earlier.

Scott (1998) also highlights that, for a system to be successful and to get buy-ins from the stakeholders, it must be both reliable and suitable for its specified purpose. Another important aspect to be considered before implementing a new system or technology is making sure that the technology is fit for purpose and designed for the specific environment it is being installed in. For mines, system components must be rugged enough to operate for long periods of time, in harsh and dynamic underground conditions. For the alert systems, the alarms must be reliable and ensure that the number of false alarms is minimised.

Having alert and warning systems with frequent false alarms can lead to employees not trusting the systems. This, as discussed in the previous chapter, can create a false sense of security and in cases of emergencies or genuine incidents it then becomes hard for employees to differentiate between real and false alarms (Watkinson, et al., 2016).

7.3 Buy-ins

The need for the full buy-in of new systems from all mining stakeholders, from senior management to front-line workers must not be underestimated, for the successful implementation of new technologies. According to Falmagne et al. (2001), it is important to first seek the acceptance of the different new technology systems from the mine operators and other mining stakeholders before implementing the systems underground. Mottola et al. (2009) add that mine management must make sure that they do not only prioritise buy-ins from technological experts who will manage the systems, but must also convince the ordinary workers to take full ownership and accept the technologies. Without doing so, ordinary workers can easily sabotage the new systems. All mining stakeholders must be consulted, properly addressed and fully involved in the implementation. Lack of senior management support in the implementation of mining technologies can also lead to the failure of the implementation, hence buy-ins from them is critical before trying to market the idea to other stakeholders down the mining value chain.

Industrial resistance is another important aspect which must be considered before applying new technologies. The South African mining industry is known to be strongly unionised, so it is also important to ensure that the organised labour and all other mining stakeholders including government buy-in to the idea of implementation of the new systems (Pratt, 2017). These parties must be made to be fully aware of the benefits that come with implementing the technologies. Mottola et al. (2009) emphasises this by arguing that in most of the cases, technologies and new systems are implemented in mines and the end-users usually do not know or fully understand the benefits of using the technologies. The authors attribute these failures to mine management whom they claim do not involve the end-users in the strategic decision-making processes and planning stages of the deployment of the new technologies.

Involving workers in the planning and implementation of technologies also help management in developing fit for purpose standard operation procedures (SOPs) for the technologies. This speaks on the need for properly designed change management and communication plans which are discussed later in this chapter. Mine management can also motivate technology buy-ins by genuinely ranking health and safety issues at par with both production and efficiency. Buy-ins from all stakeholders before the implementation of technologies are of equal importance for high impact projects, hence must be prioritised.

7.4 Maintenance

The impact of poor maintenance can translate to high maintenance costs as well as high rates of system unavailability which in turn leads unreliability (Falmagne, et al., 2001). Maintenance requirements for the systems must be known beforehand and the maintenance schedules must be properly planned before implementation of technologies (Scott, 1998). Using advanced tools such as predictive maintenance can be helpful to curb breakdowns and enhance technologies' reliability. However, good maintenance practices can only be achieved by hiring the right people with adequate skills as discussed previously.

7.5 Collaboration

Scott (1998, p.1) states that "the successful implementation of new technologies is entirely dependent upon the actions, enthusiasm and skills of people, both as individuals and in groups". Most of the technologies and systems that are adopted by mines are usually outsourced from either one or more vendor companies. Partnering and closely collaborating with these vendor companies is also of paramount importance. The mines must nurture their working relationships with the vendor companies to ensure that the systems are fully optimised and reliable. The vendor companies and equipment manufacturers must ensure that they also provide robust systems and good service plans for their products.

For collaborations to be effective, any issues which may directly or indirectly affects any department in the mine due to the implementation of the new technology or systems must be addressed before going forward (Falmagne, et al., 2001). The electrical and information technology (IT) personnel play a critical role in the implementation of most the new systems. These people must be well informed and consulted on any of the plans of the implementation process. Competent personnel followed by appropriate and adequate continuous training of these personnel is also very important for the implementation process to be successful. It is important to note that, just like their development, the implementation of mining systems and technologies is just as complex. To reap good results and the full benefits of these technologies, different stakeholders must be committed to provide their input from their different skills background. However, depending on their skills, the levels of involvement in the implementation stage will be different. Bauer & Manthill (2013) state that for positive results to be realised, there must be 'unconditional commitments" by both management and mine workers during the implementation process.

