APPLICATION OF BUILDING INFORMATION MODELLING CONCEPTS IN UNDERGROUND MINING: A CONCEPTUAL FRAMEWORK FOR A PRODUCTION ZONE

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DECLARATION

I declare that this dissertation is my own, unaided work. I have read the University Policy on Plagiarism and hereby confirm that no Plagiarism exists in this dissertation. I also confirm that there is no copying nor is there any copyright infringement. I willingly submit to any investigation in this regard by the School of Mining Engineering and I undertake to abide by the decision of any such investigation.

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ABSTRACT

Mines generate significant amounts of data, and the data are converted into information that can be analysed, therefore, it is essential that this information be used efficiently to aid in making appropriate decisions. Failure to acquire complete, accurate data timeously affects the downstream activities in a mine, consequently, affecting the quantity and quality of the production output. It was noted that mining companies do not use data and information efficiently due to challenges associated with mining companies accessing data sets that are incomplete, inaccurate, and delayed. Therefore, this study explored an efficient approach that can be utilised to ensure that mines can have complete and accurate data timeously. The focus of the study was on the production zone of an underground conventional mine. The production zone was selected because there are numerous interconnected activities that take place in this zone such as development, stoping, vamping, sweeping, and other logistics. The research objectives were to analyse the departments associated with the production zone of an underground conventional mine, to analyse BIM concepts, and to conceptualise a BIM-based framework for the production zone of an underground conventional mine. Data were collected from various departments involved in the production zone activities on Mine A through site visits. Furthermore, research related to the Building Information Modelling (BIM) technique was sought. BIM was analysed to determine its applicability in the production zone of Mine A. The key findings for the research study were that Mine A does not have a centralised information environment where the information is shared with the various departments to ensure data integrity. From a BIM perspective, Mine A is on BIM maturity level 0 as there is low collaboration between the departments. It was noted that Mine A can transition from BIM maturity level 0 to BIM maturity level 1 whereby there would be partial collaboration through a central information environment for the integration of information from the various departments on Mine A. A BIM-based framework for Mine A with the themes, digitise, interoperability, bidirectional services, high performance, and communication, was conceptualised to assist with utilising information efficiently, thus improving communication and collaboration on Mine A. For Mine A to efficiently use information, this research study recommended that middleware and data warehousing be used as integration techniques. The combination of the two techniques caters to the flexibility and ease of storing, managing, exchanging, and viewing information. It was also recommended that the Oracle Data Integrator Enterprise Edition and the Oracle Data Service Integrator be used as these two tools cater to the four themes identified in the BIM-based framework for Mine A. A backup system for the information generated by the mine was also recommended.

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1. INTRODUCTION

Mining is a primary industry that plays a role in various countries across the globe. It is noted that more than 150 countries globally have mining operations that contribute to the country's gross domestic product (GDP). In 2017, the global run of mine (ROM) production was 18.5 billion tonnes, with Asia-Pacific being the largest contributor to the ROM (Mining Technology, 2018). Figure 1.1 illustrates the global ROM production growth and the share of major commodities across the globe in 2017 and the predicted share for 2022.

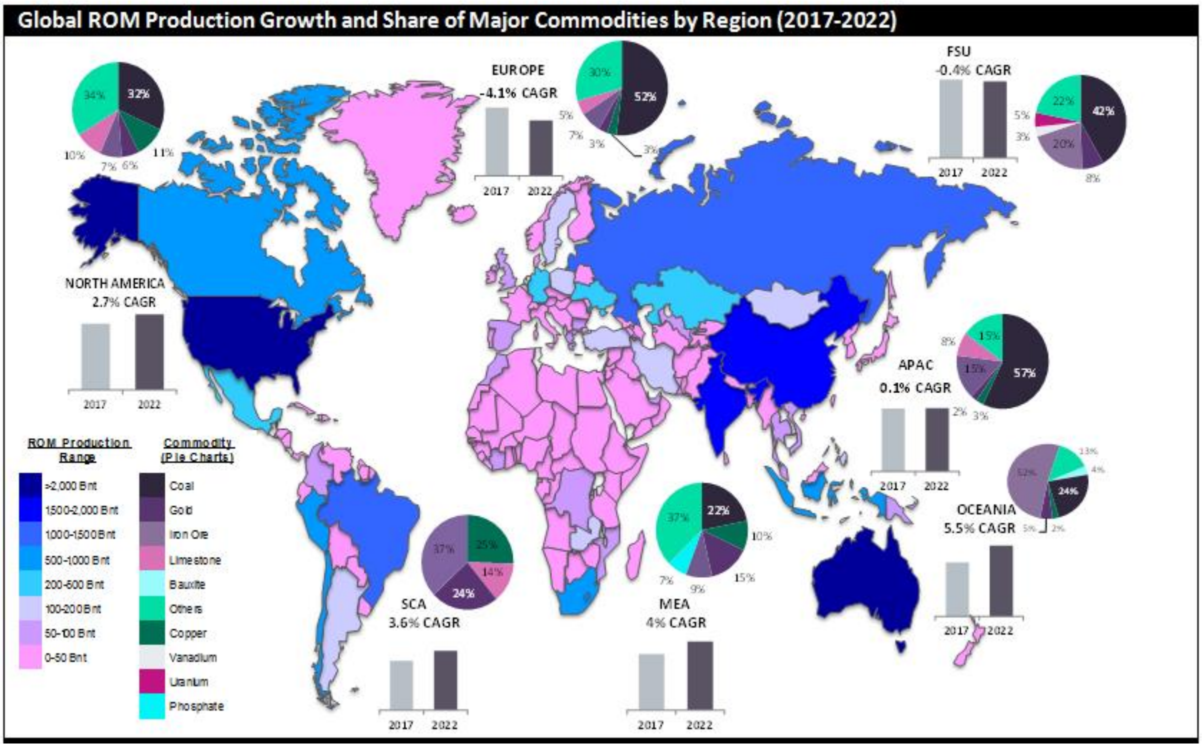

Figure 1.1: Global ROM production and share of major commodities: 2017 - 2022 (Mining Technology, 2018)

Furthermore, Figure 1.1 shows that mining takes place in most continents, regardless of how small or large the ROM production might be. Although coal is the leading commodity in terms of production output in most of the continents, it is noted that through to 2022, there will be a decline in the production of coal (Mining Technology, 2018). The decline in the coal production will be a result of climate and environmental regulations, and the use of renewable energy and natural gas as alternative sources of energy (Gross, 2019). The ROM production for iron ore will increase through to 2022 (Mining Technology, 2018) as a result of mine expansions in Brazil and output increases in India (Brightmore, 2019).

From Figure 1.1, it is noted that South Africa had the largest ROM production in Africa which may be because of the various commodity types that are mined in South Africa. South Africa produces various minerals such as platinum, manganese, chromium, palladium, coal, iron ore, gold, diamonds, copper, and nickel (South African Institute of Race and Relations, 2019). Figure 1.2 illustrates the percentage growth in production for 2017 for some of the minerals that are produced in South Africa.

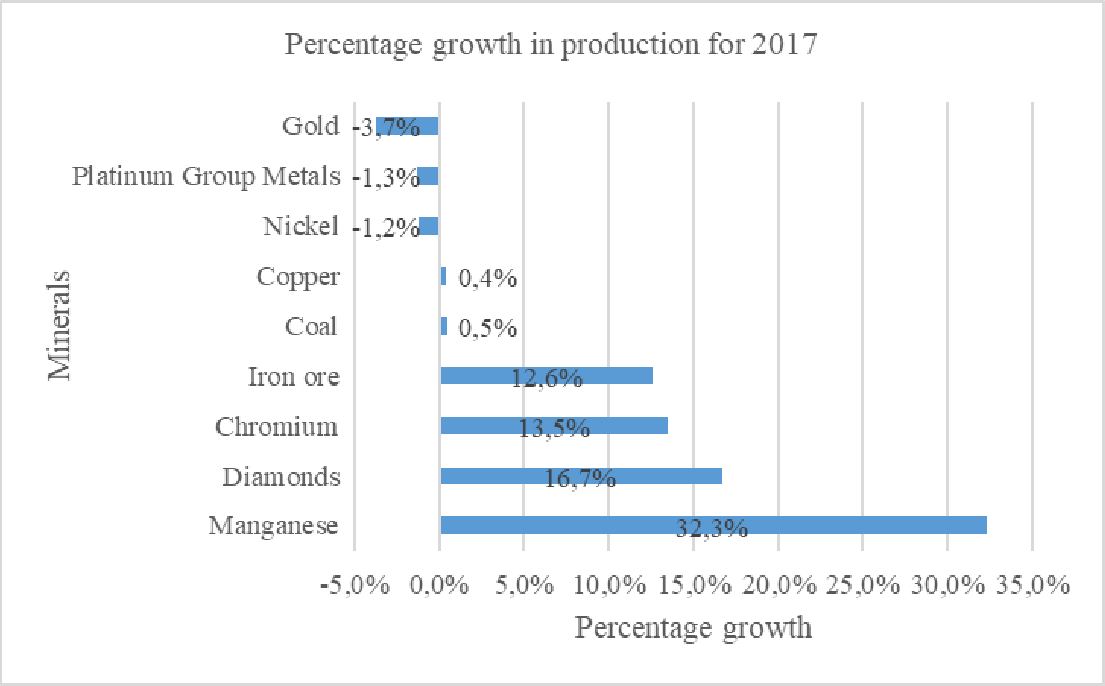

Figure 1.2: Growth in production output for minerals produced in South Africa (Adapted from Statistics South Africa, 2018)

The rise in manganese production was driven by the increase in demand for steel in China. Chromium and iron ore are also used in the production of steel and it is for this reason that they experienced an increase in production (Statistics South Africa, 2018). Diamond production also experienced a production increase of 16.7% due to the expansion of Venetia Diamond Mine, Finsch Mine and Cullinan Mine (Zimnisky, 2017). Although, gold experienced the highest production decline of 3.7% in 2017, South Africa still has approximately 39 years of gold reserves that are accessible (Statistics South Africa, 2018). This shows that there is still potential for growth and contribution to the GDP from the gold mining industry.

In South Africa, mining is the largest industry in the North West, Limpopo, Mpumalanga, and Northern Cape provinces (Statistics South Africa, 2018), with the Mineral Resources in the country potentially being worth approximately R35 trillion (Vegter, 2019), thus indicating that

South Africa is a mineral-rich country. It is noted that the South African mining industry’s GDP contribution has decreased from 21% in 1980 to approximately 7% in 2019 (South African Institute of Race and Relations, 2019). However, the South African mining industry makes a significant contribution of 17% through supply chains (Minerals Council South Africa, 2018), thus showing that the South African mining industry plays a significant role in the economy of South Africa.

It has been noted that the mining industry is faced with various challenges which require solutions to ensure that the industry remains globally competitive. Some of these challenges include, but are not limited to, market volatility, commodity price downturns (Maennling & Toledano, 2019), having a deeper understanding of the resource base, improving productivity and maintenance, optimising the flow of material and equipment, and improving safety (METS Ignited, 2017). Several trends have been identified as a means of assisting with finding solutions to some of the complex challenges faced by the South African mining industry and ensuring that mining companies remain globally competitive (Maennling & Toledano, 2019). Some of the trends are illustrated in Figure 1.3.

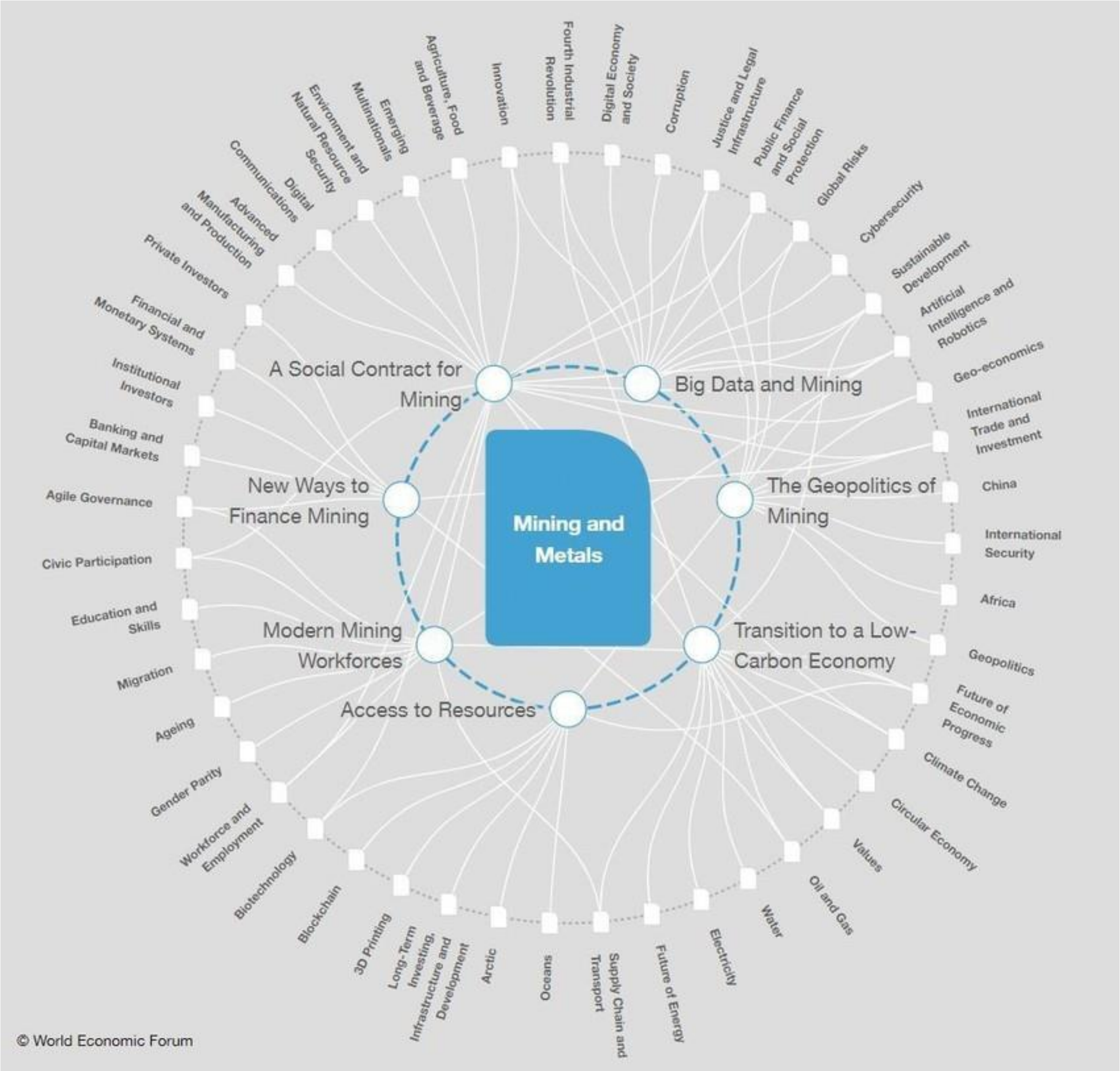

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Figure 1.3: Trends shaping the mining industry (Maennling & Toledano, 2019)

From Figure 1.3, the seven trends that are shaping the mining industry include big data and mining, the geopolitics of mining, transition to a low-carbon economy, access to resources, modern mining workforces, new ways to finance mining and a social contract for mining. The factors that are shown in a circle around the seven trends, are some of the factors that are considered when focusing on a particular trend as a solution to a challenge faced by the mining industry. For example, when focusing on big data and mining as a solution to the inefficient use of data in the mining industry, some of the factors that will be considered include innovation, fourth industrial revolution (4IR), digital economy and society, cybersecurity, sustainable development, artificial intelligence and robotics.

The seven trends that are shaping the mining industry are described in more detail as follows:

- Big data and mining: data is described as the collection of text, number and symbols that need to be processed to be meaningful. The result of processed data is known as information. Information provides context to the processed data and is used for insights (Cambridge International Examinations, 2017). The ability to collect and process large amounts of data is essential for mining companies as they move towards digitisation and automation. Big data will assist with determining which data should be made available to various stakeholders. The sharing of certain types of data will assist with improving data transparency and the relationship between the mining companies and its various stakeholders (Maennling & Toledano, 2019);
- The geopolitics of mining: geography and economics have influence on the politics and relations between different countries. The study of this influence is known as geopolitics. A sudden and significant increase in the oil price due to the tension between Saudi Arabia and Iran, is an example of a geopolitical risk that an investor needs to consider before making the final investment decision to invest in an oil production company (Morrison, 2016). The mining industry operates in some countries that are geopolitically complex, thus making it highly exposed to this risk. The mining systems and value chains are at the core of shaping geopolitics due to the significant role that the mining industry plays in various sectors and systems. An example is a smartphone which is developed using various minerals that originate from different countries that are associated with different forms of conflict and competition (World Economic Forum, 2016). Therefore, the future of mining also rests on being able to remain competitive even in a geopolitically plagued world;
- Transition to a low-carbon economy: since the 18th century, fossil fuels such as coal, have been used as a source of energy. However, fossil fuels have led to global warming due to high greenhouse gas emissions. To reduce the rate at which global warming is taking pace, energy systems will have to reduce the amount of carbon compounds emitted. It is noted that low-emission energy and transportation systems require significant amounts of minerals (Maennling & Toledano, 2019). For example, the hydrogen fuel cell will require significant amounts of platinum. The platinum will be used as a catalyst and an electrolyser to produce hydrogen, thus increasing the demand for platinum. This means that the transition to a low-carbon economy has the potential to create opportunities in the mining industry (Creamer, 2019);

- Access to resources: the use of technology will ensure that mining is more efficient as mining companies will use technology to improve mining and processing. Mining companies will also need to consider mining methods that will allow mining to take place in areas that were previously considered as uneconomical to mine. Some of the mining methods that will be considered include in-situ leaching and bio mining. As investors seek to invest in new mining projects that have high grade ore deposits, mining companies and the government will have to investigate the economic viability of deep see and asteroid mining. Deep sea and asteroid mining will bring forth new opportunities for technology and the mining industry (Maennling & Toledano, 2019);
- Modern mining workforces: it is essential that the workforce be skilled to be able to efficiently use the technology that is being implemented and to have a better understanding of the evolving business models. Although, there will be certain employees who will not be absorbed by the digitally transforming mining industry, the government and mining companies will have to reskill and upskill the employees so that they can be employable in other industries (Maennling & Toledano, 2019) as well as be self-employed;
- New ways to financing mining: the financing of mining deals was previously done through capital market transactions (Vella, 2019). Capital markets are described as markets where there is trade of financial securities such as bonds and stocks between the buyer and the seller (The Economic Times, n.d.). However, there are new ways of financing mining deals. Some of these new ways include, but are not limited to, production-based financing and private equity financing. Production-based financing is becoming common in the mining industry and it involves companies selling their rights to receive future production from the mines. Private equity financing involves the offering of money to a mining company by a private equity, for a minority stake in the project as return to the capital invested (Vella, 2019); and
- A social contract for mining: it is essential that mining companies create benefits for the communities in which they operate. This will ensure that there is minimal opposition from the community such as protests, and that mining companies are granted the social license to operate. It is noted that mining companies have insufficient funds to cater for remediation, have minimal employment opportunities, and increased water stresses. Therefore, mining companies must develop new business models that will

benefit the communities that are affected by the actions of the mining companies in the long run (Maennling & Toledano, 2019).

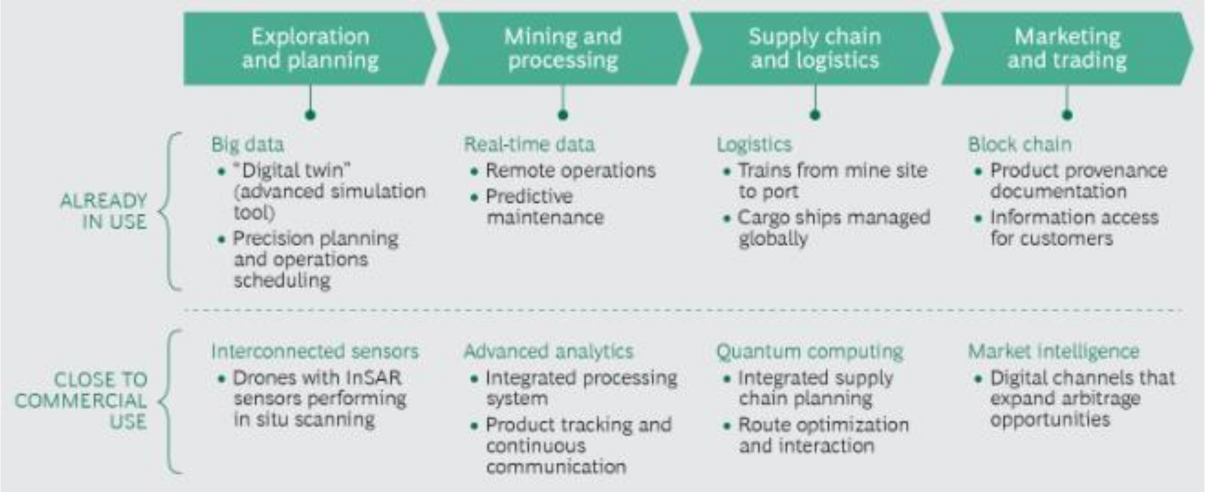
Considering the various challenges that are faced by the mining industry, it is noted that digital technologies have the potential to solve some of these challenges (METS Ignited, 2017). Therefore, it is essential to determine which digital technologies are relevant for finding solutions to some of the challenges that the mining industry faces. This chapter provides a description of the purpose of the study, research background, research motivation, problem statement, research objectives, assumptions, and outline of the dissertation.