7.6 Communication

To achieve all the aforementioned, proactive and clear communication plans must be in place. The communication channels must involve all stakeholders. Management must ensure that they provide and allocate all the necessary resources for the implementation project to be successful. The communication plans must inform on how a change in the mine culture, skill-levels as well as work habits from all mining stakeholders is needed for the implementation of the technologies. Bauer & Mantwill (2013) also add that communication strategies must aim to raise and change awareness of safety issues amongst workers. The importance of communication is further discussed under the change management section to follow.

7.7 Change Management

The introduction of new technologies and systems in mines usually cause changes in the mining processes, individual roles and organisational structures. These changes are usually the most difficult challenges that must be overcome for successful implementation of new technologies. To overcome and manage the challenges, a proper change management plan must be put in place. McCarthy (2016) states that change management is the bridge between a good technical solution and the company achieved value from implementing the solution. He further states that change management is a vehicle that is required to "create buy-ins and commitments" from all stakeholders due to implementation of any new technology. Since implementing new technologies in mines changes the ways of doing things, change management becomes significantly important. Lack of proper change management plans is ranked as one of the top causes of failure of technology implementation (Mottola et al., 2009; McCarthy, 2011; McCarthy, 2016; McKinsey & Company, 2018; Richardson, 2018).

McCarthy (2011) elaborates on the need of change management, which he defines as the "the application of processes and tools to address the people side of change". It is important to address the general resistance to change in the nature of humans before implementing new systems and technologies. McCarthy (2011) further states that one of the technologies which usually face resistance is that which involves the tracking of mining personnel and equipment. He states that "employees don't mind working or explaining what (they) did, but (they) don't like being watched while (they) are working" (McCarthy, 2011, p.3).

Mottola et al. (2009) add that, because changing people and their working methods is generally difficult, it is crucial for mine management to carefully plan for change. Proper change management can make technology transfer to operators a positive experience which can influence workers' enthusiasm, instead of creating disturbing experiences, which can incite workers' resistance (Mottola, et al., 2009). An effective change management plan enables employees to understand how a technology-enhanced system will make their lives better, safer and more productive (McKinsey & Company, 2018). The change management plan must ensure that it nurtures a change in the mine culture, skill-levels as well as work habits from all mining stakeholders. McCarthy (2011) and McCarthy (2016) state that change management can be applied under two perspectives namely, organisational change management and individual change management.

7.7.1 Organisational Change Management

Organisational change management is a process which considers the tools and actions to be used by the project team to support all the individuals across the organisation who will be affected or impacted by the proposed change (McCarthy, 2016; Prosci, 2020a). Organisational change management is generally the management of change as viewed by the manager. The managers include, the implementation project team members, human resources and the business leaders who sponsor the change (McCarthy, 2011). The organisational change management can be summarised by a framework (Table 7.1) proposed by McCarthy (2011) and McCarthy (2016).

The framework (Table 7.1) shows four areas that must be addressed in the organisational change management process. The top mine executives play a critical role in the success of organisational change management. They must adequately sponsor the change program and proactively communicate their change plans. However, McCarthy (2016) states that one of critical steps in organisational change management is establishing a change management team (CMT) during the preparation stage (Table 7.1). The CMT plays an important role in enforcing the other phases of the overall organisational change plan. McCarthy (2016) further states that the CMT will be mandated to:

- guide the development of the change management strategy
- develop the change management plans

- facilitate the training and coaching of managers and supervisors
- coach and advise the executive management who will be sponsoring the project
- monitor the change and detect any signs of resistance or opportunities to celebrate success
- ensure that the organisational change management is followed.