1.1 Purpose of the Study

Digitization in the mining industry has provided the industry with opportunities to improve the various processes on a mine. Mines acquire significant amounts of data and information that can provide in-depth knowledge in improving the efficiency of the mining process, and in-turn maximise value generated (Brzychczy, *et al.*, 2020). However, it was noted that some mining companies do not use data and information efficiently due to challenges associated with accessing complete, accurate and timely data. It is for this reason that this research study explored a digital technology that has the potential to solve the challenges associated with the efficient use of the data and information generated by mines. An appropriate digital technology model is one that ensures that mining operations can gather complete and accurate data timeously. Subsequently, aids in providing useful insights to support decision-making processes. Once the appropriate digital technology was identified, a framework for its implementation in the mining industry was conceptualised. Data can be defined as the collection of facts and information can be defined as the understanding of the facts in context.

1.2 Research Background

For more than 100 years, the mining industry has been using traditional methods that use minimal technology. However, the mining industry is on a transformation journey that involves the adoption of digital technologies. Digital technologies are being adopted throughout the mining value chain (MVC) to improve mining processes. The digital transformation in the mining industry is driven by automation, robotics and operational hardware, a workforce that is digitally enabled, the integration of systems, and improved analytics and decision making. Digital technologies are assisting mining companies with gaining insights about safety, the value chain, processes and performance (Odendaal, 2019). One of the challenges of adopting digital technologies in the mining industry includes changing the mind-set of the workers. A change in mind-set is essential as digital transformation is associated with operating differently and realising that operating differently has the potential to benefit the mining industry (Bulbulia, 2019). Figure 1.4 shows an example of digital technologies that are applicable throughout the entire MVC.



	Exploration and planning	Mining and processing	Supply chain and logistics	Marketing and trading
ALREADY IN USE	Big data • "Digital twin" (advanced simulation tool) • Precision planning and operations scheduling	Real-time data • Remote operations • Predictive maintenance	Logistics • Trains from mine site to port • Cargo ships managed globally	Block chain • Product provenance documentation • Information access for customers
CLOSE TO COMMERCIAL USE	Interconnected sensors • Drones with InSAR sensors performing in situ scanning	Advanced analytics • Integrated processing system • Product tracking and continuous communication	Quantum computing • Integrated supply chain planning • Route optimization and interaction	Market intelligence • Digital channels that expand arbitrage opportunities

Figure 1.4: Digital technologies being adopted into the MVC (Tauber, *et al.*, 2018)

Figure 1.4 illustrates that there are various digital technologies that are in the process of being commercialised for use in the mining industry. The digital technologies that are already in use have ensured precision in planning and scheduling, predictive maintenance, globally managed cargo shipping and gaining access to information for the benefit of the customer. The digital technologies that are close to being commercialised will allow for system integration, the use of drones, and digital channels that will expand arbitrage opportunities (Tauber, *et al.*, 2018). Although the adoption of digital technologies in the mining industry has the potential to improve the mining industry, various companies have a concern about the cybersecurity risk associated with digital technologies (Ernst & Young, 2018). For mining companies to protect themselves from cybersecurity risks there needs to be a change in the cybersecurity risk culture and awareness. The organisation will have to apply risk management principles that are effective. An understanding of the cybersecurity threat landscape is essential for improving cybersecurity, thereafter, cybersecurity controls will have to be implemented. The cybersecurity controls must be aligned with the cyber threats that the organisation could potentially face (Mitchell, 2018). Figure 1.5 illustrates an example of an approach for protecting against cybersecurity threats (Mitchell, 2018).

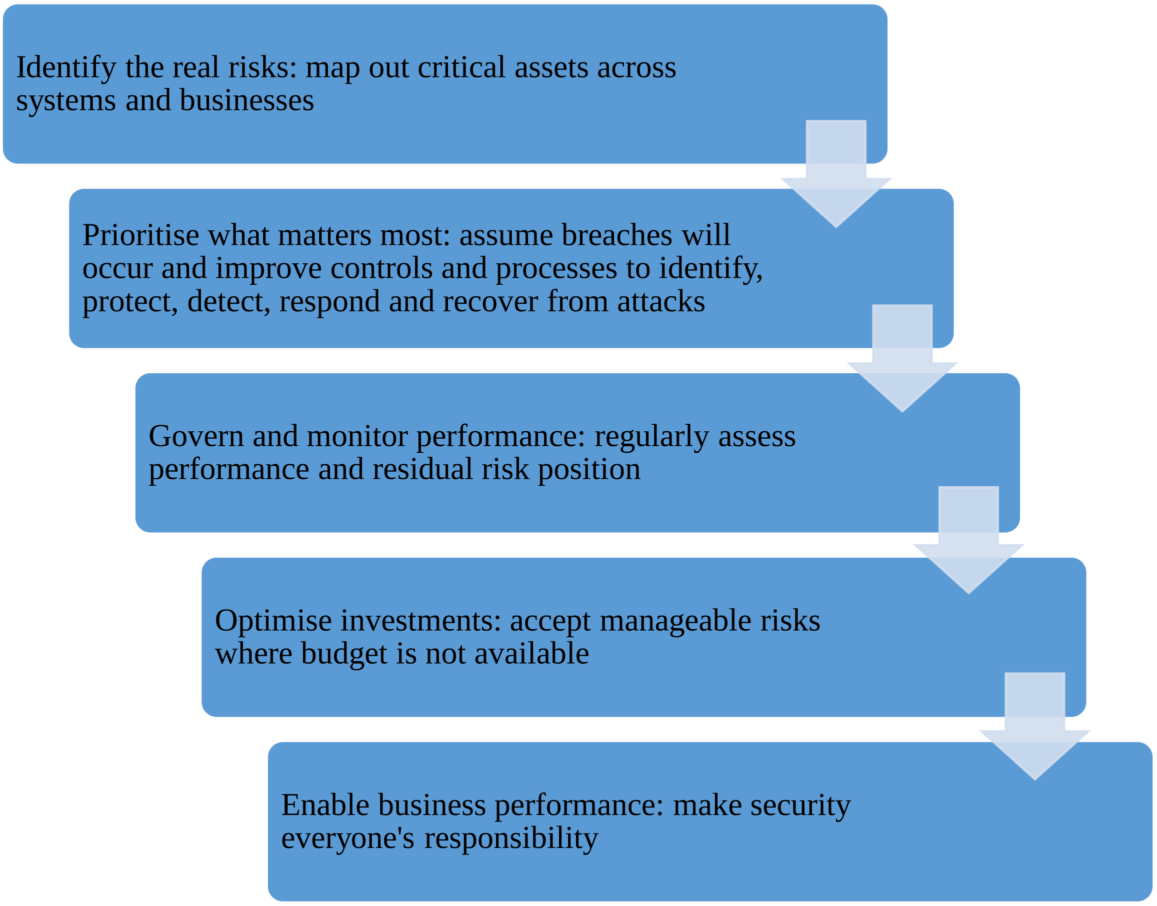


Figure 1.5: An approach for protection against cyberattacks (Adapted from Mitchell, 2018)

To remain competitive, mining companies need to promote a digital culture where real-time data are readily available in order convert it into information that can be analysed and understood for better real-time decision making (Australian Mining, 2019). Mining companies are investing in digital technologies such as analytics and artificial intelligence (AI) to efficiently collect and use the data that they generate. Efficient collection and usage of data will allow the mining companies to improve mine planning and decision making across the MVC. This improvement has the potential to improve safety, increase productivity, and reduce costs. To determine how to implement digital technologies across the MVC, mining companies are learning from other industries, which are reaping the benefits of utilising digital technologies in their value chains (Deloitte, 2019). Some of these industries include the manufacturing, oil and gas industries.

It has also been noted that mining companies have departments that operate in isolation, which means that these departments have minimal collaboration. However, it is essential that there is consolidation of the data and information from the different databases that originate from the different departments that operate in isolation. Examples of such databases include, but not limited to, enterprise resource planning (ERP) solutions, fleet management, and dispatch systems. The consolidation of the data and information will allow for the use of data analytics to determine trends and operational intelligence. This will in turn ensure that the mine is able to gain a better understanding of the operation and potentially determine solutions that will improve the operation (Accenture, 2016).

1.3 Research Motivation

The Wits Mining Institute (WMI) is a 21st century institute hosted by the University of the Witwatersrand. The research agenda for the WMI is to transfer surface digital technologies into the underground environment (Wits Mining Institute, n.d.) to improve mine safety and productivity (Wits University, 2018). These surface digital technologies are because of the 4IR. Therefore, it is essential to consider some of these digital technologies and determine how they can assist with solving some of the challenges faced by the mining industry. According to Javaid (2018), a Mining Information Model (MIM) is a platform that captures real-time data, allows for two-way communication, and assists with intelligent decision making. There are two approaches in which a MIM can be attained. The first approach is to utilise Building Information Modelling (BIM) concepts to develop a new software package that is better suited for mining, and the second approach is to integrate the already existing software packages which are used on the mine (Javaid, 2018). This research study considers the application of BIM concepts in the production zone of an underground mine without requiring the development of a new software package, however, with the aim of improving decision making in mining processes. This ensures that the research study still contributes to the conceptualisation of a MIM as it assists with intelligent decision making.

1.4 Problem Statement

Mines acquire significant amounts of data and information that can provide in-depth knowledge regarding the efficiency of mining processes. However, if the data gathered is incomplete, inaccurate, and/or delayed, it may lead to inappropriate decisions being made which may negatively affect the viability of the mining project. For example, an uneconomic block may be scheduled for extraction based on previous known incorrect grade because the geology department failed to provide the mine planning department with an updated grade value for the block model in time. Therefore, it is vital that the complete and accurate information is made available to all departments timeously. The application of digital technologies in mining has the potential to resolve the issues related to data gathering and information utilisation, which will in turn enable quicker and better decision making. The benefits of quicker and better decision making are improved safety and performance of the mine.

It is essential to note that the integration of information in a mine has the potential to improve decision making by approximately 20% to 30% (Deloitte, 2018). Therefore, for this research study, it was essential to consider a digital technology that would assist with the efficient use of information as well as improve the decision-making process of the mine through improved communication and collaboration.

BIM is a digital technology that is used in the Architecture-Engineering-Construction (AEC) industry. It is a process that ensures high efficiency and collaboration of the planning, design and construction of buildings. BIM also involves the sharing of data and information to improve accuracy, knowledge transfer, the design process, and to provide insights about the existing building. Stakeholders can access the information to make informed decisions based on the design model. The project specific information is still relevant even after the building has been constructed (Lorek, 2018). Ultimately, BIM allows for better communication and collaboration between people, technologies, and processes to improve efficiencies in the AEC industry. Therefore, BIM was identified as a digital technology that has the potential to assist in ensuring the efficient use of data and information on a mine.

Most underground conventional mines depend on individual departments to supply information to other departments at a certain time. Information may include geological conditions of a stope panel, current positions of stope panels, etc. For example, should the survey department delay in updating stope plans, this may lead to miners blasting beyond restricted areas. Consequently, compromising the integrity of the stope or the mine. There are various activities taking place in a mine such as development, stoping and logistics. These activities are interconnected; however, this study focused on the stoping related activities. The stoping activities may be referred to as the production zone. The production zone was selected based on the immediate impact it has on the run of mine (ROM), consequently, the profitability of a mine. Therefore, this begs the question: *"How will the application of Building Information Modelling (BIM) concepts improve the decision-making process in the production zone of an underground mine?"*

1.5 Research Objectives

The objectives of this research study are to:

- Analyse the different departments involved in the production zone: the BIM-based framework is conceptualised for the production zone of an underground mine. Therefore, it was essential to understand the various departments that are involved in the production zone to determine the exact areas where the BIM concepts are applicable in an underground mine environment;
- Analyse BIM: Analysis of BIM to determine which concepts are best suited for the production zone of an underground mine; and
- Conceptualise a BIM-based framework for mining: the BIM-based framework for the production zone of an underground mine will assist in determining how the BIM concepts can be applied and how they will benefit the production zone of an underground mine. Conceptualising this framework contributes to the conceptualisation of a MIM.

1.6 Assumptions

The assumptions that were made for the research study are as follows:

- The decisions that will be considered are those that are made by the departments involved in the production zone of an underground mine;
- Two-way communication is required however is currently unavailable. For this research study it is assumed that the mine has two-way communication between the underground mining environment and the surface;
- WMI has researchers that are currently working on wireless communication in underground deep to ultra-deep level mining operations. The researchers are also working on ensuring that there is a two-way communication between the underground and surface workers. This two-way communication will ensure that the decisions made on surface can be communicated to the underground workers in a timely manner. In light of the fact that the departments are located on surface, it is assumed that once the decisions have been made on surface, they can be communicated to the underground mining environment in a timely manner;
- The production zone only includes the stoping areas as this is the area where the ore is produced; and

- The research study only focuses on the Technical Mining division as this is the division that is directly linked to the production zone, therefore, the views gathered from the data collected do not automatically apply to the other divisions in the mine such as human capital and finance.

1.7 Limitations

The limitations identified during the research study are as follows:

- Data collection at Mine A was limited to four of the departments within the Technical Mining division, namely; the survey, drafting, ventilation and environmental engineering, and rock engineering departments. The data set collected from these departments was deemed sufficient for the scope of this research study for the following reasons:
    - The departments are linked – the survey and drafting departments provide information to the rock engineering and ventilation and environmental engineering departments, respectively.
    - The link between the departments allows for an information flow chart to be generated.
    - The link between the departments allows for a BIM-based framework to be conceptualised.
    - The conceptualised framework can then be utilised to link the other departments in the Technical Mining division of Mine A.
- The data used in the research study are from Mine A and it is assumed that the recommendations made are only applicable to Mine A. However, the basic principles may be used to develop a similar framework for a different mining operation;
- Although BIM has many concepts that would assist the mining industry in various ways, Mine A is not yet ready for the application of majority of the concepts. At this stage, the mine is still working on digitising their documents. Therefore, when considering which BIM concept to apply, it was essential to select a concept that would assist with making Mine A ready for the application of the other BIM concepts; and
- Mine A has a department that is working on the digital transformation of its operations. However, information regarding the digital transformation of the mine could not be gathered due to protection of intellectual property. Therefore, the conclusions and

recommendations made in this research study are solely based on the data collected and are independent of the current digital transformation journey of the mine.

1.8 Outline of Chapters

The chapter outline for this dissertation is as follows:

- Chapter 1 introduced the global and South African mining industry, the challenges that are faced by the mining industry, and several trends that are shaping the mining industry. It described the purpose of the study, research background, research motivation, problem statement, research objectives, and assumptions;
- Chapter 2 focuses on digital technologies. It reviews literature that is related to digital technologies associated with the 4IR as well as those applicable in the mining industry. It also describes underground mining and BIM;
- Chapter 3 focuses on the research methodology and it describes the methodology that is used to conceptualise the BIM-based framework for mining;
- Chapter 4 focuses on BIM. It describes BIM in more detail and gives ideas on how BIM concepts can be applied in the production zone of an underground mine;
- Chapter 5 focuses on the data collected from the mine, the flow of information on the mine, the application of the BIM concept and data integration solutions;
- Chapter 6 focuses on the BIM-based framework for underground mining. It describes the current and proposed procedures used on the mine, the BIM-based framework for mining, and an implementation strategy for the BIM-based framework; and
- Chapter 7 provides the conclusions and recommendations of the research study.

2. DIGITAL TECHNOLOGIES

Digital technologies are electronic devices and systems that can generate, store and process data (Victoria State Government, 2018). Businesses use digital technologies to address some of the challenges that they face (Hargan, 2016). Some examples of digital technologies include, *inter alia*, data mining and analysis, internet of things (IoT), cloud computing and robotics (PricewaterhouseCoopers, 2015). Figure 2.1 illustrates digital technologies that Chief Executive Officers (CEOs) consider as being important for any organisation.

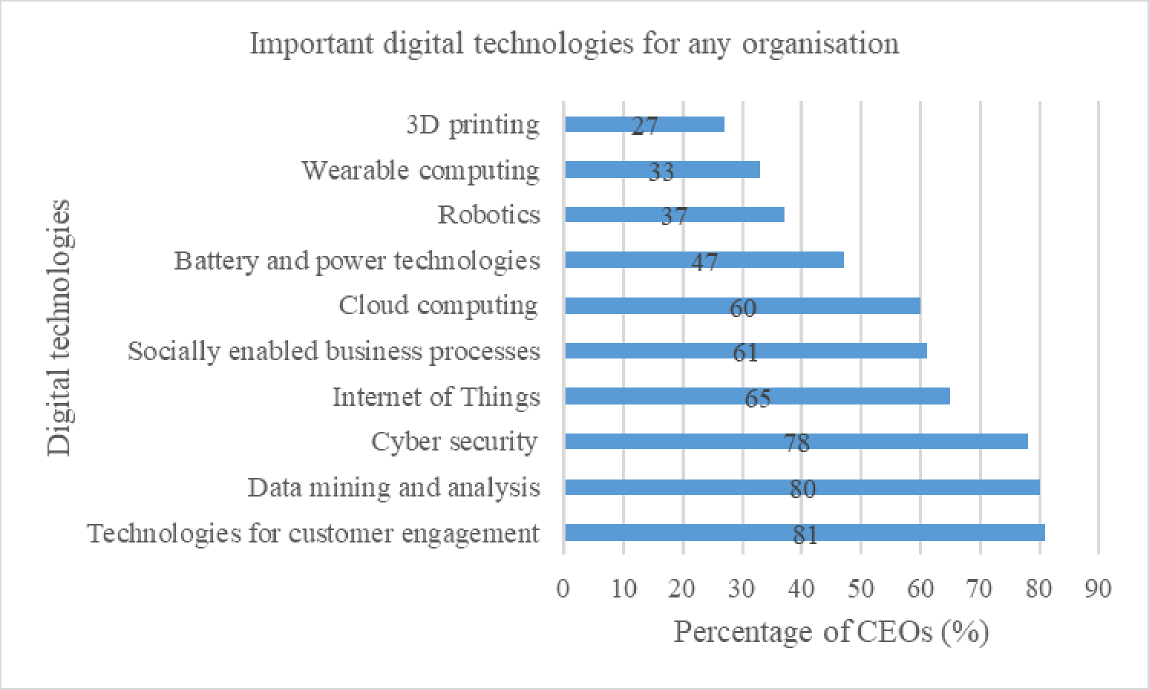


Figure 2.1: Important digital technologies for organisations (Adapted from PricewaterhouseCoopers, 2015)

As indicated in Figure 2.1, many CEOs believe that mobile technologies for customers, data mining and analysis, and cybersecurity are the three digital technologies that are important for any organisation that aims to transform digitally. These are the most important because they can enhance customer experience, improve access, analysis and circulation of data, and protect data (PricewaterhouseCoopers, 2015). This chapter describes some of the digital technologies that are associated with the 4IR, BIM and mining.

2.1. Fourth Industrial Revolution

The 4IR involves the fusion of various technologies to integrate the biological, digital, and physical spheres. The 4IR builds on the third industrial revolution, which was characterised by the use of electronics and information technology (IT) (Schwab, 2015). Figure 2.2 illustrates the four industrial revolutions. The first industrial revolution is characterised by the mechanisation of production, the second by mass production, the third by automation of production and the fourth by advanced technology (Xu, *et al.*, 2018).