Table 7.1 Organisational Change Management Framework (McCarthy, 2011; McCarthy, 2016)

Phase	Activities
1. Preparing for change	•understand the business reasons for the change; establish a sense of urgency •develop a vision for the changed state •assess the organisation's current state and ability to change •assesss the magnitude of the change •select and prepare a change management team •prepare sponsor
2. Planning for change	•prepare the following change management plans: •communications plan •sponsor road map •resistance management plan •coaching plan •training plan
3. Implementing change	•implement change •measure progress •identify gaps •resolve issues and adjust plans •manage resistance and recognise show stoppers
4. Reinforce and transition	•gather feedback on change success (or failure) •audit compliance; identify root causes of non-compliance •identify and implement corrective actions •generate and celebrate short-term wins •integrate change into culture

The role of communication in an organisational change management process cannot be underestimated. The selection of the right messengers during the communication process is also very important for the change to be effective. McCarthy (2011) states that the change message delivery must be carried out at two distinct levels. The first level must be from senior mine management level to their employees and the second level must be from the management level represented by employees' direct supervisors.

McCarthy (2011) states that the messages from the senior management must be able to make it clear to the general populace of employees why there are changing. The senior management message delivery must also highlight the risks which come if the business does not change and also how the changes align with the overall vision and direction of the company. From the second level of message delivery, employees expect their direct supervisors to explain the impacts of the changes at individual levels as well as their team level (employee and team members). At this level the employees also expect their immediate supervisor to highlight how the changes will affect their day-to-day responsibilities.

Most importantly the direct supervisor must be able to highlight the direct benefits which come with the changes to their employees at both individual and team level. McCarthy (2011) and McCarthy (2016) call these the important 'what's in it for me?' and 'what's in it for us?' questions, which the workers want their direct supervisors to answer when proposing a change. Being able to answer these questions and convince employees at the two distinct levels is very important for a successful organisational change management.

7.7.2 Individual change management

As highlighted earlier, the other important aspect of change, is individual change management. Individual change management is the management of change considering the employee (McCarthy, 2011; McCarthy, 2016). Individual change management involves processes of trying to understand how the individual employees experience change and what they need to change successfully. For individual change management, more emphasis is placed on the different tools and techniques that can be called on to help employees in transitioning through the whole change process. Prosci (2020a) states that if employees at an individual level do not embrace and adopt change, projects will fail.

Hence, for an organisation to succefully change their way of doing things and reap the desired results, they must first ensure their employees are successful at an individual level.

To help with successful individual change management, a model called the Awareness, Desire, Knowledge, Ability and Reinforcement (ADKAR) model was proposed by a change management research group called Prosci (McCarthy, 2011; McCarthy, 2016; Creasey, 2019; Prosci, 2020b). The ADKAR model summarises how individuals progress through change. It emphasises that when individual change management is carried out, following the model can lead to highly successful change in organisations. The 5 stage process of implementing the ADKAR model in individual change management is summarised in Figure 7.1.

According to McCarthy (2011), McCarthy (2016), Creasey, (2019) and Prosci (2020b), the ADKAR model achieves its purpose by introducing 5 staged activities which focus on,

- building awareness in employees or individuals on the need to change;
- monitoring and instilling the desire to participate and support change;
- emphasising on building knowledge of how individuals can change;
- assessing individuals' abilities to demonstrate their skills and implement the actual change in their daily work activities and;
- finding ways of reinforcing the new ways to keep the change in place and not go back to the old ways.

7.7.2.1 Awareness

The awareness programs for mining employees can be carried through messages from executive mine management by hosting events and general employee communications such as (but not limited to) emails and memos. During the events mine management must transparently show and convince their employees at individual level, the importance of the change. Lack of awareness can lead to resistance to change from individuals (Prosci, 2020b).

7.7.2.2 Desire

To incite and to motivate the employees to desire and accept the proposed change, there is need for visible leadership from the highest level of the organisation. The project must be well sponsored and employees must be engaged on all the aspects of the change (McCarthy, 2011; McCarthy, 2016; Creasey, 2019; Prosci, 2020b). There is need for management through the CMT to identify any areas which face resistance and they must proactively manage the resistance. One other motivating factor can be tying the successes of the change to some incentives.