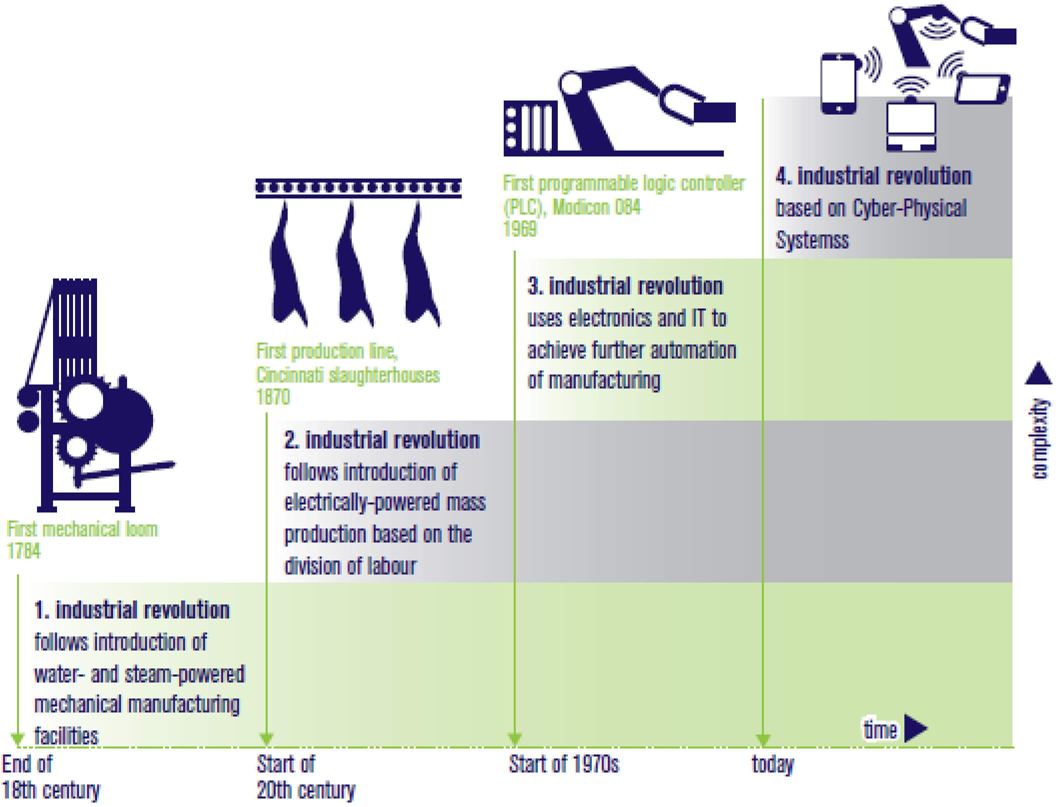


Figure 2.2: Industrial revolutions (Kagermann, *et al.*, 2013)

The 4IR differs from the third industrial revolution in that it is evolving at an exponential pace and disrupting various industries. The breadth and depth of the changes are a sign that transformation of the production, management and governance systems, needs to take place (Schwab, 2015) to remain competitive. Some of the digital technologies associated with the 4IR include, amongst others, three-dimensional (3D) printing, AI, the fusion of technologies, robotics and IoT (Schwab, 2015). The opportunities and challenges associated with these digital technologies are discussed in the following subsections.

2.1.1 Three-dimensional printing

3D printing involves using a digital design file to create a physical object. The physical object is formed from the layering of materials during printing (Autodesk, n.d.). 3D printing will play a significant role in reducing the barrier between inventors and markets as it will allow inventors and entrepreneurs to produce a physical 3D prototype for what they are inventing or plan on making available to the market. The physical 3D prototype can be created relatively quickly thus removing the time constraint which is associated with traditional prototyping techniques (Xu, *et al.*, 2018). Table 2.1 shows some of the advantages and disadvantages of 3D printing.

Table 2.1: Advantages and disadvantages of 3D printing (Adapted from Ink Toner Store, n.d.)

Advantages	Disadvantages
Printing out of customised designs	Decrease in manufacturing jobs
Constant prototyping that allows for prototype improvements	Limitation in terms of the object size to be printed
Relatively cheaper in terms of manufacturing and labour costs, for single items	Limitation in terms of the raw materials that can be used
No storage cost required because products are printed when needed	Violation of copyrights due to the printing of counterfeit products
Increased demand for engineers who will design and build the printers	Dangerous items such as guns and knives can be created

The fact that 3D printing allows for the printing out of customised designs means that spare parts of different shapes can be printed. Therefore, 3D printing can be used in mining to produce spare parts on site. This would assist with solving the maintenance and downtime challenges due to poor optimisation of inventory on the mine. It would take less time to maintain and overhaul mining equipment because the spare parts would be readily available, thus, reducing downtime. This would also reduce the costs associated with purchasing, transporting and storing spare parts. Figure 2.3 shows an example of a bolt being printed using a 3D printer. The bolt can be used when maintenance is being done on the mining equipment.

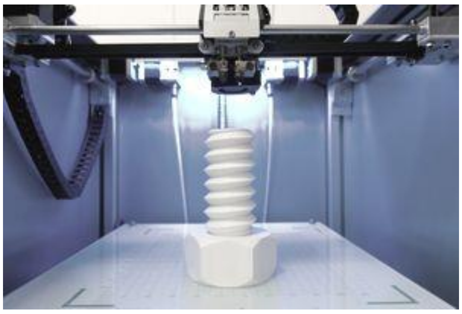


Figure 2.3: An example of a bolt from a 3D printer (Burger, 2019)

2.1.2 Artificial intelligence

AI involves activities that make machines intelligent. The intelligence in AI is the quality that allows the machine to be able to function in an appropriate manner and be cautious of its environment (Nilsson, 2010). AI assists with solving complex problems and offers the potential for growth in businesses and the economy (Xu, *et al.*, 2018). Some applications of AI include voice recognition, machine learning, text analytics, robotic process automation, and decision management. Table 2.2 shows some of the advantages and disadvantages of AI.

Table 2.2: Advantages and disadvantages of AI (Adapted from Lath, 2018)

Advantages	**Disadvantages**
Decisions taken by a machine are based on a set of algorithms, which reduces room for error	The overall cost of implementing an AI machine is relatively high, therefore only a few companies can make use of it
The ability to make right decisions in a short span of time	The dependency of humans on machines is ever increasing
In workplaces where the safety of a workers is uncertain, an AI machine that is fitted with predefined algorithms can be used	With efficient and 24/7 AI and automation, traditional human jobs will soon be replaced by machines in the future
Since a machine does not get tired, it can work continuously without taking any breaks if maintenance is excluded	Machines cannot think creatively or out of the box

From Table 2.2, it is noted that the adoption of AI in the mining industry could assist mines with making accurate decisions, improving health and safety, boosting efficiencies by eliminating errors and having a smaller environmental footprint (Deloitte, n.d.). An example of AI in mining is the use of autonomous drills, loaders, and trains. Rio Tinto uses 76 autonomous ore hauling trucks in their mining operations in Australia. The autonomous ore hauling trucks are safer and approximately 15% cheaper to operate than trucks that are operated by human beings (Walker, 2019). Figure 2.4 shows the Komatsu 980E-4 electric dump truck.

Figure 2.4: A Komatsu 980E-4 electric dump truck (Rolling Meadows, 2018)

The Komatsu 980E-4 electric dump truck uses AI as it has autonomous capabilities (Wisely, *et al.*, 2017). This means that the truck is self-driving and can operate for longer periods of time without requiring a break (Walker, 2019).

2.1.3 Fusion of technologies

The fusion of various technologies involves the creation of hybrid technologies from the combination of existing technologies (Kodama, 1992). The combination of the existing technologies allows for the creation of a new product market and growth opportunities. An example of technology fusion is the combinations of the mechanical and electronic engineering sectors to form mechatronics (Tidd & Sammut-Bonnici, 2017).

A mining related example of the fusion of technologies is the integration of the various mine software packages to create a new product which is better suited for the market (Javaid, 2018). This fusion allows for data integration, which has the potential to assist with better decision making on the mine. Some of the advantages and disadvantages of software integration are shown in Table 2.3.

Table 2.3: Advantages and disadvantages of software integration (Adapted from MyABCM, 2018; Hiscox, 2016)

Advantages	Disadvantages
Integration of the various departments because the system collects information from all the departments in an organisation, organises the information and makes it available to management	If one system gets hacked, then the hacker can get access to the other systems. Therefore, cyber security is a concern
Fewer errors, for example, class detections can be done	Difficult to debug
Allows for processes to be done relatively quickly and easily	

The advantages of software integration are the reason why system integration is considered as one of the approaches for the conceptualisation of MIM (Javaid, 2018). Figure 2.5 illustrates an example of the integration of various software, which are known as building blocks, to create the MineRP Optimisation and MineRP GeoFinance software packages.

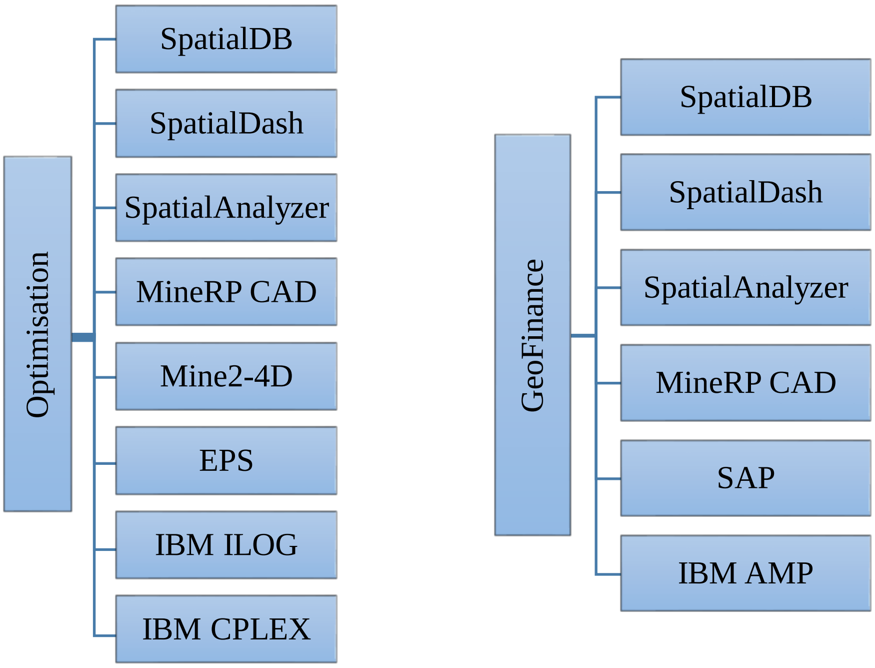


Figure 2.5: Illustration of system integration from MineRP (Adapted from Javaid, 2018)

The MineRP Optimisation software package is used as an optimisation tool and the MineRP GeoFinance software package is used as a financial modelling tool (Javaid, 2018). The functions for each of the building blocks in Figure 2.5 are shown in Table 2.4. The integration of these building blocks has resulted in the creation of software packages which have optimisation and financial modelling capabilities that can assist the mine with better decision making.

Table 2.4: Building blocks of MineRP Optimisation and MineRP GeoFinance (Adapted from Javaid, 2018; van Schalkwyk, 2019)

Software	Function
SpatialDB	Data storage
SpatialDash	Visualisation
SpatialAnalyzer	Analysis
MineRP CAD	Design
Mine2-4D	Mine planning and scheduling
Enhanced Production Scheduler (EPS)	Updating the schedules while considering the design
IBM ILOG	Decision management and optimisation
IBM CPLEX	Solving mathematical problems, improving efficiencies and reducing costs
SAP	Financial and logistical planning
IBM AMP	Data analytics

2.1.4 Robotics

Robotics is the study of machines, which are also known as robots, that can automatically perform computer programmed actions (Ben-Ari & Mondada, 2018). Robots can execute tasks that human beings can execute (Siciliano, *et al.*, 2010) and have the potential to improve the quality of existing jobs (Xu, *et al.*, 2018). Figure 2.6 shows a robot working in an underground mine tunnel.

Figure 2.6: Robotics in mining (Chakravorty, 2019)

Figure 2.6 shows a robotic equipment deployed in an underground mine tunnel to navigate the flooded passages in the Idrija mercury mine in Slovenia. This robotic equipment has an onboard multispectral camera which enables it to distinguish different minerals (Chakravorty, 2019). Table 2.5 shows some of the advantages and disadvantages of robotics (Granta, 2017).

Table 2.5: Advantages and disadvantages of robotics (Adapted from Granta, 2017)

Advantages	Disadvantages
Continuous operations provided that the robots are maintained correctly	Potential job losses
Accurate production and checking of items	Relatively high initial investment cost
Increased productivity because the robots will be able to do the more repetitive tasks while the human beings can focus on developing other skills	Difficult to find skilled staff who can programme and operate the robots
Robots can work in hazardous environments	

Robots can be used in various other fields such as manufacturing, medical, educational, defence, and at home (Ben-Ari & Mondada, 2018). In mining, robots can be used as an exploration tool in mines that have flooded sections. The robot would use its multispectral camera to identify different minerals, which are hidden by the dark and dirty water (Chakravorty, 2019). This application has the potential to increase the resource base of a mine.

2.1.5 Internet of things

According to GSMA (2014), IoT is the use of intelligently connected systems and devices to efficiently use the data gathered from sensors and machines. IoT is also about gaining insights and interactions from these connected systems and devices. Real-time or near real-time data, analytics and big data are the other key factors of IoT (Lee & Prowse, 2014). Some of the advantages and disadvantages of IoT are shown in Table 2.6. (GSMA, 2014).

Table 2.6: Advantages and disadvantages of IoT (Adapted from Saxena, 2016)

Advantages	Disadvantages
Allows for the gathering of more data, thus assisting with decision making	The system is complex, thus making it vulnerable to failure
Keeps track of quality and viability	All the data must be encrypted to keep it private
Allows for better monitoring	At risk of cyber-attacks

IoT is being used in the mining industry due to some of the advantages associated with it. Figure 2.7 illustrates the components of the IoT technologies used in mining. The four components of the IoT technologies used in mining include, firstly, the things; secondly, the communicators and controllers; thirdly, the IoT platform and processors; and lastly, the human and external interface. The things are the sensors and devices that can be connected to the internet. The communicators and controllers are the devices that allow for the connection between the things and the internet. The IoT platforms and processors are the platforms where the data received from the sensors and devices are processed and analysed. The human and external interface is the interface where intelligent decisions can be made by using the processed and analysed data. IoT has the potential to assist with asset utilisation, energy management, predictive maintenance, inventory and asset tracking, loss prevention, integrated remote operations centres, geostability modelling and decision making (Lee & Prowse, 2014).

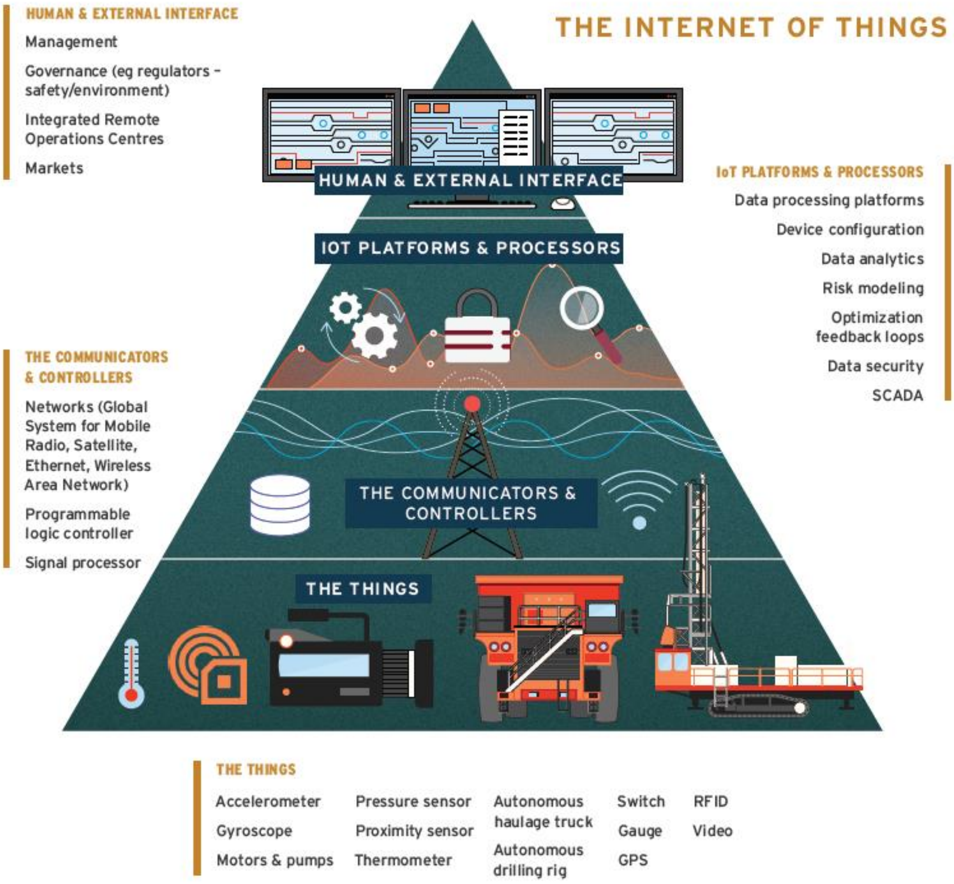


Figure 2.7: IoT technologies in mining (Lee & Prowse, 2014)

2.1.6 Big data analytics

The creation, replication and consumption of all the digital data in one year is known as the digital universe. It is noted that only 3% of the data produced in the digital universe in 2012 were recognised and stored, with only 0.5% of it being analysed and made ready for use (Gantz & Reinsel, 2012). However, big data analytics has the potential to assist with making sense of the data that has not been analysed yet (Pickell, 2018). Big data is described as data that are large, complex and cannot be processed by using traditional data processing software. The five characteristics of big data include volume, velocity, variety, veracity, and value, as various data types that have the potential to add value are being generated in significant amounts and at an increased speed. Some of the uses of big data include product development, predictive maintenance, customer experience, fraud and compliance, operational efficiency, and driving innovation (Oracle South Africa, n.d.). Although, big data analytics has various potential advantages, it also has various disadvantages (Harvey, 2018). The advantages and disadvantages of big data analytics are shown in Table 2.7.

Table 2.7: Advantages and disadvantages of big data analytics (Adapted from Harvey, 2018)

Advantages	Disadvantages
Better decision making	Need for talent
Increased productivity	Data quality
Reduced costs	Need for cultural change
Improved customer service	Compliance
Fraud detection	Cybersecurity risks
Increased agility	Hardware needs
Greater innovation	Software costs

Table 2.7 shows that the use of big data analytics has the potential to improve the decision making and productivity of an entity. Mines generate significant amounts of complex data and it is noted that big data analytics has the potential to assist mining companies with unlocking more value. The use of big data analytics would improve productivity, decision making and collaboration on a mine (Wipro, n.d.). For example, the mobile drill rigs that will be used in future will be able to collect, analyse and access large and complex geochemical and geophysical data. The use of big data analytics will ensure that the large and complex geochemical and geophysical data are processed, analysed and used for better decision making on the mine (Chakraborti, n.d.).

2.1.7 Digital twin technology

Digital twins are the virtual replicas of any physical objects or systems such as a building or a mine. The virtual replicas can be used for simulations before any decision is made. The digital twin is constructed such that it is able to receive real time data from sensors. This ensures that the simulations are in real time thus offering better insights in terms of performance and any potential challenges that could arise (Shaw & Fruhlinger, 2019). The use of IoT in digital twinning has made it possible for real time data to be accessed from the sensors. An example of the application of digital twinning is General Electric’s (GE) digital wind farm. The digital twin is used to provide information about the configuration of each wind turbine before its construction (Marr, 2017). In the health care industry, digital twin technology is used for digitally cloning a hospital. The digital clone assists hospital administrators, doctors and nurses with monitoring patients and coordinating equipment. The results of using digital twin technology for a hospital include reduced waiting times in the emergency room, improved patient flow, decreased operational costs and enhanced patient experiences (Monteith, 2019). The advantages and disadvantages of digital twin technology are shown in Table 2.8.

Table 2.8: Advantages and disadvantages of digital twin technology (Adapted from Identity Management Institute, n.d.; netObjex, n.d.)

Advantages	Disadvantages
More efficient delivery	Cybersecurity risk
Improved productivity and operational efficiencies	Challenging to ensure that all devices are always connected to the internet
Remotely configured customised products	

The application of digital twin technology has proved to have various benefits for other industries and its benefits have attracted mining companies to consider its application. Exxaro is the first mining company in South Africa to take the digital twin approach, with Belfast Coal Mine being the first digital twin mine in South Africa. The equipment on the mine such as crushers and water meters are digitally enabled and are connected to sensors. Exxaro plans on using the digital twin technology to access real time data throughout the entire mine value chain. The accessibility to this type of data will improve the productivity and safety at the mine as well as make it more competitive (Exxaro, n.d.). In the future, the digital twin could possibly be able to make operational decisions without human interference. It is at this point where AI will be managing the mine (Kilian, 2018).

The subsequent section discusses a digital technology used in the AEC industry.