7.7.2.3 Knowledge

The building of knowledge stage on the change must be carried out through formal trainings and education. There must also be easy access to information on the change to general employees. Mentoring programs at different levels must be initiated. There must be comprehensive employee coaching programs (Creasey, 2019). These coaching programs must include one-on-one sessions as well as group sessions. There must clear guidance on how to troubleshoot some of the problems which might rise due to the change (McCarthy, 2011; Prosci, 2020b).

7.7.2.4 Ability

Building individual employee abilities on the change must be done through practice. Employees must be offered adequate time to learn and develop the necessary skills required. There must also be adequate support from management through coaching and supply of the right tools for the job (Mottola, et al., 2009). Experts in the fields of the proposed change must be accessible and available to guide and help individuals when necessary. Giving feedback on performance is also critical on this stage and clear performance monitoring schemes must be put in place (Prosci, 2020b).

7.7.2.5 Reinforcement

When the employees eventually adopt and embrace the change there is need for the organisation to celebrate on the successes and make sure the changes stays in place. Employees must be rewarded for the successes. Mine management must put up compensation and appraisal systems which make sure the change goes forward. These compensation systems must be fully be backed by visible and transparent performance scorecards. Any areas of weaknesses must be identified and if any failures are met on the way, corrective actions must be implemented. Accountability mechanisms must be emphasised for the successful reinforcement of the change (Prosci, 2020c).

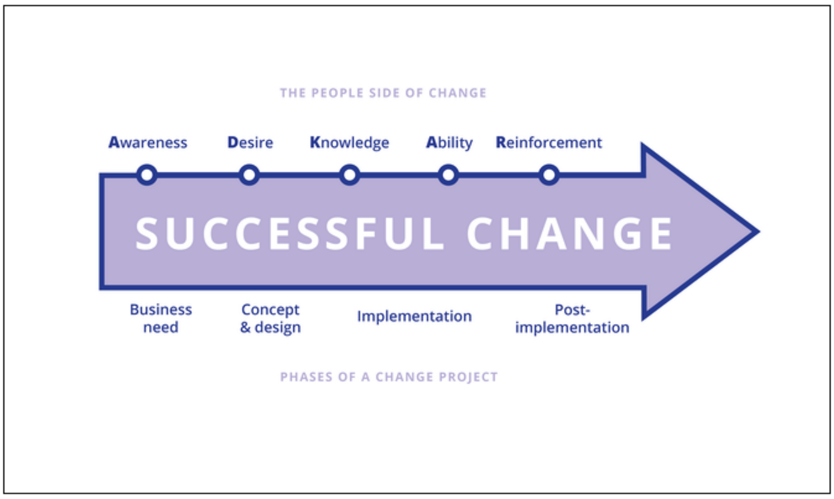


Figure 7.1 showing a Roadmap of a Successful Individual Change Management (Creasey, 2019)

Successful change management addresses the most critical factors (training, collaboration, buy-ins and communication) discussed earlier in this chapter which lead the successful implementation of new technologies and systems. Hence it is imperative for a mine to have a solid change management plan which emphasises on both individual and organisational change, because without both, it is highly likely that implementation of new systems will be unsuccessful.

7.8 Staged Implementation

Apart from all the aforementioned, staged implementation of the technologies mines can also lead to successful projects. Staged implementation of the systems allows for time for the workforce to make a swift cultural shift and develop the necessary skills to optimise the new technology. Staged implementations allow for the mines to run pilot tests in small sections of the mine and after successful test periods, upscale to full implementation throughout the whole mine. This makes it possible to reduce and spread the potential risks over time (Richardson, 2018). Staged implementations according to Richardson (2018) lead to reduced downtimes, which could come from going too fast in implementing some technologies. Richardson further adds that staged implementation also ensures that there is sufficient infrastructure in place and control systems sufficiently modernised to handle the additional demands from data collection and processing that come with the full technology implementations.

Scott (1998) adds more to the foregoing, by stating that staged implementations of technology can help management in addressing and managing the human-technology interfaces problems. Management of the interface between people and technology must be given enough attention before and during the implementation of the technologies. This aspect must be addressed by the engineering, industrial relation, training, operators and management. For all these to be sustainable, long-term technology policies must be developed. Staged implementation of technologies will also reinforce the change management plans, as it will be easy to track the project successes and failures.

7.9 Proper Risk Management

The need of proper risk assessments and management for the new technologies before implementing them cannot be underestimated. Failure or malfunction of sensor systems can lead to catastrophic events (Pratt, 2017). However, through proactive risk assessments and management programs, adequate controls and mitigation plans will be made available. Mines must make sure they put in place proper risk management plans to deal with risks such as network infrastructure failure, inability to secure skilled workers to operate, manage and maintain the systems; failure of technology vendor companies meeting their obligations, high unavailability of IT services due to downtimes; server data losses which cannot be recovered; poor service delivery and poor quality and design of products (Spacey, 2016), data loss (need for back-ups) cyber security (unauthorised access and algorithm interference) and computers and software going 'corrupt' because of viruses.

To manage some risks, such as network failures and destruction of power or network cables, mines must invest in R&D for redundant systems. As mentioned earlier, Mochubele (2014) adds that one the major risk in mining is the lack of skills, hence for the successful implementation of technologies, addressing this problem is very critical. The risk of system sabotage from miners due to privacy issues which are brought up by monitoring systems must also be properly managed. It is important to note that, new technologies also bring about the rise of new risks, and this emphasises the need for continuous risk assessment and management programs.

Another important risk that must be addressed, is alarm fatigue. There is a high risk that some employees, especially control room operators may develop alarm fatigue, since they work in an environment where they have to respond to a number of alarms from all the underground working areas (Watkinson, et al., 2016). The major cause for alarm fatigue is false alarms. High frequency of false alarms will eventually leave control room operators with not being able to distinguish between real threatening alarms and false alarms. The risk of alarm fatigue can be significant and fatal in some life and death situations in the underground environment, hence there must be proper alarm management plans supported with proactive risk assessment and management plans. It is important that overall, proactive continuous risk assessments and management strategies are put in place before implementing the technologies so the systems may reap the desired results and ultimately achieve the goal of zero harm in the mining industry.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

There has been a significant improvement in mining fatalities over the years in South Africa. However, the goal for zero harm has not yet been achieved. The introduction of mining technologies such as AMS and tracking systems are cited as some of the contributors to the improvements in mine fatal incidents. There is additional potential to achieve more by implementing these technologies throughout the mining industry. Nonetheless, despite these improvements, the research showed that the global mining industry (South Africa included) is still focusing more on safety related fatalities than health related ones. There are significantly more fatalities due to health related issues in the mining industry but due to their long-term effects and the delay in causing death and hence less media attention, health issues are ignored and underreported. The research emphasised the need for the mining industry to give more or at least equal attention to health issues as they do to safety issues since the consequences of health risks are long term and cause more fatalities. The research further showed that there is a great potential in using technology to manage risks and enhance both health and safety in underground mines.

To answer one of the fundamental questions posed in this research, it can be concluded that, yes, control room operators can be enabled to communicate health and safety decisions to the underground workers in real-time and help in eliminating fatal accidents using some of the available technologies. From the research findings of the study, it is important to note that, for the mining industry to realise the full benefits of these decisions, there is the need to use integrated systems. The research also highlighted the need to integrate human decision-making with Artificial Intelligence systems to minimise errors.

The research also managed to answer the fundamental question on, how Section 23 of the MHSA can be implemented using technology. The research findings also cite the causes of a considerable number of past accidents which occurred underground as due to the ‘blame game’ between miners and mine management on the issue of entering and withdrawing from dangerous workings. Miners claim that their right to withdraw from dangerous workings is usually difficult to exercise especially when there is no real-time evidence to substantiate the presence of dangerous conditions. This either leads to fatal incidents or in some cases victimisation of the miners. To the contrary, mine management claim that miners are sometimes negligent and usually enter unauthorised, risky working areas, regardless of them being empowered to use their right to withdraw from dangerous workings. The findings from the research show that the use of integrated technologies can help in successfully implementing Section 23 of the MHSA by geofencing these areas as well as warning miners and providing evidence to justify the decisions by both miners and mine management with regards to withdrawing from and entering dangerous workings.