2.2 Building Information Modelling

The AEC industry is gradually being reshaped by a concept known as BIM (Azhar, *et al.*, 2012). BIM is described as "a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward" (National Institute of Building Sciences, 2007, p. 21). This definition shows that BIM is both a process and a technology as it allows for the use of 3D models as well as changing the way in which projects are being done (Azhar, *et al.*, 2012), thus allowing it to play a significant role in project management (Bryde, *et al.*, 2013). Integrated project delivery, the construction project life cycle and the applications of BIM are discussed in the following sub-sections.

2.2.1 Integrated project delivery

Integrated project delivery (IPD) is well supported by BIM and allows for better project management (Bryde, *et al.*, 2013). According to the American Institute of Architects (2007), IPD is a type of project delivery that allows for the integration of people, business structures, systems and practices. This integration ensures that there is a collaboration of talents and insights. In doing so, IPD results in project optimisation, waste reduction, and efficiency maximisation throughout the design and construction phases.

Before the implementation of IPD, traditional project delivery (TPD) was used. TPD involves having fragmented and hierarchical teams, linear and segregated processes, individually managed risks, individually pursued rewards, paper-based communication, analogue technology and unilateral agreements. The implementation of IPD has resulted in having integrated teams who openly communicate, multi-level processes, collectively managed risk, value-based rewards, virtual communication, digital technology, and collaborative agreements (American Institute of Architects, 2007). This shows that IPD can assist in improving the way in which an organisation operates.

IPD is an essential part of BIM as it allows for improved collaboration and communication. IPD is considered as a way in which creativity, reliability and success can be unlocked for complex projects (Pease, 2018). To get the best out of IPD, it is essential that all the parties within the project life cycle change their mindset. A change in mindset requires all the parties to embrace the principles of IPD, which are shown in Figure 2.8.

Figure 2.8: Principles of IPD (Adapted from American Institute of Architects, 2007)

The collaboration associated with IPD is built on trust, hence mutual respect and trust are the first principles of IPD. The presence of mutual respect and trust discourages hostility between parties, thus ensuring that all parties focus on the outcomes of the project (American Institute of Architects, 2007).

2.2.2 Construction project life cycle

BIM can be used at every stage of a project life cycle. Figure 2.9 illustrates the construction project life cycle.

Figure 2.9: Construction project life cycle (Azhar, *et al.*, 2012)

The use of BIM in the project life cycle of a construction project was described by Azhar, *et al.* (2012) as a concept that allows project teams to analyse and understand the complexity of space, standards and regulations. This allows the team to do more activities that have the potential to add value. The project design stage comprises of schematic design, detailed design, and construction design, and BIM can be applied in any type of design. This can be done by using various dimensions of BIM which are shown in Table 2.9. These dimensions are discussed in detail in Section 3.4.

Table 2.9: BIM dimensions summary (Adapted from India CAD Works, 2018)

Dimension (D)	Explanation
3D	The creation of a 3D model on a CAD platform
4D	Linking time-related information to the 3D BIM model
5D	Linking cost-related information to the 4D BIM model
6D	Addressing sustainability issues on the 5D model
7D	Focused on the overall construction project life cycle

In the pre-construction phase, BIM is used for estimation, site coordination and constructability analysis. In the construction phase, BIM is applied in the monitoring of the progress of a project, meetings for trade coordination, and the integration of information requests and change orders in the model. In this stage, the model is updated continuously to ensure that the most recent information is available in the model. The post-construction stage includes operations and demolition. In this stage, the information that is gathered and continuously being updated in the previous stages is now being used to make intelligent decisions. It can be used by facility managers in order to operate and maintain the facility in a more efficient manner (Azhar, *et al.*, 2012).

The use of BIM in the AEC industry has proven to have many benefits. Some of these benefits include better collaboration and communication, model-based cost estimation, preconstruction project visualisation, improved coordination and clash detection, reduced cost and risk mitigation, improved scheduling or sequencing, increased productivity and prefabrication, safer construction sites and stronger facility management (Hall, 2018). Some of the drawbacks of BIM include incompatibility with partners, legal issues, software cost and lack of expertise (National Institute of Building Technology Nashik, 2018). However, it is noted that there is a future for BIM as many design teams have plans to adopt BIM and many others have an interest in BIM (Bryde, *et al.*, 2013). Other industries such as mining can adopt certain BIM concepts to improve their operations.

Although the BIM model can be applied throughout the MVC, for the purpose of this study it was only applied for the optimisation of the production zone in an underground conventional mine. To conceptualise the BIM-based framework for an underground conventional mining environment, it was essential to consider a BIM-based project life cycle, which is shown in Figure 2.10.

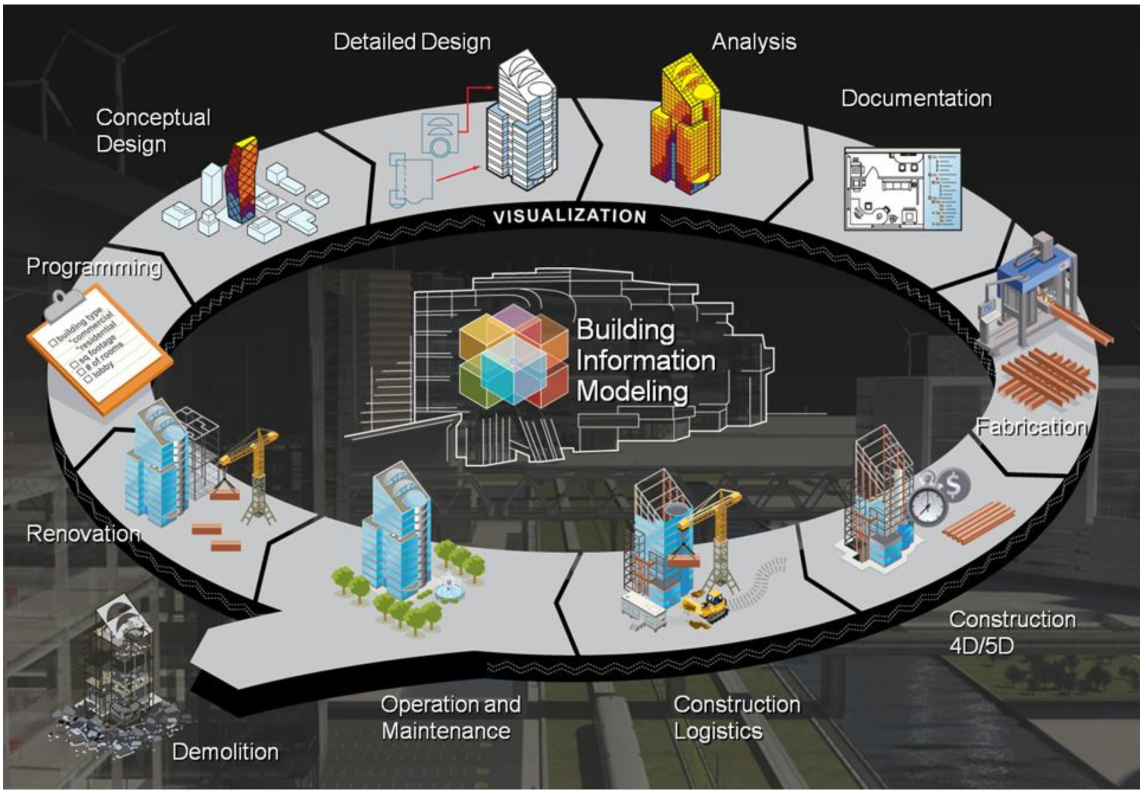


Figure 2.10: BIM-based project life cycle (Dispenza, 2010)

Although an in-depth understanding of BIM was required, it was hypothesised that all the stages in the BIM-based project life cycle can be applied in the production zone of an underground mine. The reason for this hypothesis is that during programming stage, BIM can be used for understanding the underground environment, standards to be used and regulations that must be considered in mine planning. Table 2.10 shows the hypothetical mining application of BIM.

Table 2.10: Hypothetical mining application of BIM

BIM Stage	Hypothetical Mining Application
Conceptual and detailed designs	Essential in mine planning as they assist with visualisation
Analysis	Assist with getting a better understanding of the underground environment to determine how to mine the orebody
Documentation	Assist with keeping records as well as continuous communication of ideas
Fabrication	Assist with 3D visualisation of the orebody and the underground environment
Construction of 4D, 5D and logistics	Allow for optimised scheduling, costing and efficient progress reporting in real time
Operation and maintenance	BIM would be essential for decision making and maintenance scheduling
Renovations	Can be referred to as maintenance in mining, BIM can assist with determining when equipment should be repaired or replaced before the equipment breaks down
Demolition	Would be mine closure, BIM can be used to determine which environmental aspects need to be considered to ensure successful mine closure and rehabilitation

2.2.3 Applications of BIM

The BIM technology was used in South Africa during the construction of stadiums and other facilities for the Federation Internationale de Football Association (FIFA) 2010 World Cup such as in the construction of the Nelson Mandela Bay and Mbombela stadiums (Chimhundu, 2015). This was the first time that BIM technology was embraced in South Africa. Since then, BIM technologies have become widely used in South Africa. However, some of the project managers highlighted that the challenges that they faced with BIM include legal issues, lack of interest among project stakeholders, lack of local expertise in BIM technology and poor technical support. It is noted that there is potential for the adoption of BIM in other African countries such as Nigeria, to improve efficiencies (Ogwueleka & Ikediashi, 2017).

Worley, an engineering consulting firm, has started using BIM in mining as they have implemented 3D, 4D and 5D data mapping in their mining and minerals projects. BIM was adopted to create a design platform that is integrated and incorporates scheduling and cost. Worley is also operating in the 7D space where there is real time access to the operational data of the project. The advantage of using BIM in mining is that it has the potential to improve productivity and reduce cost (Creamer Media Reporter, 2018). The opportunity for BIM in mining is that it can be used for forecasting future expenditures, planning for maintenance and improving the operational processes (Mokhtar, 2018). The subsequent section discusses the mining life cycle.

2.3 Mining Life Cycle

Mining involves the extraction of minerals that are economically valuable. These minerals are extracted from the earth's crust and can be found in various forms such as veins, lodes, reefs, and seams (Balasubramanian, 2017). To successfully extract the minerals, the mining life cycle is followed as illustrated in Figure 2.11 (Bester, *et al.*, 2016).

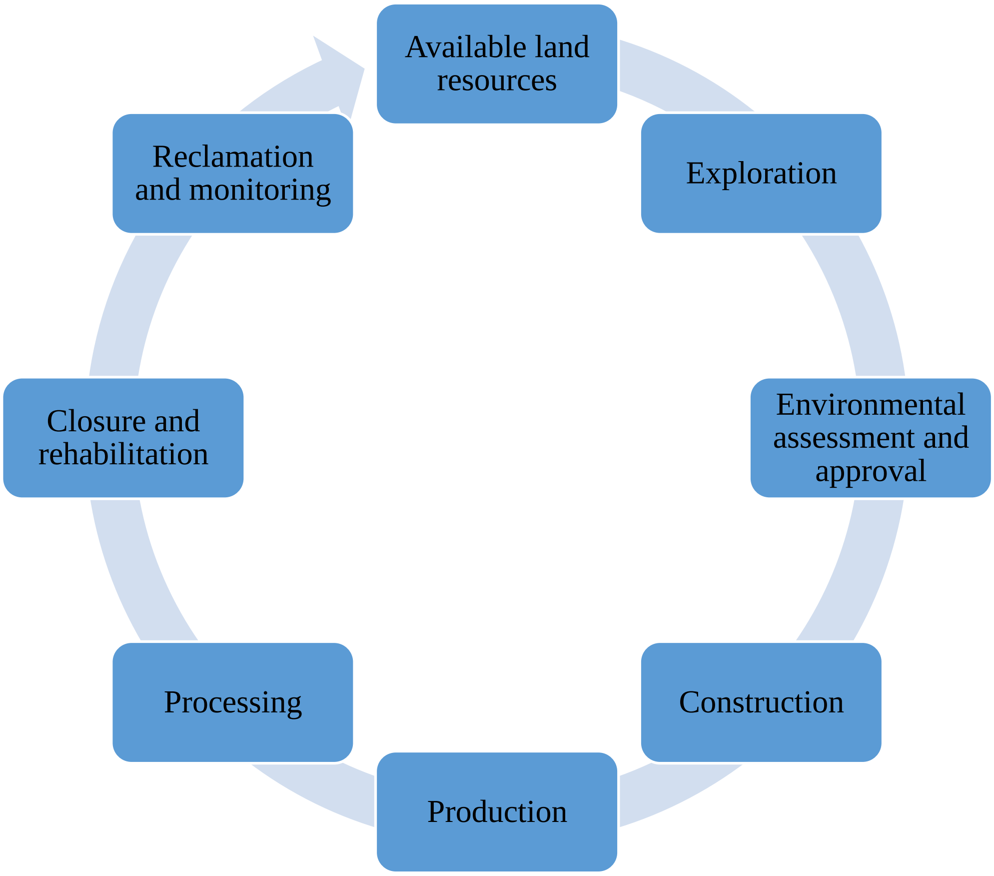


Figure 2.11: Mining life cycle (Adapted from Balasubramanian, 2017)

The mining life cycle in Figure 2.11 can be linked to Figure 2.10 as shown in Table 2.11.

Table 2.11: BIM stages linked to the mining life cycle stages

BIM Stage	Mining Life Cycle Stage
Conceptual and detailed designs	Available land resources and exploration
Analysis	Exploration, environmental assessment and approval
Documentation	Exploration, environmental assessment and approval
Fabrication	Exploration, environmental assessment and approval
Construction of 4D, 5D and logistics	Construction
Operation and maintenance	Production and processing
Renovations	Closure and rehabilitation
Demolition	Reclamation and monitoring

The three major components of the mining life cycle are exploration, production and processing (Balasubramanian, 2017). These are the major components as it is at these stages where value is created, produced, and realised (Bester, *et al.*, 2016). Exploration involves the collection of core samples to evaluate the deposit in terms of grade and potential size. It is during exploration where the value of the Mineral Resource is determined, thus allowing for the estimation of the Mineral Reserve (Ovalle, n.d.). The production stage involves the extraction of the mineral of concern by using machinery and tools such as drill rigs and loaders (Mining Global, 2015). During processing the valuable minerals are separated from the barren material, thereafter, the valuable minerals are melted to extract the metal content (Mining Global, 2015). However, not all minerals that are sent to the plant for processing are extracted, but some minerals are not recovered during processing given their economic value thus are dumped in the tailings dam.

The common methods used to extract minerals of economic value are surface, placer mining, solution mining, and underground mining methods (Hartman & Mutmansky, 2002). Surface mining is used when the valuable minerals outcrop or are close to the surface and are sufficiently big in size. Some of the surface mining methods include open-pit mining, quarrying, auger mining, and open-cast mining (Gogolewska, 2011). Underground mining is the extraction of minerals from below the earth's surface. This type of mining is used for orebodies that are too deep to mine by using surface mining methods. Some of the underground mining methods include room and pillar, cut and fill, block caving, longhole stoping and longwall mining (Gogolewska, 2011).

This research study is focused on the production zone of an underground mine, the stoping area. Mine planning is an important aspect in the stoping area as it is in this phase that blocks of ore to be extracted are identified and scheduled to maximise the economic value of the project. Therefore, mine planning may be viewed as the vital stage of the mine value chain optimisation. Mine planning is discussed in the following subsection.

2.3.1 Mine planning

Mine planning is the process of planning how to extract the economically payable minerals from the earth's crust within the expected time frame. The extraction must be at the lowest cost possible and fulfil the targets of the company in terms of safety, productivity and profit (Fuykschot, 2009). Mine planning has four main levels, namely: scenario, strategic, tactical, and operational planning. Scenario mine planning involves the generation of multiple scenarios that are based on different future views of the mine. The outcome of scenario mine planning is a specific scenario that maximises the objectives of the mine. The specific scenario is then used in strategic mine planning, where the main goal of the mine is defined (Kloppers, *et al.*, 2014). The main goal can be defined as safely extracting the economically payable minerals at a profit. The plan on how the company's objectives will be achieved is defined during strategic mine planning. The goal is achieved during tactical mine planning. The method required to achieve the objectives defined during strategic mine planning is developed in tactical mine planning (Kear, 2006). Operational mine planning involves the linking of the strategic and tactical mine plans. Milestones, conditions for success and the implementation of the strategic mine plan within a particular period are described during operational mine planning (Riskope, 2014). The differences between strategic mine planning and tactical mine planning are shown in Table 2.12.

Table 2.12: Differences between strategic and tactical mine planning (Adapted from Kear, 2006)

Strategic mine planning	Tactical mine planning
To determine the objectives	To attain the objectives
Obtain the best value	Obtain the lowest costs
Determine limitations and constraints	Identify the resources to achieve the plan
Match the components to maximise the objectives	Allocate the resources to particular tasks
Test the effect of various strategies and scenarios	Test the effect of various operating practices
Identify variances and develop corrective strategies	Identify variances and develop corrective practices
Loose structure	Tight structure

Table 2.12 illustrates that strategic mine planning is associated with value, and tactical mine planning is associated with costs and efficiencies. It is noted that tactical mine planning plays a significant role in the mine production environment (Kear, 2006), which is also known as the mine production zone. Strategic mine planning and tactical mine planning are two processes that are interdependent (Smith, *et al.*, 2008). The absence of strategic mine planning results in operational challenges which could, in turn, result in production requirements not being met. The absence of tactical mine planning results in the mine objectives not being realised thus also resulting in production requirements not being met (Kear, 2006).

Strategic mine planning is focused on the revision of the long-term mine plans, tactical mine planning is focused on the revision of medium-term mine plans, (Dos Santos, 2016) and operational mine planning is focused on the revision of short-term mine plans (Fuykschot, 2009). Long-term mine plans are associated with plans that deal with the entire life of the mine and these plans are the foundation for the short-term mine plans. Long-term mine plans must be updated on an annual basis. Medium-term mine plans are five-year plans and focus on the optimisation of the operation. Medium-term mine plans must be reviewed on an annual basis. Short-term mine plans are two-year plans and focus on the detailed procedures such as shift by shift scheduling (Phakoago, 2018). Short-term mine plans should be updated monthly, weekly and daily (Fuykschot, 2009).

It is noted that tactical mine planning is useful for the application of new technologies and the improvement of efficiencies (Kear, 2006), which are meant to optimise the strategic mine plan. Therefore, the research study focuses on operational mine planning as this type of mine planning links tactical mine planning and strategic mine planning.

It is essential that there be compliance with the mine plans to reach production targets and improve efficiencies. Mine plan compliance is discussed in the following subsection.

2.3.2 Mine plan compliance

Mine planning allows for the optimal extraction of the Mineral Reserves and is dependent on the quality of the geological information and the parameters which are required to ensure that the plan is executed accordingly. Some of these parameters include equipment availability, equipment utilisation and influences from the external market (Angelov & Naidoo, 2010). To determine the operational performance of an operation, the planned and actual targets must be considered (Musingwini, 2016). Therefore, it is essential that there is compliance with the mine plan. The mine plan must be monitored for any deviations to remedy the situation which has caused the deviation (Angelov & Naidoo, 2010). Since mine planning plays an essential role in the MVC, deviations from the mine plan have a direct impact on the value creation, cost and efficiencies.

2.4 Chapter Summary

There are various digital technologies associated with the 4IR. These include 3D printing, AI, fusion of technologies, robotics, IoT, big data analytics, and digital twinning. Some of the disadvantages associated with these digital technologies include complexity, relatively high implementation costs and cyber-attacks. Some of the advantages include improving decision making, monitoring and safety. These digital technologies can be implemented in the mining industry to yield the same benefits. The next chapter discusses the BIM concepts in detail.

3. BIM CONCEPTS

The AEC industry has gone through a design evolution, which is illustrated in Figure 3.1. In hand drafting, designs were done using paper and pencil. While 2D and 3D CAD designs are designs that are done on a digital platform in 2D and 3D, respectively (Goubau, 2016). BIM is a platform where there is collaboration and communication between all the parties involved in the construction project life cycle. BIM is considered as an important revolution in the AEC industry (Bentley Institute Press, 2017).

Figure 3.1: Design evolution in the AEC industry (Adapted from Goubau, 2016)

3.1 Introduction to BIM

BIM is a process that combines information and technology to create a project that is digitally represented and can integrate data from various sources. The process is applied throughout the construction project life cycle and ensures that data is created, managed and shared. The aim of BIM is to improve efficiency and communication between all parties that are working on the construction project (Construction Federation Industry, n.d.), thus ensuring that there is a connection between project teams in different disciplines (Theodora, 2018). The communication is improved by ensuring that the data is hosted in a common data environment (CDE) where it can be easily accessed and managed by various parties that are working on the construction project (Construction Federation Industry, n.d.). This allows all the parties to have a common understanding of the objectives and progress of the project, as well as communicate updates in a timely manner. The output of BIM is a model that is in a digital format and describes all the aspects of the project life cycle thus supporting decision making. A BIM model also allows for scenario planning as various scenarios can be created to determine the best scenario for the project. Standards and specifications can be added to the BIM model to ensure that all models comply with the standards and specifications required (Goubau, 2016).

BIM allows designers and engineers to optimise their designs and to produce buildings of high-quality. Scheduling and cost information can also be linked to the model to optimise the design. Clash detections are also an essential part of BIM as they ensure that there is no conflict between any objects within the individual models and between models generated during the integration of the data from the different parties. This ensures that all the issues relating to the constructability of the building are resolved before any construction begins. The advantages of clash detections include the prevention of conflicts, delays, changes in the design, and exceeding the budget requirements (Theodora, 2018). An example of clash detection is being able to determine the exact location where plumbing fitting clashes with electrical fittings and being able to rectify this error in the model before construction begins (Goubau, 2016).

BIM has level of information (LOI) and level of detail (LOD) that are collectively known as levels of definition. Level of definition is essential for clarifying the amount of data that is required at each stage of creating the information model. LOI is associated with the non-graphical information such as scheduling and cost. LOD is associated with the graphical information such as the 3D model of the building (The B1M, n.d.).

The BIM database is essential as it ensures that there is a CDE in which models are shared. The database also ensures that when changes are made to the model, these changes are propagated throughout all the other models and documents. This allows for better collaboration, quality control and planning (Vercator, n.d.). It has been argued that BIM will improve efficiencies and reduce costs in the AEC industry (Succar, 2008). Some of the benefits of adopting BIM include coordination and collaboration, conflict detection and risk mitigation, faster drafting without loss of cost and quality, easy maintenance of building life cycle, optimisation of schedule and cost, and high level of customisation and flexibility (Goubau, 2016).

BIM allows for an increase in efficiency due to the data that is being exchanged across the construction project life cycle. This is because digital data is relatively easier to manage, use and store than designs done on paper (Construction Federation Industry, n.d.). The information hosted in the model is related to the different objects that make up the building and provides feedback relating to the performance of the objects throughout the building’s life cycle (Theodora, 2018).

Digital data reduce the need for duplication of data thus minimising errors. CDE ensures that there is better communication and collaboration between all the parties that are involved in the construction project life cycle. BIM also allows for real-time updates of graphical information thus improving the collaboration (Construction Federation Industry, n.d.).

A positive return on investment has been noted by 75% of the companies that have adopted BIM. The other benefits include reduced project life cycle and savings on material costs (Agarwal, *et al.*, 2016), because of 4D BIM and 5D BIM, respectively.

Although BIM has various benefits, its adoption has challenges. Some of these challenges include data uncertainty, managing the transfer of information and controlling the progression that stems from 3D BIM to 7D BIM (India CAD Works, 2018). Other challenges include scepticism as many small business owners believe that the adoption of BIM is more troublesome than what it is worth as it requires new software such as buildingSMART. Another challenge is that there needs to be a change in the mind-set of the people. All parties need to be willing to be fully collaborative and have their work being easily accessible (Construction Federation Industry, n.d.).

Accessibility to data is essential for improved collaboration and communication, and to ensure that the data can be shared and accessible on the CDE. It is essential that the different software packages allow for the exchange of data. In terms of the ability to exchange data, there is closed BIM and open BIM, and they are discussed in the subsequent section.

3.2 Open BIM versus Closed BIM

Closed BIM is known as proprietary BIM and it only allows for the exchange of data from the same type of software vendor. This type of BIM is relatively expensive to maintain, support and develop (Construction Federation Industry, n.d.). Since companies use software packages from different software vendors, it means that in a closed BIM environment, the different parties would not be able to exchange data. This would in turn limit the amount of collaboration and effectiveness.

Open BIM is known as interoperable BIM and it allows for the exchange of data regardless of the type of software the data originates from. Many companies use software packages from different vendors therefore open BIM allows companies to exchange data without requiring new software packages from the same software vendor. Therefore, open BIM offers a relatively less expensive option for the adoption of BIM (Construction Federation Industry, n.d.). buildingSMART is an industry body aimed at driving digital transformation in the industry of built assets (buildingSMART International, n.d.). buildingSMART ensures that open BIM takes place as it supports five standards that allow for importing and exporting of data between different software packages. It also encourages better collaboration as comments and snapshots can accompany the imported and exported data shared between the various software

(Construction Federation Industry, n.d.). In the subsequent section, the BIM framework is discussed.

3.3 BIM Framework

BIM framework is the supporting structure around which BIM is built (Cambridge Dictionary, n.d.). It consists of fields, stages and lenses and is illustrated in Figure 3.2. BIM fields are the activities that identify the main players and deliverable of BIM. BIM stages describe the implementation levels and BIM lenses provide the enquiry process that is required for identifying, assessing, and qualifying the BIM fields and stages (Succar, 2008).

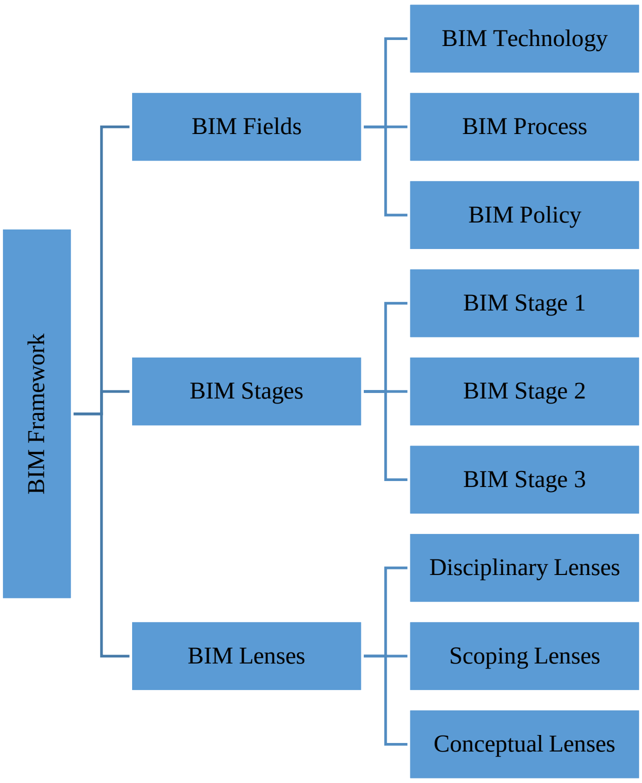


Figure 3.2: BIM framework (Adapted from Succar, 2008)

BIM fields are the first component of the BIM framework and consist of three activities known as technology, process and policy (TPP). Each of the activities have players, deliverables, and requirements. Figure 3.3 shows the BIM fields.

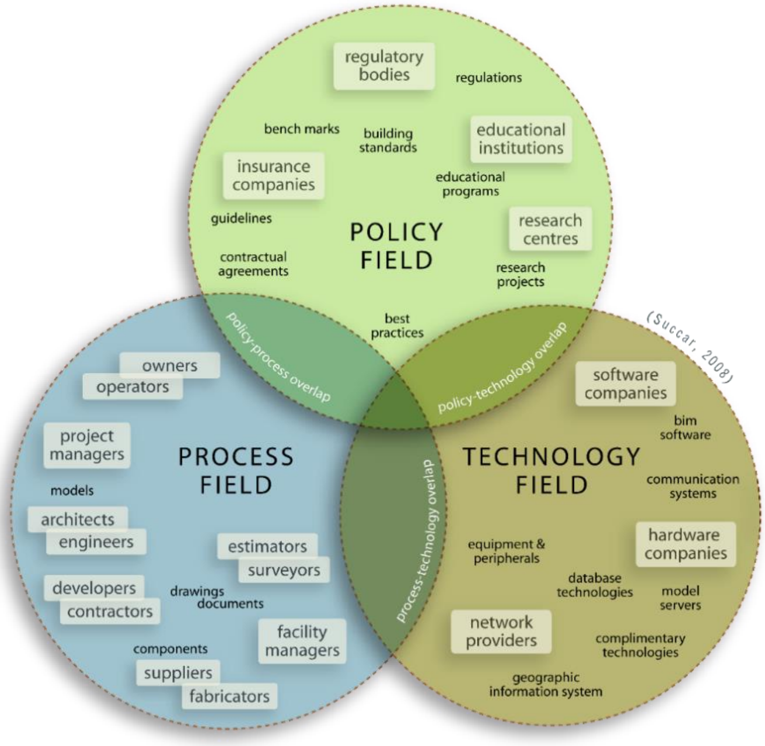


Figure 3.3: BIM fields (Succar, 2008)

The technology field consists of players who develop software, hardware, equipment and networking systems. The products that are developed are essential for increasing efficiencies, productivity and profitability. The process field consists of players who design, construct, use, manage and maintain the structures. The policy field consists of players who deliver research, allocate and minimise risk in the AEC industry. The players in the policy field are essential for regulatory and contractual roles in the process of design, construction and operation (Succar, 2008).

BIM stages are the second level of the BIM framework and consist of three stages. BIM stages are the stages that stakeholders have to gradually implement within an organisation or project (Succar, 2008). Figure 3.4 shows the three BIM stages (Succar, 2010).

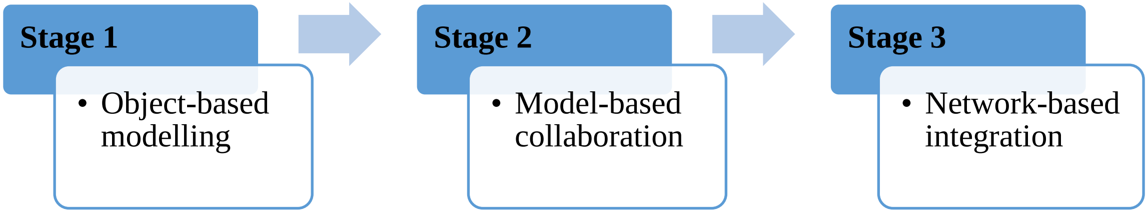


Figure 3.4: BIM stages (Adapted from Succar, 2010)

The first stage is known as object-based modelling and it involves the creation of 3D CAD designs. These designs are created on a software tool such as Revit or Tekla. In BIM stage 1, the generation of 2D documents and 3D visualisations are automated. However, there is no collaboration at this stage. The second BIM stage is known as model-based collaboration and it is in this stage where collaboration begins. The collaboration is between the various parties who are involved in the construction project life cycle. Model-based collaboration allows for the generation of 4D and 5D models. The third BIM stage is known as network-based integration. In this stage, the BIM model has significant amounts of information that is essential for the project. The model is shared to increase the level of collaboration. The information rich model includes information associated with business intelligence, policies, costing, 6D and 7D BIM information (Succar, 2008).

The third level of the BIM framework is BIM lenses. BIM lenses are the different layers that are required for the analysis of the BIM fields and BIM stages, as illustrated in Figure 3.5, and allows for more focus within any aspect in the AEC industry. There are three types of BIM lenses known as disciplinary, scoping and conceptual lenses. The BIM lenses ensure that there is flexibility in the project life cycle as the lenses create different views (Succar, 2008) so that strategic planning can be done.

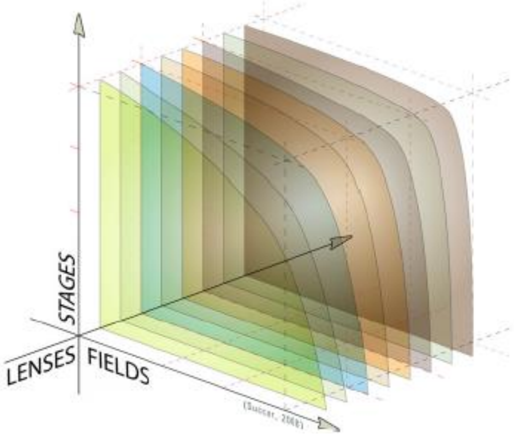


Figure 3.5: BIM lenses (Succar, 2008)

The application of BIM fields is essential for the generation of the different BIM views in the disciplinary lens. Examples of BIM disciplinary lenses include change, risk, process, data, design and financial management. In the scoping lens, unwanted information is filtered out, and the conceptual lens allows for the application of different concepts on the model. The concepts are related to deliverables, equipment and tasks (Succar, 2008).

BIM has different dimensions and each dimension consists of pieces of information that make the model more intelligent. The BIM dimensions are discussed in the subsequent section.

3.4 BIM Dimensions

BIM dimensions show the development of the virtual 3D model throughout the construction project life cycle. The BIM dimensions show the time frame, cost, and the performance of the building during its operational phase. Figure 3.6 shows the BIM dimensions.

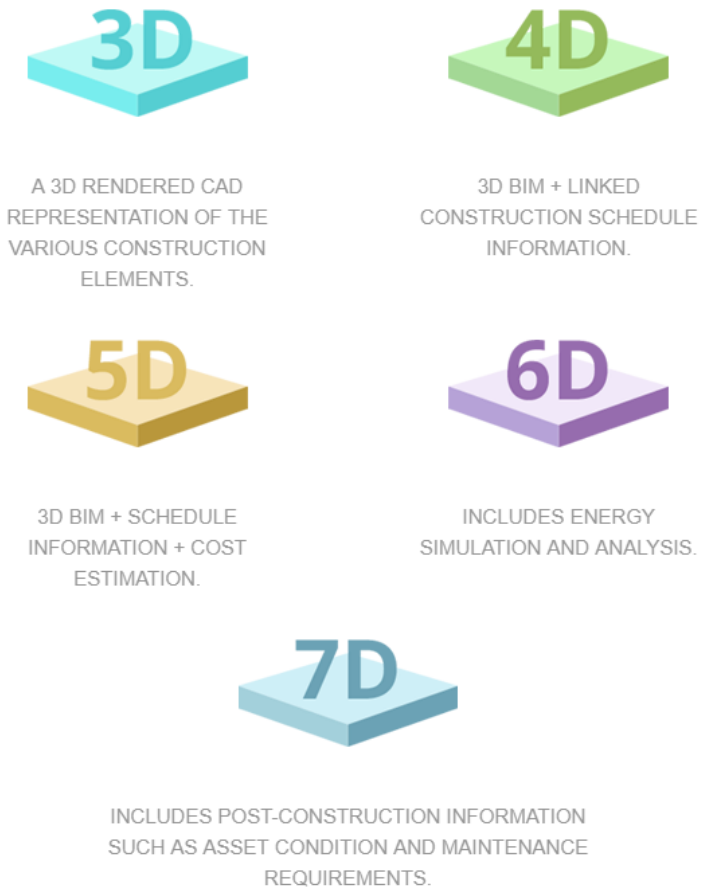


Figure 3.6: BIM dimensions (India CAD Works, 2018)

3D BIM involves the creation of a 3D model on a CAD platform. The model contains relevant information such as plumbing, electrical, mechanical and architectural information. Throughout the construction and operational process, the 3D BIM model can be updated with new data to improve predictions pertaining to potential problems. The benefits of 3D BIM include improved project visualisation, improved collaboration, and less reworking of designs (India CAD Works, 2018).

4D BIM involves linking time-related information to the 3D BIM model. It provides a schedule for construction. This means that the sequence of events that will take place in the construction phase can be visualised. The schedule can stem from initial investment to the completion of the project. The benefits of 4D BIM include optimised planning process, improved fabrication and logistics, and improved coordination of site activities (India CAD Works, 2018).

5D BIM involves linking cost information to the 4D BIM model. The 5D BIM model allows for cost estimations, analysis and tracking of the budget. The 5D BIM model combines scheduling and costing thus allowing for both to be considered during the design process. The benefits of 5D BIM include more accurate budgets and cost analysis, more efficient planning, and overall cost reduction (India CAD Works, 2018).

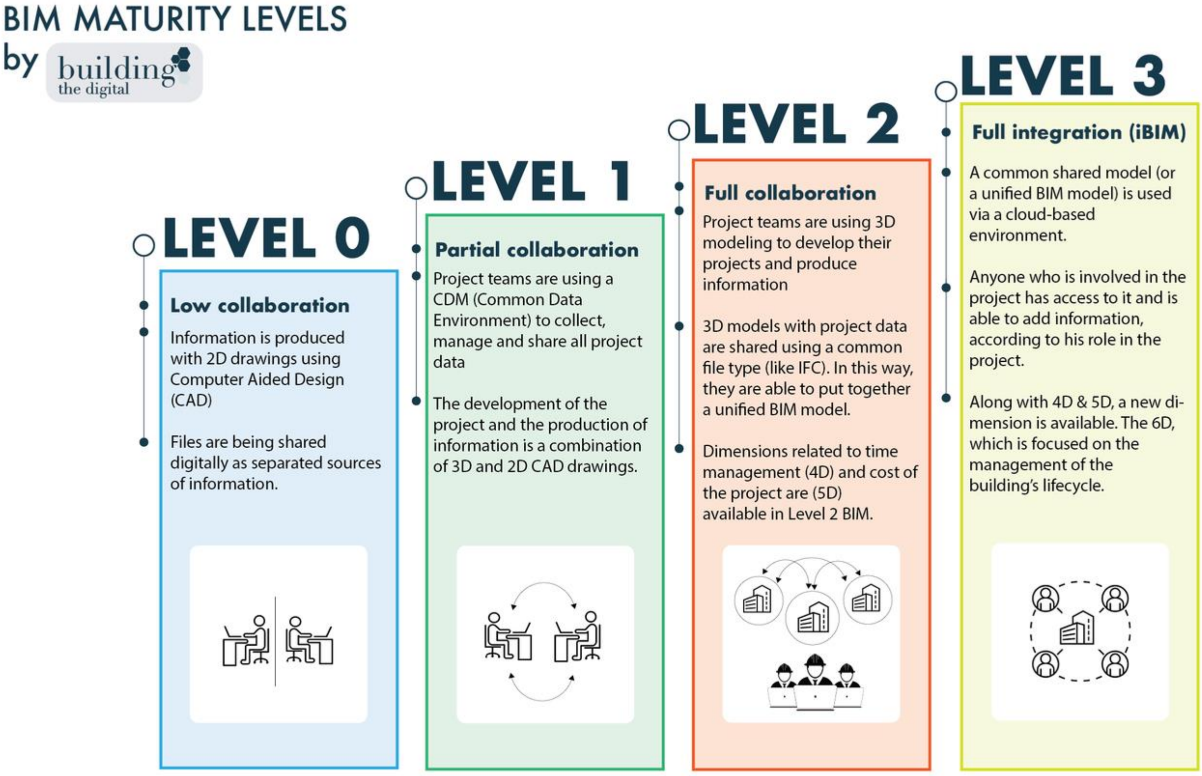
6D BIM addresses sustainability issues such as those pertaining to energy. 6D BIM ensures that the energy analysis and calculations are more accurate, thus allowing for adjustments to be made when energy is being wasted. In 6D BIM, real time information can be added to the 5D model to verify any estimates that were made in the initial stages of the project life cycle. The benefits of 6D BIM include reduction in energy consumption, improved energy analysis, and more sustainable design methods and models (India CAD Works, 2018).

7D BIM is focused on the overall construction project life cycle. Information pertaining to the condition of the building and its elements, technical specifications, maintenance schedules, equipment manuals and warranty details are stored in the 7D BIM model. This information can be easily stored and viewed on the model. The 7D BIM model ensures that the elements of the building are repaired and replaced timeously. The benefits of 7D BIM include easy storage and retrieval of all information and documentation related to the project, improved and efficient asset management, and increased lifespan of the asset (India CAD Works, 2018).

The 7D BIM model is relevant for the operational phase of the project. This model consists of information pertaining to the schedule, cost, sustainability and day-to-day operation of the building. To get the best out of the different levels of BIM, it is essential that there is collaboration between all the parties working on the construction project. The level of collaboration is determined by the BIM maturity levels, which are discussed in the subsequent section.

3.5 BIM Maturity Levels

BIM has four maturity levels and each level represents an increase in the maturity of BIM (see Figure 3.7). An increase in BIM maturity means that the ability to exchange information digitally has increased and that the degree of collaboration between different parties has also increased (Theodora, 2018).



Level 0 – Low collaboration

- Information is produced with 2D drawings using Computer Aided Design (CAD)
- Files are being shared digitally as separated sources of information.

Level 1 – Partial collaboration

- Project teams are using a CDM (Common Data Environment) to collect, manage and share all project data
- The development of the project and the production of information is a combination of 3D and 2D CAD drawings.

Level 2 – Full collaboration

- Project teams are using 3D modeling to develop their projects and produce information
- 3D models with project data are shared using a common file type (like IFC). In this way, they are able to put together a unified BIM model.
- Dimensions related to time management (4D) and cost of the project are (5D) available in Level 2 BIM.

Level 3 – Full integration (iBIM)

- A common shared model (or a unified BIM model) is used via a cloud-based environment.
- Anyone who is involved in the project has access to it and is able to add information, according to his role in the project.
- Along with 4D & 5D, a new dimension is available. The 6D, which is focused on the management of the building's lifecycle.