The research also discussed some of the leading practices that can help the mining industry to achieve healthy and safe workplaces. The research further reviewed case studies on some past and recent fatal mining accidents that could have been avoided if some of the leading practices and new available mining technologies had been installed at the mines. After reviewing the case studies, a number of monitoring and control systems capable of continuously monitoring, the real-time underground atmospheric conditions, miners’ and equipment locations were identified and tested. The tests proved that it is possible to monitor the atmospheric conditions, miners’ and equipment locations in real-time and also sent the data to and from the surface control room. The research findings also showed that the systems can be set up such that, the rules of data being relayed to and from the control room to the production zone, are measured against Standard Operating Procedures (SOPs) and the MHSA guidelines.

The research tested a few available standalone systems and the tests proved that it is possible to use these systems to manage different ventilation related risks in the underground environment. However, the research findings emphasise on the need to integrate standalone systems. The findings showed that to achieve proactive risk management in underground mines, systems integration is critical. The research put forward a systems integration framework, which highlighted the roles which must be played by different stakeholders as well as technologies to achieve zero harm. The research highlighted that for the mining industry to have a solid defence-in-depth strategy to curb fatalities, there is a need for empowering the front-line mine workers to exercise their decentralised decision-making role. For the miners to be able to exercise this role freely and effectively, there is need for continuous training on proactive risk management. The framework also highlighted the role of the regulatory body in having a mandate to inspect and enforce the regulations and SOPs when establishing the rules for data entering the control room. This will ensure mines promote lawful and compliant mining operations.

The research also showed that achieving zero harm in the mining industry does not only lead to the saving of lives but also helps the mining companies in preventing loss of production due to Section 54 production stoppages. By involving the regulatory body in the implementation of these technologies it helps in the reduction of the risk of regulatory burden to the mining industry. The research also showed that any mining company with high fatalities has a high risk of damaging its reputation which can affect its social licence to mine as well as investor confidence. There are also some other benefits other than safety that come with implementing the proposed framework. One of the benefits is that of energy savings through VOD. The research highlighted that the use of VOD can lead to high energy savings, and since energy costs are a significant part of the total costs of mines, this can save money which can be channelled to either safety projects or shareholder dividends.

To effectively and successfully implement technologies in the mines, there is need for mining companies to put up a solid implementation plan. The research showed that failure for mining companies to have a proper implementation plan can lead to good technologies failing. The implementation plans must make sure that there is a proper change management process before rolling out the technologies. Collaborations and buy-ins from all mining stakeholders is also critical before implementing technologies. There might be great need for the mining industry to hire new skills to manage and use new technologies in the mines. Staged implementation of technologies is crucial to ensure that the reliability and shortcomings of the systems are determined before deploying them to the whole mine. Above all, the research showed that nurturing a solid safety culture in the mining industry is the most important. Introducing technologies and other risk management tools will supplement the safety culture. Frontline miners play an important role as ‘sensors’ and their decentralised decision-making duty acts as the ultimate line of defence in cases of emergency. It is important that the miners are properly trained to play their critical role as decentralised decision-makers.

8.2 Recommendations for future work

It imperative that future research be conducted to independently test the effectiveness and reliabilities of available technologies from vendor companies. The tests must be carried out by research institutes with no economic interests in the projects, so that when the integrated systems are recommended for implementation in underground mines, their actual capabilities and shortcomings will be fully known. Government must also invest into R&D projects and collaborate with mining companies, vendor companies as well as research institutes. This is to ensure that the price of mining technology systems are subsidised and perhaps this will motivate mining companies to accelerate the adoptions of mining technologies to enhance health and safety in underground mines. Further research must be undertaken to check the compatibilities of the different technologies in the proposed framework of integrated systems. There is also need for the regulatory authority to initiate research studies into the available technologies, so that they will be guided in formulating regulations that will govern the use of different technologies in the mining industry.

Ultimately, there is great potential for the mining industry to achieve the goal of zero harm through the use of integrated systems. Miners and control room operators can be empowered through the use of technology to respond to typical health and safety exposure risks in the production environment.