Figure 3.7: BIM levels (Theodora, 2018)

The first BIM maturity level is known as Level 0, which represents an environment where there is minimal digital collaboration and 2D CAD designs are being used. The second BIM maturity level is known as Level 1, which represents an environment where there is a combination of 2D and 3D CAD designs with the information being shared on a CDE such as a cloud-based service (McPartland, 2014). The third BIM maturity level is known as Level 2, which represents an environment where every object in the design is in 3D CAD and has information about cost and scheduling linked to it. All the parties that are working on the construction project are able to combine their data and share it through the CDE. The fourth BIM maturity level is known as Level 3, which represents an environment where there is a greater level of collaboration due to more data being integrated. At this level of maturity, all the parties can access and modify the data, however, the modification of the data is subjected to processes and security restrictions (Construction Federation Industry, n.d.).

Although BIM is mostly used in new construction projects, it is also applicable for already existing buildings. The scan-to-BIM concept has made it possible for BIM to be applied to existing buildings and the scan-to-BIM concept is discussed in the subsequent section.

3.6 Scan-to-BIM

BIM can be used for buildings that exist and those that are yet to be built. The scan-to-BIM concept is relevant for building that already exist. The way in which it is achieved is through 3D laser scanning. The laser scanner such as a Light Detection and Ranging (LiDaR) scanner, is used to capture a 3D scan of the existing building. The scan is then imported into an environment that allows for 3D modelling. Thereafter, an accurate as-built model is created (Dekker, 2019). The 3D laser scanner provides an accurate point cloud dataset and model (Vercator, n.d.).

3.7 Chapter Summary

BIM is a digital technology that can be used to improve collaboration and communication between parties who are involved in the project life cycle. The application of BIM has the potential to improve productivity and cost. BIM has been applied in various parts of the world such as Asia, Europe and Africa and it is a concept that is gaining popularity. Worley has applied BIM in mining and is currently operating in the 7D dimensional space of BIM to gain real time access to the operational data of the mining project. This chapter provided a more in-depth understanding of BIM to identify which aspects of BIM would be better suited for application in the production zone of an underground mine. The next chapter discusses data integration in detail, which is an essential aspect for the application of BIM in the production zone of an underground mine.

4. DATA INTEGRATION

An organisation generates significant amounts of data that have different sizes and formats and originates from various sources. The IT department is then responsible for ensuring that the data that is generated can be managed relatively easily. Data integration is a modern solution for ensuring that various systems and applications can be connected in a flexible manner for an organisation to gain insights from the data. Through data integration, the various business units within an organisation will be able to consistently access the data (Hughes, 2018). The data from the different sources is combined into a centralised location such as a data warehouse (Safe Software, n.d.).

Some of the benefits of data integration are (Hughes, 2018):

- Data integration is capable of supporting different datasets that have different attributes, thus ensuring that different types of data can be supported;
- Organisations can gain more insights that can open new opportunities for the company;
- Data integration manages the complexity that is associated with migrating the data. Therefore, the data becomes less complex and relatively easier to deliver to any system;
- There can be a combination between structured and unstructured data, as well as, internal and external data. The combination allows the data to be more valued and for greater insights to be gained;
- The data becomes easily accessible by the various parties in the organisation;
- Improved collaboration between the various parties in the organisation; and
- The data becomes more accurate, consistent and with less errors, thus improving the integrity of the data and making the data more valid and viable for decision making.

Although data integration has various benefits, it also has limitations. Some of the limitations associated with data integration include (Hughes, 2018):

- During data integration, data originates from different sources and formats, thus making the data more complex and difficult to manage. Therefore, to overcome the complexity and management challenges, data mapping must be done. Data mapping will ensure that the data is in sync and does not overwhelm the system. A data integration tool that can transform the data from one format to another is able to automatically map the data. The transformation of the data facilitates the communication and integration of the data;

- The data that is being integrated will have to be updated on a regular basis. Therefore, to ensure that the data remains valid, it is essential to programme the data integration tool such that there is consistency in the definitions and rules of the data; and
- It is essential for the company to work with a trusted data integration solution provider. The data integration solution provider must be able to cater to any obstacles that could arise, manage the deployment and implementation of the data integration solution, and assist the company with keeping sight of the outputs they require from the data integration.

When integrating data, it is essential to consider the data integration techniques, tools, and requirements, and these are discussed in the subsequent subsections.

4.1 Data Integration Techniques

A data integration technique is a technique used for combining different data set to form a whole to enable synchronisation of the data set to aid in the analysis for decision making. Some of the data integration techniques include manual, middleware, data warehouse, and data virtualisation (Haider, 2019). Manual data integration involves an individual user having to manually collect the data from various sources, cleaning the data as required, and uploading it to the central database where it can be stored. Manual data integration is inefficient and inconsistent. Some of the advantages and disadvantages of manual data integration are shown in Table 4.1.

Table 4.1: Advantages and disadvantages of manual data integration (Adapted from VL OMNI, n.d.)

Advantages	Disadvantages
Provides a strong focus on the core competencies for the business	Higher margin of error
It can decrease expenditures	Slow and inefficient

Middleware data integration involves the use of middleware, which is the software that connects different applications, to structure the different data sets such that they are in a format that can be uploaded onto the central database. Middleware is used when there is difficulty with accessing data from a particular software (Talend, n.d.). Some of the advantages and disadvantages of middleware data integration are shown in Table 4.2.

Table 4.2: Advantages and disadvantages of middleware data integration (Adapted from Miaoj, 2012)

Advantages	Disadvantages
Deployed relatively easily	Can sometimes threaten the real time performance
Operates faster	Not popular which leads to lack of experts
Easy to manage and maintain	A minor change in the system can lead to a major downtime of the real time application
Always accessible	High cost
Real time information between the systems	
Maintains information integrity	
Helps different systems to interact	

“Data warehouses are stores of structured, curated data pulled from separate intermediary databases that make it easy for analysts from different parts of an organisation to access and analyse for their respective purposes” (Panoply, 2019, p. 8). Data warehousing involves the movement of data from its source to the data warehouse. In data warehousing, the data are stored, viewed and managed in a centralised location thus offering more flexibility than the other types of data integration. Some of the advantages and disadvantages of data warehousing are shown in Table 4.3.

Table 4.3: Advantages and disadvantages of data warehousing (Adapted from Lorecentral, 2018)

Advantages	Disadvantages
Better access to data	It requires continuous cleaning, transformation and data integration
Extensive and exhaustive data	In an implementation process, difficulties may be encountered in relation to the different objectives that an organization intends
The different systems work better	They require a review of the data model, objects, transactions and in addition to storage
Provides key information for business decision making	They have a complex and multidisciplinary design
Improves the quality of decisions made	They require a restructuring of the operational systems
Very useful for storage of analyses and queries	Once implemented, it can be difficult to add new data sources
Relatively easy to install	Data warehouses may become obsolete relatively soon
It allows greater flexibility	It is not very useful for making decisions in real time due to the long processing time it may require
Provides reliable communication between all departments of the company	Throughout its life the data warehouse can suppose high costs. Maintenance costs are high
It allows for effective planning	
Reduces response times	

Data virtualisation involves having an abstract layer that provides a joint view of the different systems. The data physically remains in the system. To get the data, a request is made through the virtual layer. Changes are made on the virtual layer before they are made on the system. However, this type of data integration cannot be used for bulk data (Haider, 2019). Some of the advantages and disadvantages of data virtualisation are shown in Table 4.4.

Table 4.4: Advantages and disadvantages of data virtualisation (Adapted from TBConsulting, 2019; Urbach, 2019)

Advantages	Disadvantages
Reduced spending on storage	When the server is down then the virtual database is also down, thus affecting ability to work for the employees
Easier backup and disaster recovery	
Better business continuity	Network traffic due to various information requests
More efficient IT operations	

Data integration will eliminate the process of sending information via email to the different departments, as illustrated in Figure 6.15, as the data will be on a common data environment. The data integration technique that has been proposed for this research study is discussed in Section 7.

The different data integration techniques give insight of appropriate techniques a company can use to integrate their data. Furthermore, it is essential to consider other data integration tools to aid in selecting a technique that is best suited for Mine A. Some of the data integration tools are discussed in the subsequent subsection.

4.2 Data Integration Tools

Data integration tools are tools that can integrate data from different sources. It is essential that the tools can clean, transform, map and monitor the data being integrated (Alley, 2018). The main purpose of the data integration tools is to combine the data in an efficient manner that will ensure that the data is available to the various departments within the organisation (Hughes, 2018). Some data integration tools include, but are not limited to, IBM InfoShere, Microsoft SQL and Oracle Data Service Integrator (Alley, 2018). The IBM InfoSphere is an information server that is responsible for data warehousing and data integration. Some of its functionalities include source data profiling, data quality assurance, data transformation and data delivery. This means that the IBM InfoSphere can detect any inconsistencies or problems with the data. It is also able to clean, standardise and merge the data. Thereafter, the data are integrated and transformed. By using the extract, transform and load (ETL) process, the integrated and transformed data are loaded onto a data warehouse and delivered to the end user (Alooma Team, 2018a). The Microsoft SQL is a server integration service that can gather data from various data sources in different formats. It can manipulate, migrate, transform, integrate, monitor and manage different tasks (Alooma Team, 2018b). Oracle Data Service Integrator can develop and manage data services from different data sources. It considers the different standards for the different data sources and allows for the re-usability of the data. Oracle Data Service Integrator is the only data integrator that can support the reading and writing of data from different data sources (Oracle, n.d.).

The data integration tools provide a platform onto which the data integration can be conducted. In conjunction with the data integration tools, it is essential to consider the data integration requirements. The data integration requirements are discussed in the subsequent section.

4.3 Data Integration Requirements

There are certain data integration requirements to ensure that data integration can be done successfully. It is essential that there is a clear understanding of how the data flow within the organisation. It is also essential that the data can originate from any source, it can be stored on a cloud or premise, it improves performance, it can be accessed at any time of the day, and it is of such quality that it can be trusted and used for decision making (Anon., 2013) as illustrated in Figure 4.1.

Figure 4.1: Requirements for data integration (Anon., 2013)

Due to the relatively high speed and size of data, it is essential that the data integration tool used is not affected by any changes in the speed or size of the data. The chosen data integration tool must have the capability to respond to an event timeously. This timeous response assists in reducing time delays between an event occurrence and response time. Although, there are software packages that support cloud-based integration, there are companies who still prefer to have their data being stored on an on-premise system. Therefore, it is essential that the data integration tool to be considered be one that can easily and effectively synchronise with both cloud and on-premise systems (Krishnan, 2016).

4.4 Chapter Summary

Data integration is a modern solution for ensuring that various systems and applications can be connected in a flexible manner for an organisation to gain insights from the data. Data integration has various techniques that guide the way data can be integrated, and it is through these techniques that data integration tools are created. The next chapter discusses the methodology used to meet the research objectives and answer the research question.

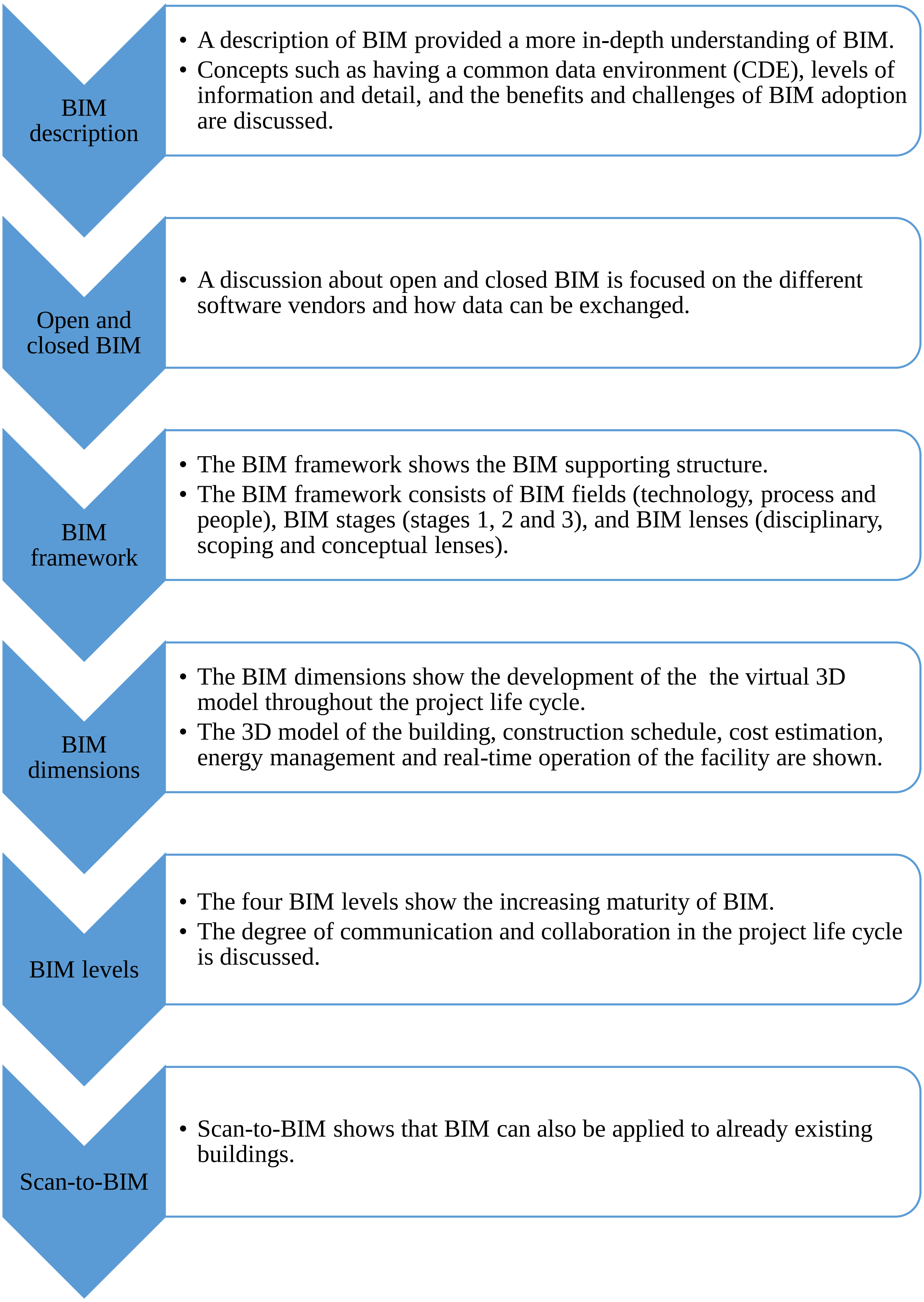
5. RESEARCH METHODOLOGY

An underground conventional mine (Mine A) was used for the case study of applying the BIM concepts in a mining environment. Mine A is situated in South Africa and extracts gold as the main mineral of economic value. Mine A was selected as a sight for investigation because it is on a digital journey that is aligned with the research study. The proposed investigations that took place on Mine A involved collecting information from the various departments on Mine A to determine how BIM concepts can be applied to Mine A. The data set was sourced from various departments in the mine.

In this chapter, the analysis of BIM is discussed first, followed by the sourcing of the data, understanding the chosen BIM concept to be applied, conceptualising the BIM-based framework for mining, and lastly, the validation of the MIM framework.

5.1 BIM Analysis

BIM is centred around having a shared knowledge of resources to improve the way in which the construction project is being conducted. There are many other concepts to BIM that had to be understood for the research study. An understanding of these concepts assisted with determining how BIM can be applied to the production zone of an underground mine. Therefore, it was essential to do an analysis of BIM. The concepts that were considered during the analysis of BIM are shown in Figure 5.1. BIM is a concept that requires significant transformation in the organisation, therefore, before considering which BIM concepts could be applied, it was essential to determine whether Mine A was ready for the implementation of BIM. To determine this, information regarding the Mine A’s digital transformation journey had to be considered. Once the BIM concept that would be applied was identified, it was essential to determine what type of data would be required from the mine to apply the BIM concept.



BIM description

- A description of BIM provided a more in-depth understanding of BIM.
- Concepts such as having a common data environment (CDE), levels of information and detail, and the benefits and challenges of BIM adoption are discussed.

Open and closed BIM

- A discussion about open and closed BIM is focused on the different software vendors and how data can be exchanged.

BIM framework

- The BIM framework shows the BIM supporting structure.
- The BIM framework consists of BIM fields (technology, process and people), BIM stages (stages 1, 2 and 3), and BIM lenses (disciplinary, scoping and conceptual lenses).

BIM dimensions

- The BIM dimensions show the development of the the virtual 3D model throughout the project life cycle.
- The 3D model of the building, construction schedule, cost estimation, energy management and real-time operation of the facility are shown.

BIM levels

- The four BIM levels show the increasing maturity of BIM.
- The degree of communication and collaboration in the project life cycle is discussed.

Scan-to-BIM

- Scan-to-BIM shows that BIM can also be applied to already existing buildings.

Figure 5.1: BIM concepts

5.2 Data Collection

The data were collected from Mine A. Once BIM was analysed, the concept that could be applied to the production zone of the underground mine was identified. Having identified the concept to be applied, the research study focused more on the different departments within the Technical Mining division, instead of focusing only on the mine planning department. The reason for the wider focus was to examine how the different departments operate and how they are linked. The data set was collected from each department and as categorised in Figure 5.2.

Figure 5.2: Information requested from the different departments

5.3 Understanding the BIM Concept to be Applied

After data were collected from the mine, it was essential to create an information flow diagram to understand how the departments are connected and avoid duplication of data sources in the Technical Mining division. The information flow diagram indicated that the various departments are not linked through a centralised system as files are being shared via email. This aided in determining how the BIM concept could be applied in the Technical Mining division. More literature was reviewed about the concept that would be applied. The literature reviewed provided a guide as to how the BIM-based framework for mining could be conceptualised.

5.4 Conceptualising the BIM-based Framework for Mining

The BIM-based framework for mining is linked to the current way in which the information flows between the different departments and how the different departments are linked to each other. It shows a proposed way in which the information can flow, how it can be stored and how it can be shared between the different departments. The framework will be similar to the figure shown in Figure 5.3.

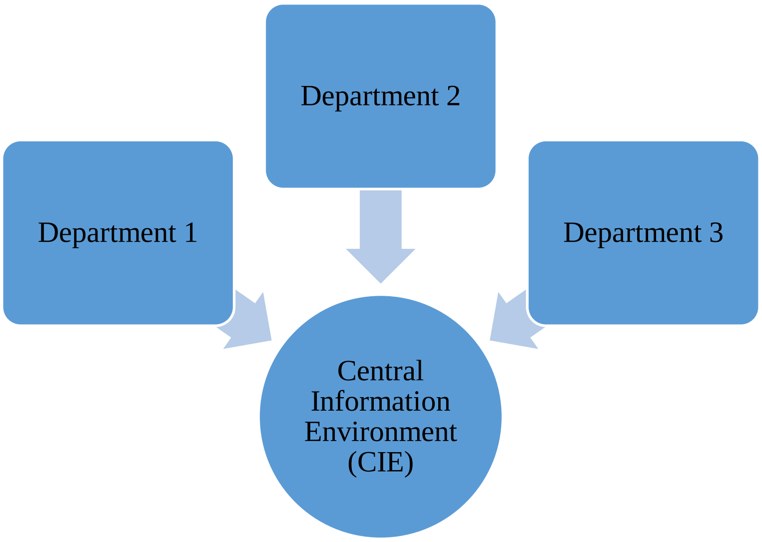


Figure 5.3: Schematic of the BIM-based framework for mining

5.5 Validation of the BIM-based Framework

Validating the BIM-based framework is essential to determine whether the framework is providing the desired outcomes. The BIM model can be validated by running several simulations using data from the four departments used in this study. The simulation results will provide guidance on areas that need modifications and improvements to enhance the efficiency of the model. However, since there are various steps that need to be taken before the BIM-based framework is implemented at the mine, the validation of the framework could not be done. The mine was not yet ready for the application of the framework but would need to apply the concept outlined in the framework to be prepared for the application of the other BIM concepts.

5.6 Chapter Summary

BIM is the backbone of the research study and it is for this reason that the result of the research study is a BIM-based framework for the production zone of an underground mine. The methodology that is outlined in this chapter was used to resolve the problem outlined in the problem statement. The next chapter presents the results discussion.

6. UNDERGROUND MINING PRODUCTION ZONE

For this research study, the production zone refers to the stoping area, which is the part of the underground mine where the ore is extracted. Therefore, it is essential to consider the activities that take place in the stoping area. The primary activities that link to the production zone for the research study are drill, blast, load and haul, and supporting the strata. Therefore, the production zone activities considered for this research study are drilling, charging, blasting, cleaning and supporting, as illustrated in Figure 6.1.

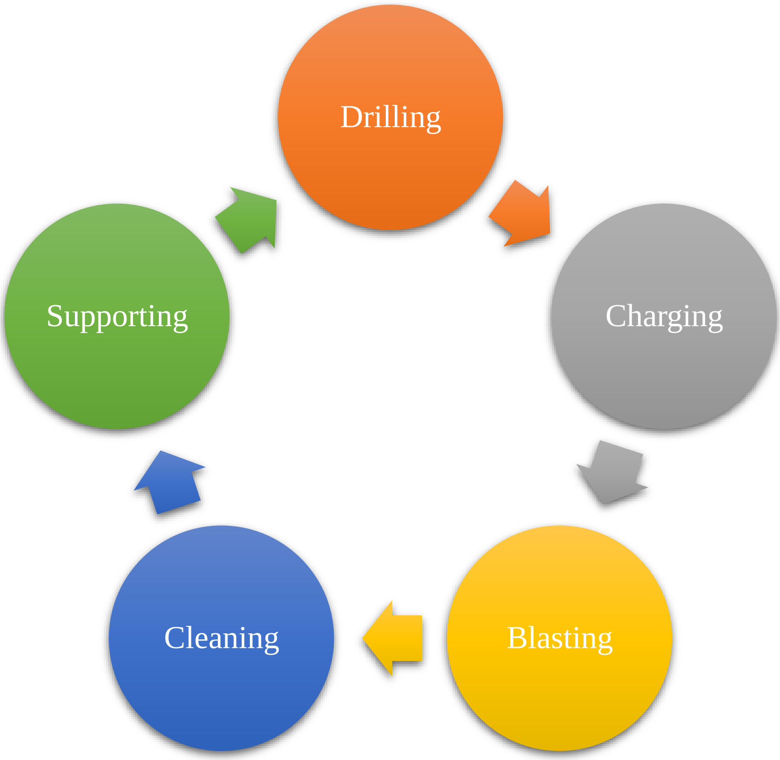


Figure 6.1: Primary production zone activities

Since the BIM concepts will be applied to the production zone of an underground mine, it was essential to determine which departments in the mine have significant impact on the activities in the production zone. Although mining companies have various divisions that contribute towards ensuring that the mine is operational, the Technical Mining division was identified as the division that has a significant impact on the production zone activities. Therefore, the Technical Mining division is the focus for this research study. The Technical Mining division focuses on the operational planning of the mine, which links directly to the production zone, and consists of the following departments; mine planning, geology, survey, mineral resource management (MRM), ventilation and environmental engineering (VEE), rock engineering, engineering and mining. In this study, various flow charts depicting the primary information each department is responsible for in a Technical Mining division of an underground conventional mine were developed (see Figure 6.2 to Figure 6.9).

The rock engineering department is responsible for designing and supporting the excavations to ensure that the underground mine environment is safe for the workers and machines. Figure 6.2 shows the information that is managed by the rock engineering department.

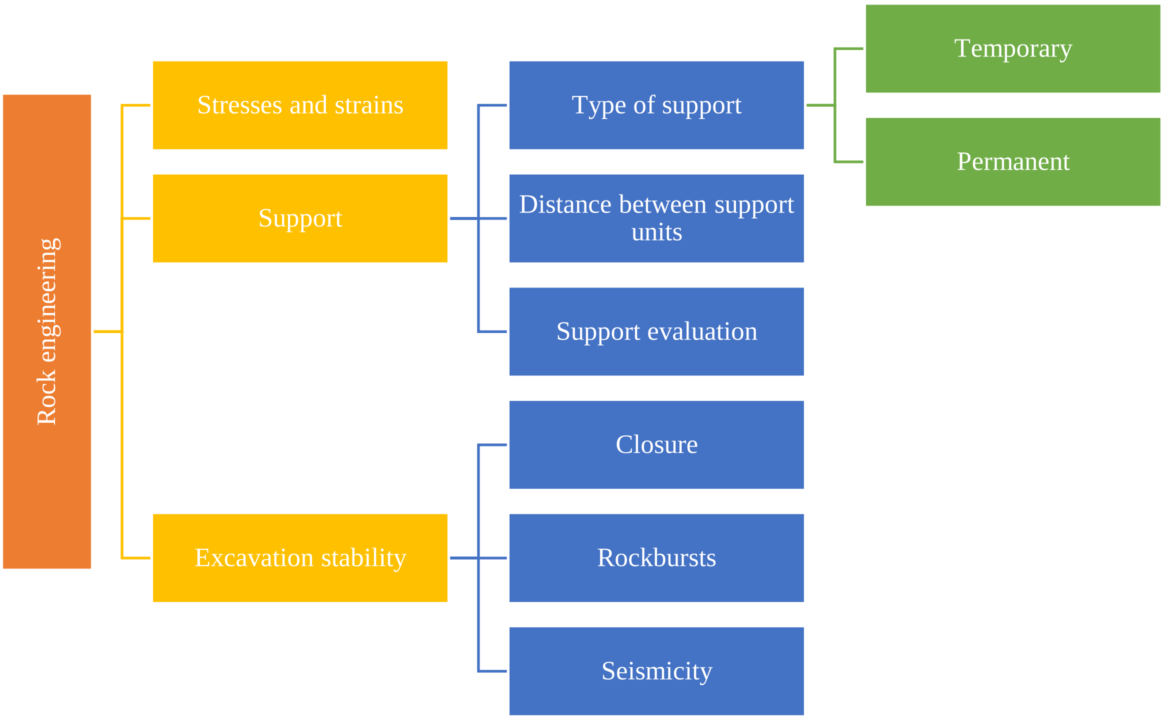


Figure 6.2: Rock engineering information from the rock engineering department

The mine planning department is responsible for developing the short-term, medium-term and long-term mine excavation layouts. It is essential that the mine plans are created in compliance with the statutory and company requirements (Kimberly Ekapa Mining, 2016). Figure 6.3 shows the information that is managed by the mine planning department.

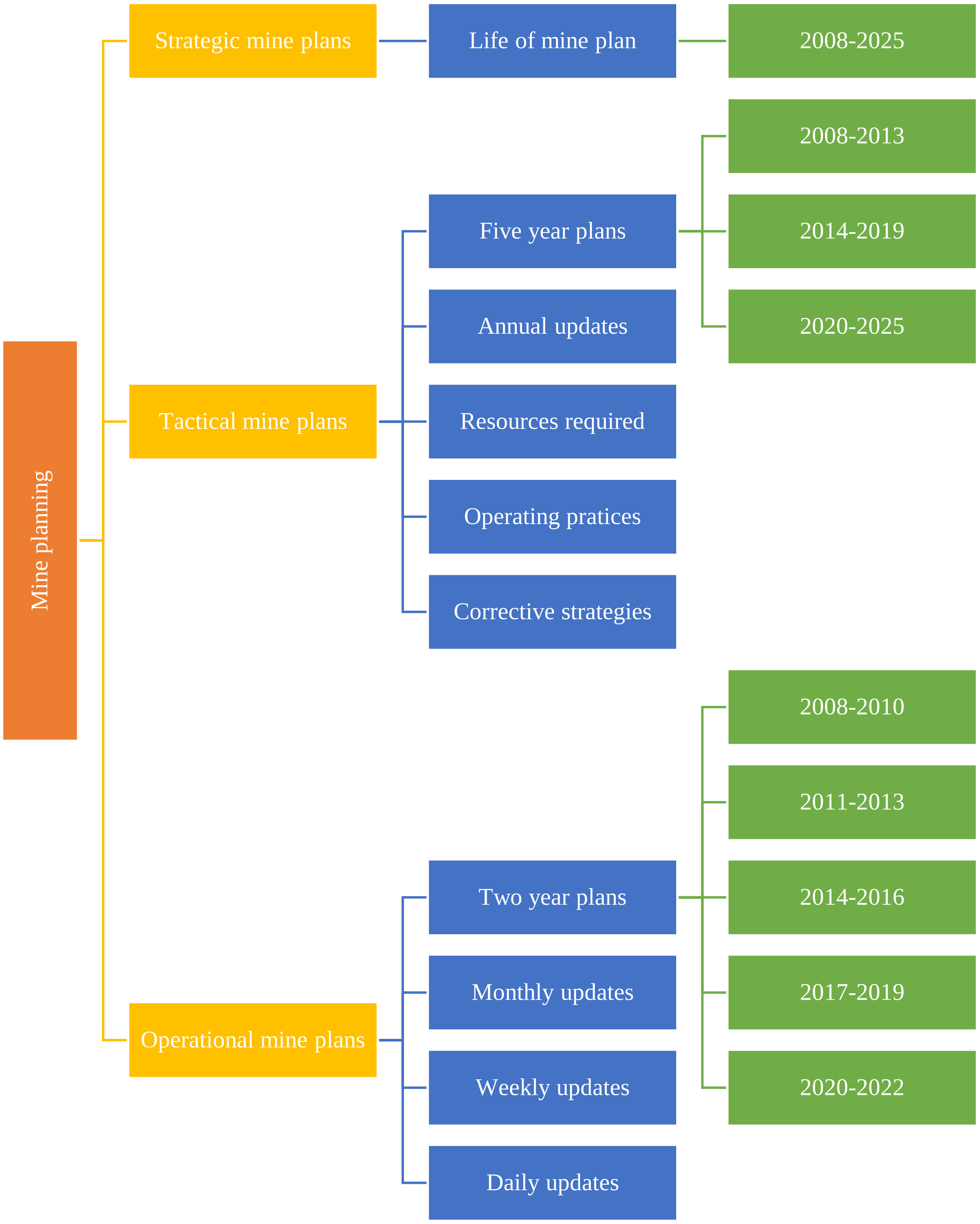


Figure 6.3: Mine planning information from the mine planning department

During exploration, the geology department is responsible for locating and evaluating the deposit and determining whether the deposit is economically valuable. During the operation of the mine, the geology department determines the location and grade of the ore. Figure 6.4 shows the information that is managed by the geology department.

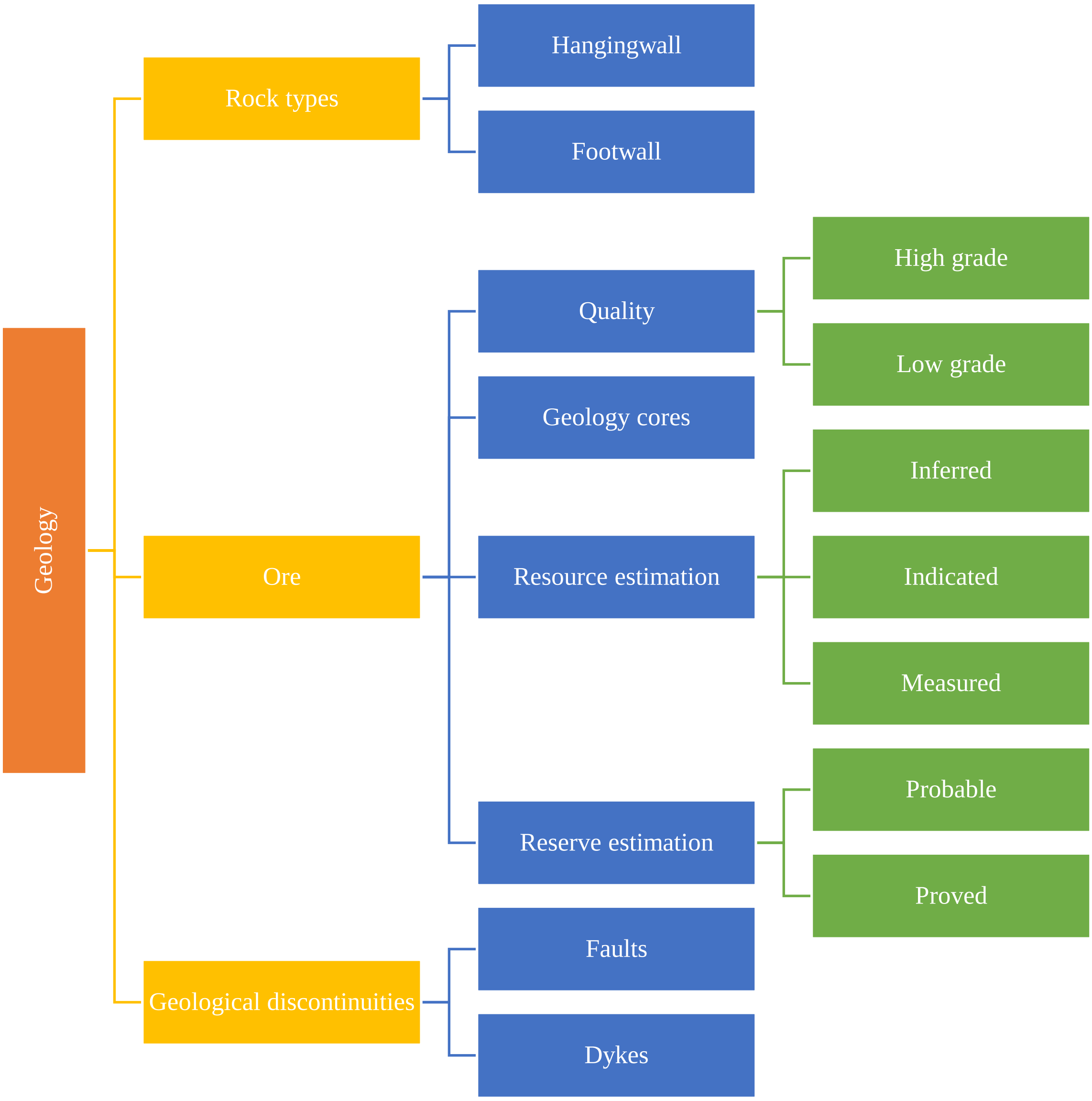


Figure 6.4: Geology information from the geology department

The survey department is responsible for keeping record of the mining operation. They survey the underground mine workings after several blasts and are also responsible for maintaining the plans of the entire mine and ensuring that they are accurate. They also update the surface layouts whenever there is new surface infrastructure. Figure 6.5 shows the information that is managed by the survey department.

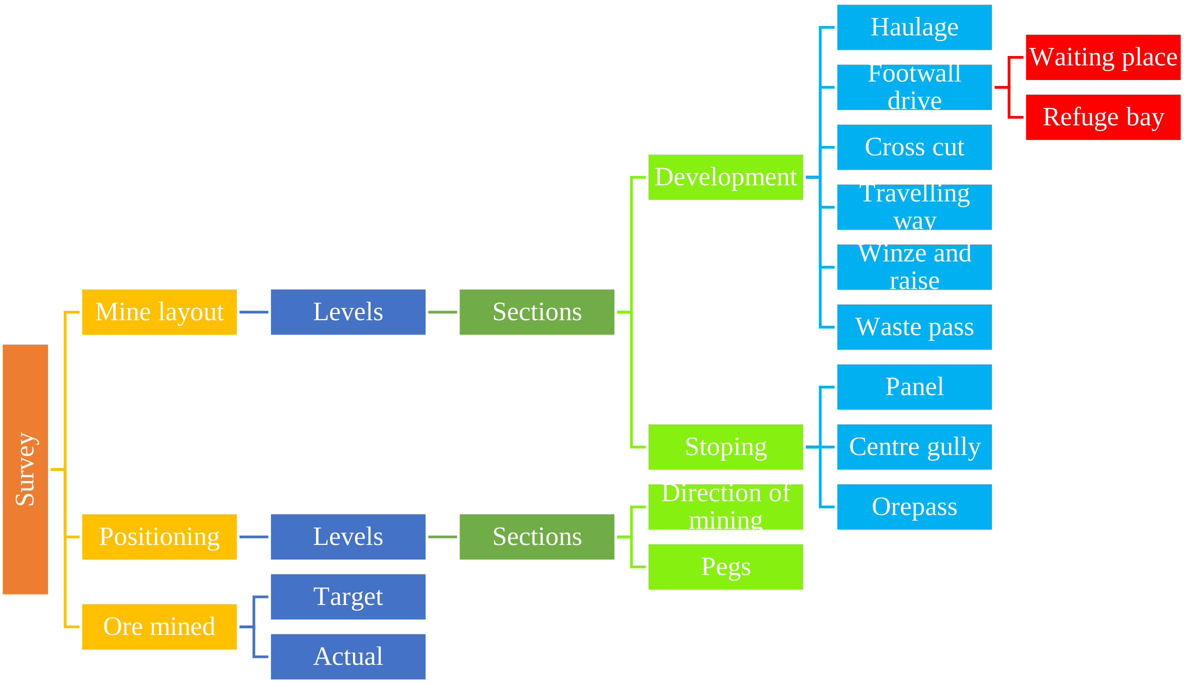


Figure 6.5: Survey information from the survey department

The MRM department focuses on the definition, planning, and depletion of the ore reserves (Acheampong, 2004). Figure 6.6 shows the information that is managed by the mineral resource management department.

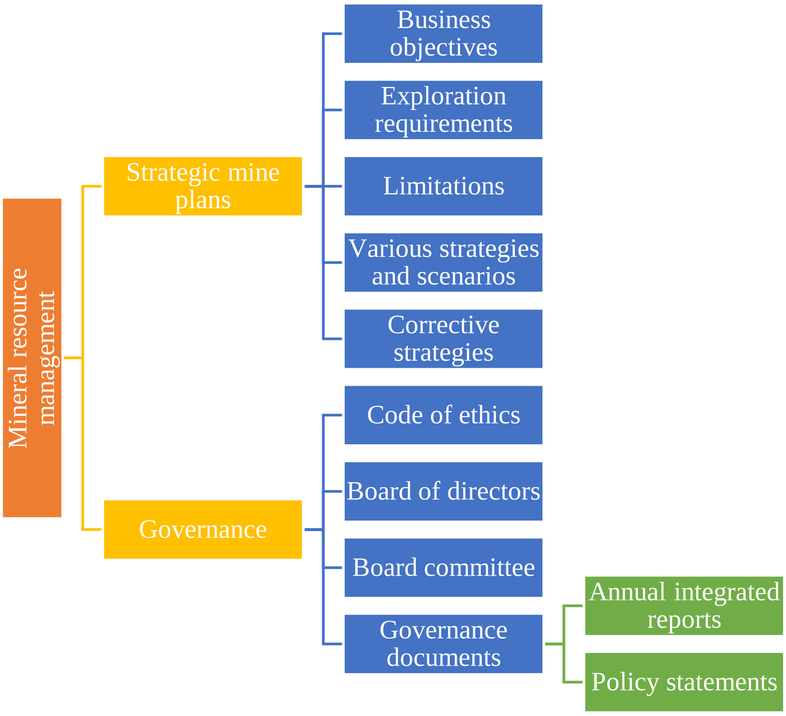


Figure 6.6: Mineral resource management information from the mineral resource department

The engineering department is responsible for the maintenance of the underground infrastructure such as the electrical substations, pumps, ventilation pipes, water pipes, and shaft (Sibanye-Stillwater, n.d.). Figure 6.7 shows the information that is managed by the engineering department.

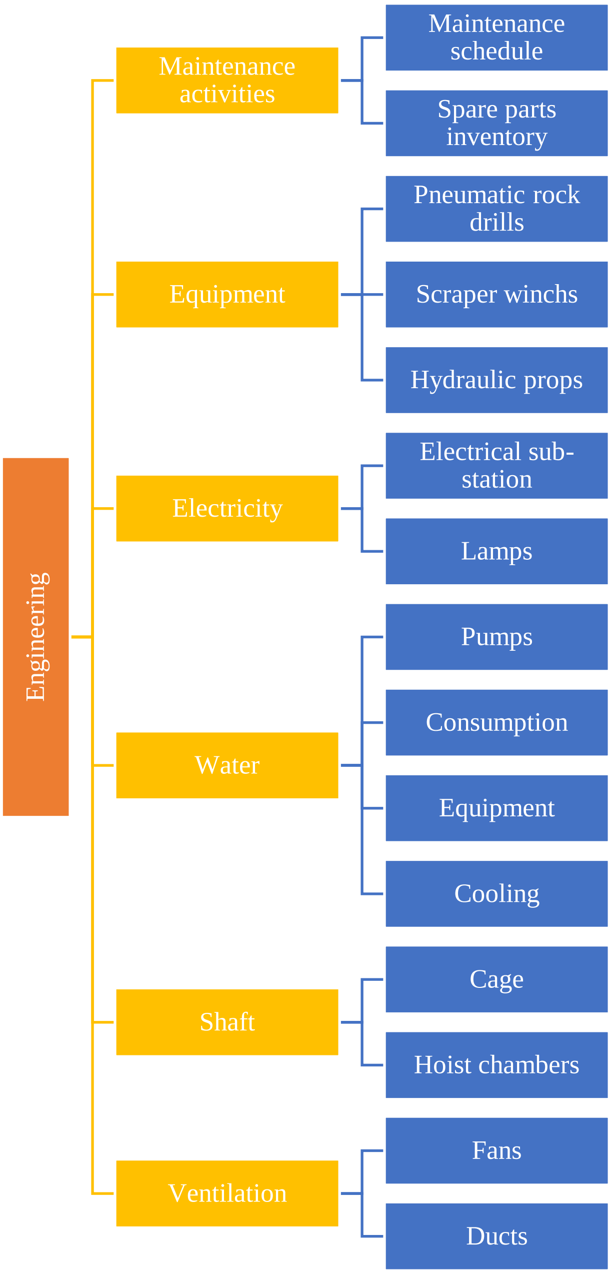


Figure 6.7: Engineering information from the engineering department

The VEE department is responsible for the implementation of a ventilation system to create a conducive environment for workers in terms of health and safety in the mine (Keith, *et al.*, 2014). Figure 6.8 shows the information that is managed by the VEE department.