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APPENDICES

Appendix A Equipment Calibration History

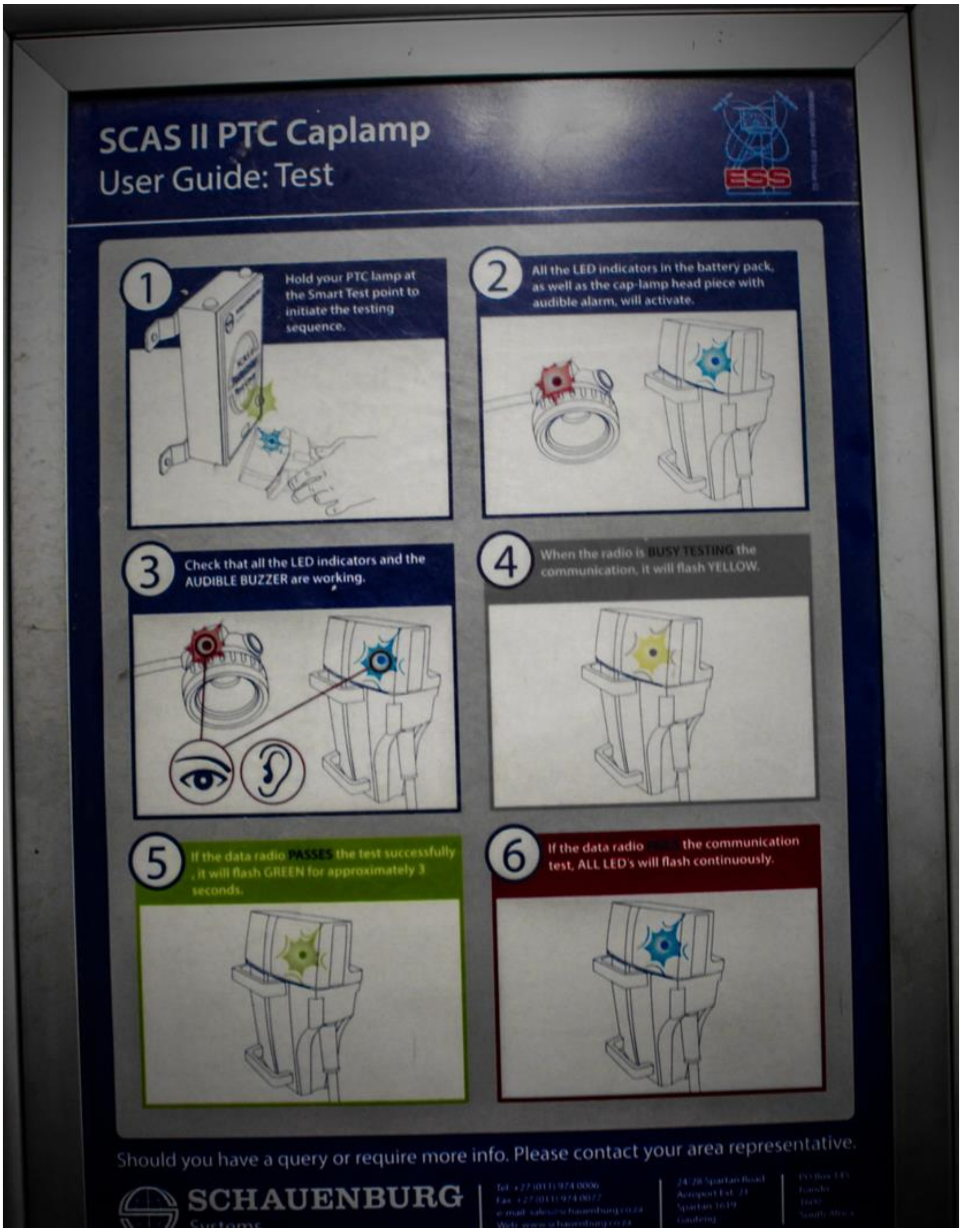
MIMACS-II — **Test And Calibration History Report** — **Wits University**

Start Time = 2018-01-01 15:30:05 | End Time = 2019-11-10 15:30:05 | Equipment Id = SEN001 | Lamproom = [No Filter]

Date and Time	Station Type	Type	Gas Type	Measured Value	Outcome
2019-09-25 08:22	FastAutoTest	Tested	CH4		fail
2019-09-25 08:22	FastAutoTest	Tested	CO		fail
2019-09-26 10:37	AutoCalibration	Calibrated	CO	348.00	pass
2019-09-26 10:37	AutoCalibration	Calibrated	CH4	2.50	pass
2019-09-26 11:48	AutoCalibration	Calibrated	CO	348.00	pass
2019-09-26 11:48	AutoCalibration	Calibrated	CH4	2.50	pass
2019-10-18 14:41	AutoCalibration	Calibrated	CH4	2.50	pass
2019-10-18 14:41	AutoCalibration	Calibrated	CO	348.00	pass

2019-11-10 15:30:47 1/1

Appendix B Procedure for the PDS functionality test



Appendix C MIMACS System generated report for the LMS testing events

Time	Type	Response Code	Response Message	Employee Id	Person	Equipment Id	Location
2019-12-18 09:32:06	Access Denied - Measurement required	test-required	test-required:Not Tested	SCH0030	DE LANGE AJ	SC2450	Underground Entrance 4
2019-12-18 09:32:16	Access Denied - Measurement required	test-required	test-required:Not Tested	SCH0030	DE LANGE AJ	SC2450	Underground Entrance 4
2019-12-18 09:32:30	Access Denied - Measurement required	test-required	test-required:Not Tested	SCH0030	DE LANGE AJ	SC2450	Underground Entrance 4
2019-12-18 09:33:07	Access Allowed	pass	pass:Proceed	SCH0030	DE LANGE AJ		Underground Return 4
2019-12-18 09:42:09	Access Denied - Measurement required	test-required	test-required:Not Tested	SCH0030	DE LANGE AJ	SC2450	Underground Entrance 1
2019-12-18 09:42:09	Access Denied - Measurement required	test-required	test-required:Not Tested	SCH0030	DE LANGE AJ	SC2450	Underground Entrance 1
2019-12-18 09:42:18	Access Denied - Measurement required	test-required	test-required:Not Tested	SCH0030	DE LANGE AJ	SC2450	Underground Entrance 1
2019-12-18 09:42:58	Access Allowed	pass	pass:Proceed	SCH0030	DE LANGE AJ		Underground Return 1
2019-12-18 09:49:06	Access Denied - Assigned assets missing	assigned-assets-missing	assigned-assets-missing:Asset Missing	SCH0030	DE LANGE AJ		Underground Entrance 4
2019-12-18 09:50:00	Access Denied - Assigned assets missing	assigned-assets-missing	assigned-assets-missing:Asset Missing	SCH0030	DE LANGE AJ		Underground Entrance 4
2019-12-18 09:50:09	Access Denied - Assigned assets missing	assigned-assets-missing	assigned-assets-missing:Asset Missing	SCH0030	DE LANGE AJ		Underground Entrance 4
2019-12-18 09:50:22	Access Denied - Assigned assets missing	assigned-assets-missing	assigned-assets-missing:Asset Missing	SCH0030	DE LANGE AJ		Underground Entrance 4
2019-12-18 09:50:34	Access Denied - Assigned assets missing	assigned-assets-missing	assigned-assets-missing:Asset Missing	SCH0030	DE LANGE AJ		Underground Entrance 4
2019-12-18 09:50:57	Access Allowed	pass	pass:Proceed	SCH0030	DE LANGE AJ		Underground Entrance 2
2019-12-18 09:51:24	Access Allowed	pass	pass:Proceed	SCH0030	DE LANGE AJ		Underground Return 1
2019-12-18 09:51:46	Access Allowed	pass	pass:Proceed	SCH0030	DE LANGE AJ		Underground Entrance 1
2019-12-18 09:52:08	Access Allowed	pass	pass:Proceed	SCH0030	DE LANGE AJ		Underground Return 1