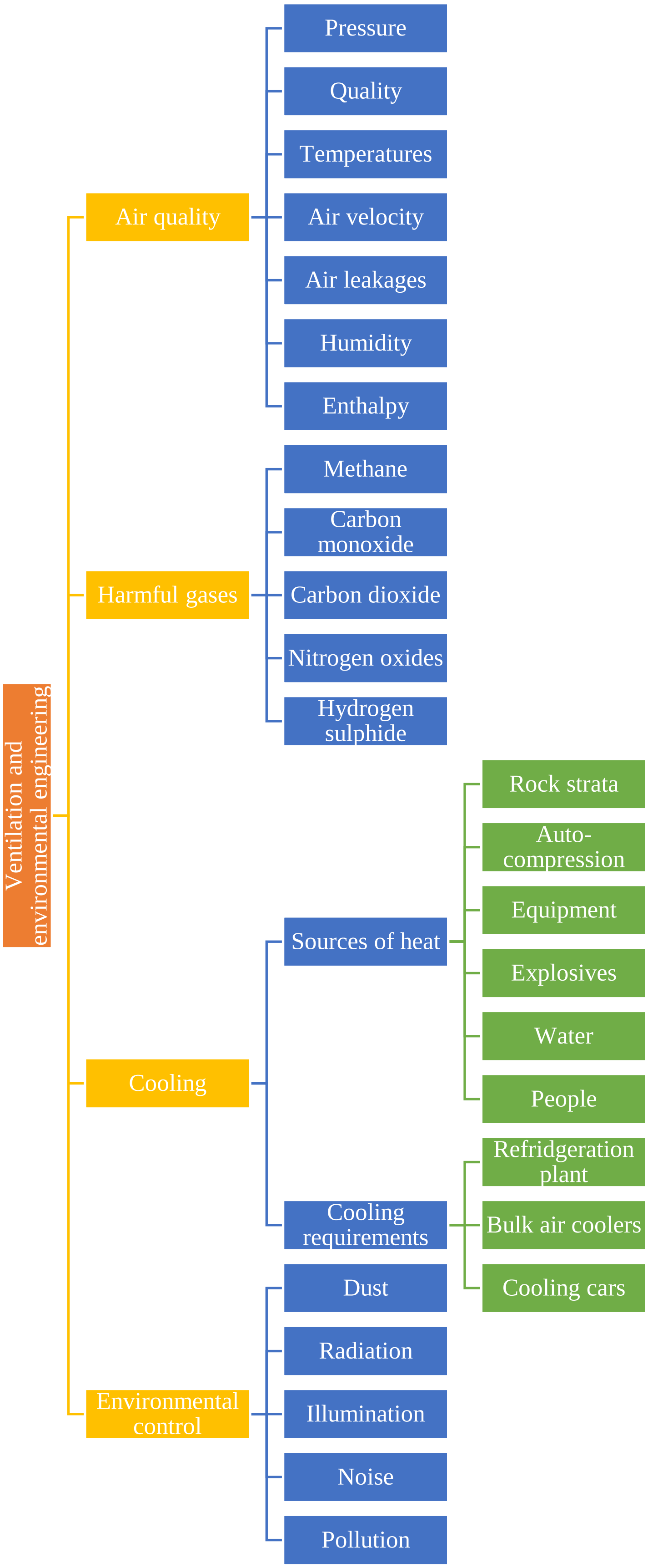


Figure 6.8: Ventilation and environmental engineering information from the ventilation and environmental engineering department

The mining department is responsible for ensuring that the underground workings are excavated as planned and in a safe manner. Figure 6.9 shows the information that is managed by the mining department.

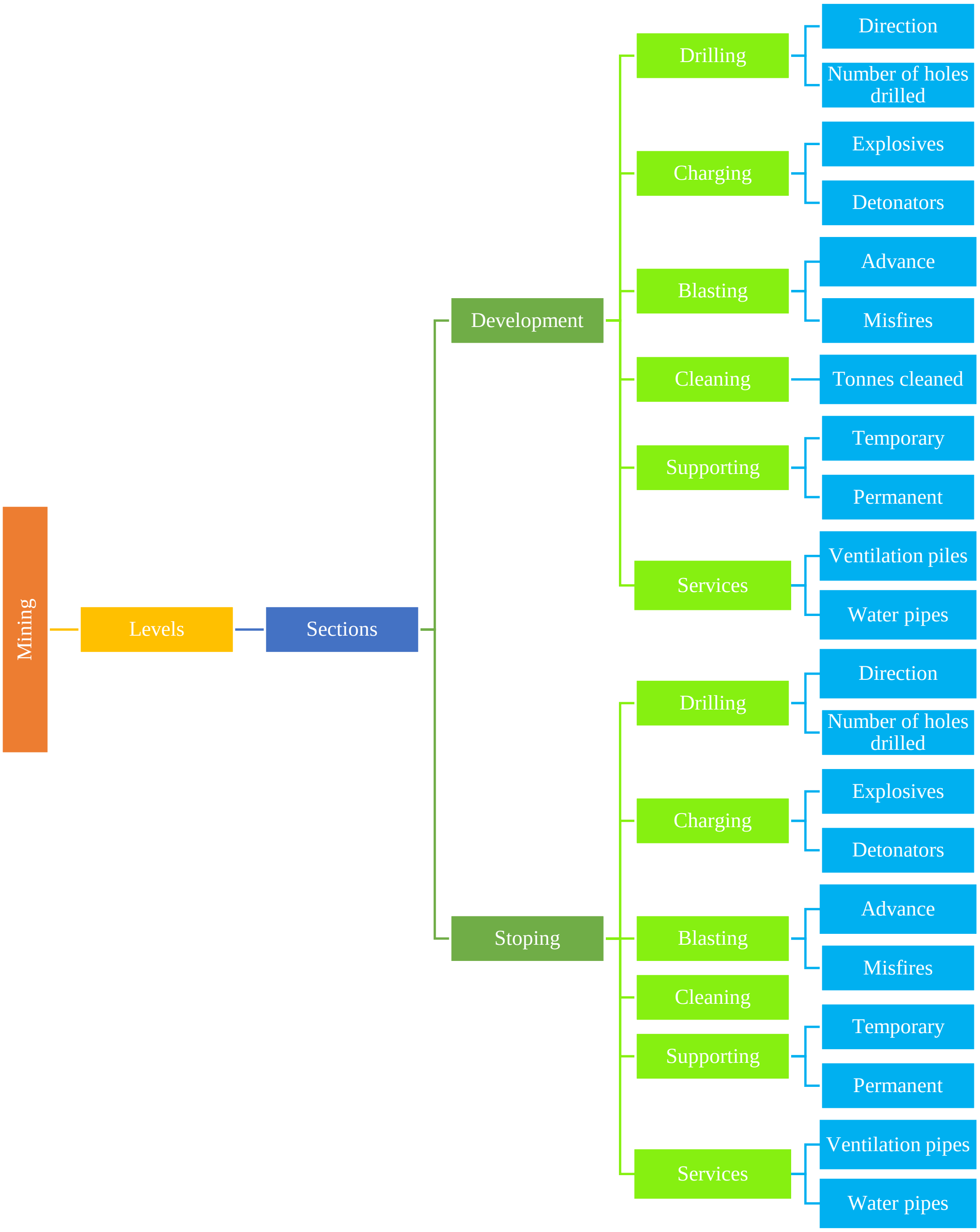


Figure 6.9: Mining information from the mining department

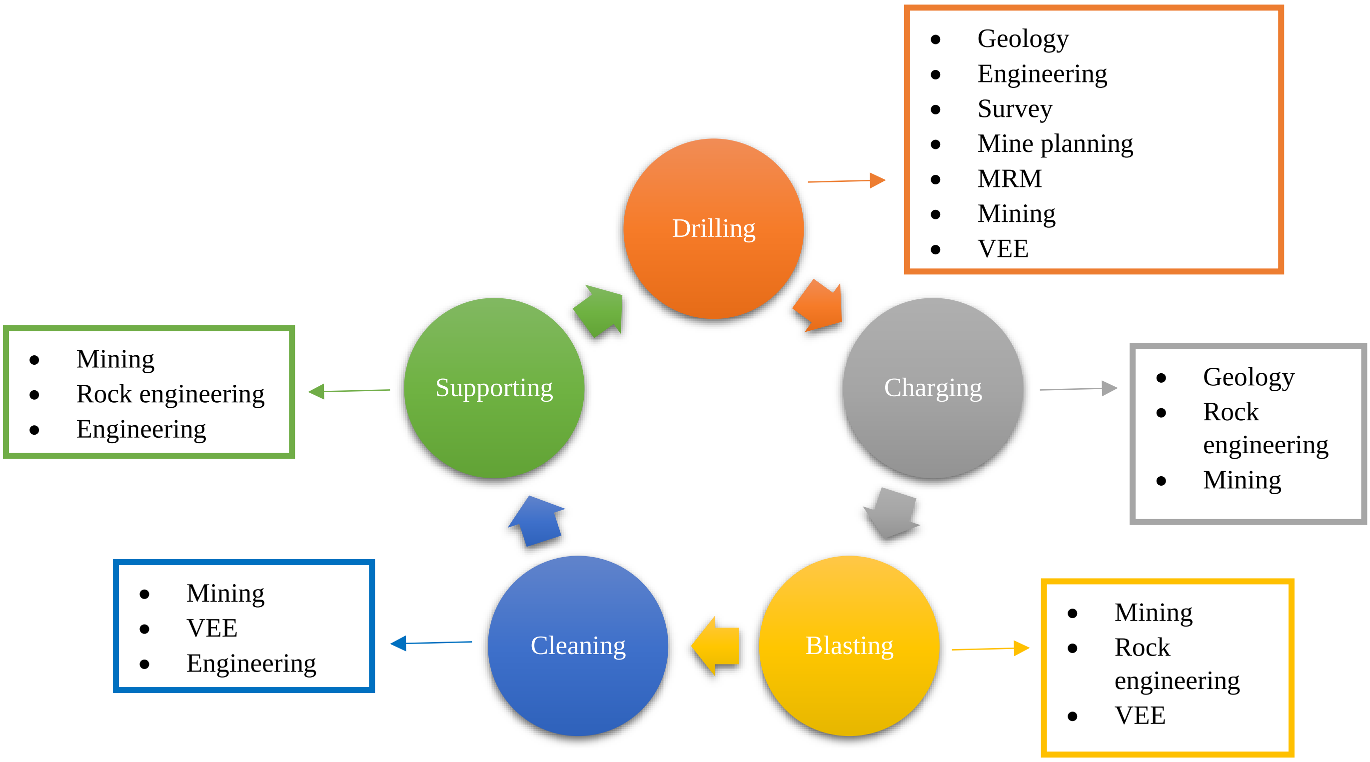


Figure 6.10: Technical Mining divisions linking to the production zone activities

With focus being on the primary activities, Figure 6.10 illustrates that drilling is linked to the geology, engineering, survey, mine planning, MRM, mining and ventilation departments. Charging activities are linked to departments such as geology, rock engineering and mining. Blasting activities are linked to departments such as mining and ventilation. While cleaning is associated with logistics and other departments. Furthermore, supporting can be closely related to rock engineering. Each department on the mine must collect data to ensure that the mining of the orebody takes place in a safe and economical manner. The data and information found in the different departments in the Technical Mining division are discussed in the subsequent section.

6.1 Information Flow

The data collected by the different departments are sourced from different parts of the underground mining environment. Thereafter, the data are uploaded onto a computer software and transformed into information that can be analysed and used for decision making. The decisions that are made by each department have the potential to impact another department. For example, the survey department is responsible for surveying all the excavations. However, if the survey department does not update the plan of the underground workings accordingly and share the plan with the VEE department. The VEE department will not know that a ventilation design is required for that excavation. Another example is, if that excavation is not on the plan of the underground working environment, should an incident occur, it will be difficult to locate an individual who is trapped in that area. The difficulty retrieving updated information from specific departments results in unnecessary delays which could put workers' wellbeing at risk. Therefore, it is essential that there is data integrity as the data produced and recorded have an impact on the different departments on the mine.

For the different departments on the Technical Mining division, it was essential to determine the data sources which software is used to record and analyse the data, the purpose of the data recorded, effect of the data to the other departments, and how the different departments are linked.

It is important to note that although drafting is part of the survey department, it is shown as separate department to better illustrate the flow of information. The data flow shows how the data are collected, cleaned, and converted into information that can be analysed and transferred between different departments. The data flow consists of data collected from Mine A.

Due to confidentiality related issues, data could only be accessed from survey, drafting, VEE, and rock engineering departments at Mine A. Therefore, data from these four departments were used for this research study, and the data flow discussed in the subsequent subsections only considers these departments.

6.1.1 Survey department

The survey department has to survey the excavations created. This is done to keep track of the direction in which mining is taking place and to keep track of the different positions in the underground mining environment. Figure 6.11 shows the data flow for the survey department.

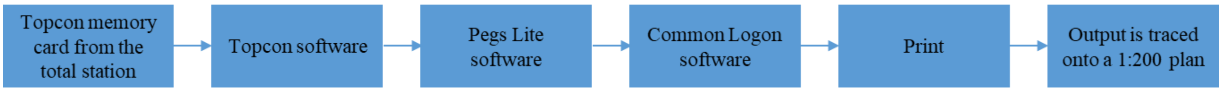


Figure 6.11: Survey department data flow

Topcon total station is used for surveying the underground workings. The total station uses the Topcon software to record the direction and positioning readings that are taken by the surveyor. The readings are stored on a memory card. Once the area has been surveyed, the surveyor places pegs on the hanging wall. These pegs are marked and represent an exact underground position. The pegs are essential for showing whether drilling and blasting operations are done in the correct direction.

Once the survey department is done surveying the underground working environment, the team returns to surface. Once on surface, the memory card is removed from the Topcon total station and inserted into the computer. Thereafter, the data on the memory card is uploaded onto the Topcon software on the computer. The purpose of the Topcon software on the computer is to view the readings and have the readings ready for importing into other software packages for different uses. The data are exported from the Topcon software and imported into the Pegs Lite software. Pegs Lite software is used to view the different pegs that were installed in the underground workings. The exact location of the pegs is provided; however, the face and direction of mining are not shown. To view the face that will be blasted and the direction of mining, the data from Pegs Lite software are exported and imported into the Common Logon software. On Common Logon software, the face, pegs and direction of mining are shown. The other face positions which have been blasted are also shown. On the Common Logon software, the surveyor can view the general layout of the panel that has been blasted and verify whether the direction of mining is correct. Thereafter, the pegs and face outline are printed out onto a sheet of paper and physically traced onto a 1:200 plan. The reason for tracing out the pegs and face is to ensure that there is a physical copy of the entire mining operation and to ensure that there are no clashes between any two stope panels. The survey department has several 1:200 traced out plans which show all the underground workings. In the event of an emergency, these plans are used to assist with determining the exact location of the incident.

6.1.2 Drafting department

The drafting department is responsible for digitising the entire mining operation, which includes both surface and underground workings. Figure 6.12 shows the data flow for the drafting department.

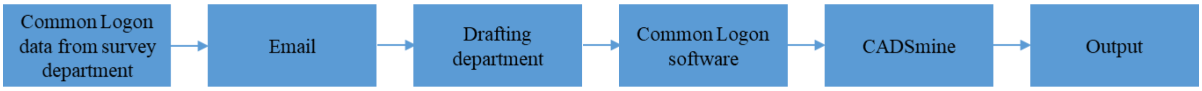


Figure 6.12: Drafting department data flow

The drafting department gets plans from the survey department so that the digitised mine plan can be updated. The survey department electronic mails (emails) the latest file from Common Logon to the drafting department. The drafting department also has the Common Logon software to view the updated pegs and face layout which were surveyed by the survey department. Thereafter, the data from Common Logon are imported to the CADSmine software. CADSmine is the software used for digitising the plans for the mine operation. All the plans which were drawn on paper are digitised on CADSmine so that there is a digital version of the entire mine. Once the data from Common Logon has been imported to CADSmine, the mine plan is updated, and the new faces are shown on the mine plan.

6.1.3 Ventilation and environmental engineering department

The VEE department is responsible for the ventilation and environmental control design of the underground mine workings. It is responsible for ensuring that sufficient air at the correct air temperature and velocity being delivered underground and that dust, heat, blasting fumes and contaminated air are dissipated from the underground workings. It ensures that there are certain environmental measures in place to create a physiologically acceptable environment to work in. Some of these environmental measures include dust, radiation and noise control. Figure 6.13 shows the data flow for the VEE department.

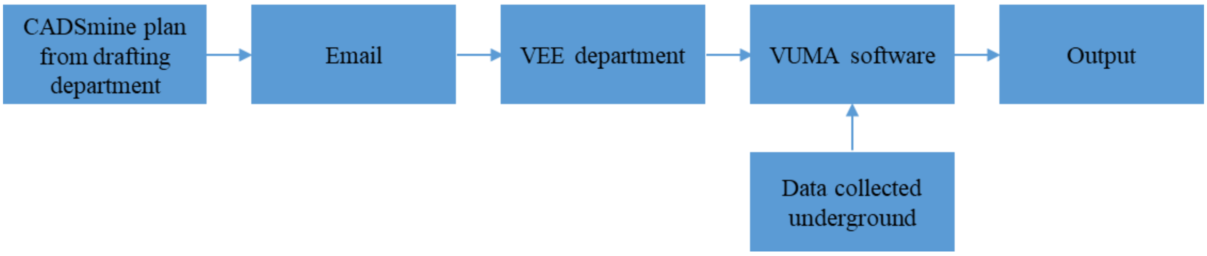


Figure 6.13: VEE department data flow

Daily some of the department members must go underground and take measurements that will determine the status of the underground working environment. The VEE department conducts the ventilation and environmental control design on the VUMA software. Some of the inputs to the VUMA software include, but are not limited to, wet-bulb and dry-bulb temperatures, air velocity, air humidity, air leakages, and virgin rock temperatures.

For the VEE department to do the ventilation and environmental control design, a digital plan of the underground mine workings is required. The digital plan from the drafting department is sent to the VEE department via email. The digital plan is then imported into VUMA, and the ventilation and environmental control design is conducted. The ventilation and environmental control design is dependent on the digital plan. Therefore, it is essential that the digital plan be a true representation of the underground workings, to ensure that the design is correct. A correct ventilation and environmental control design ensure that all the workings get sufficient air and have as little dust, radiation and noise, as possible.

6.1.4 Rock engineering department

Due to the limited access to the other departments, the information from the rock engineering department was sourced from the drafting department, therefore, it is limited as the software packages used by the rock engineering department are unknown. The rock engineering department is responsible for ensuring that the support that is placed in the underground workings is sufficient to ensure a safe working environment. Figure 6.14 shows the data flow for the rock engineering department.

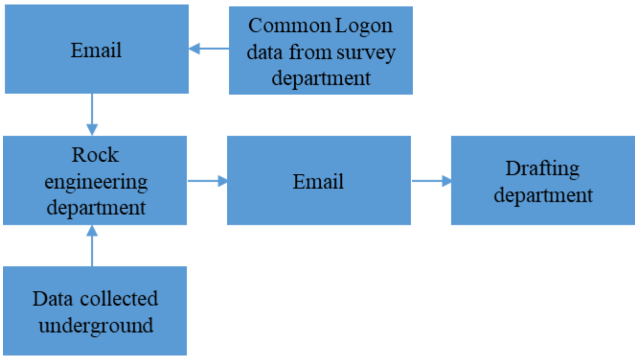


Figure 6.14: Rock engineering department data flow

The survey department would also send updated plans to the rock engineering department, and the rock engineering department would use the plans for the analysis of pillar designs. When there is a change in the pillar sizes, the drafting department must be notified so that these changes are updated on the digitised plan of the underground workings. The rock engineering department would update their rock engineering plans, thereafter email the plans and reports to the drafting department so that the changes can be captured on the CADSmine mine plan.

It is noted that the different departments are dependent on each other. The link between the four departments is shown in Figure 6.15.

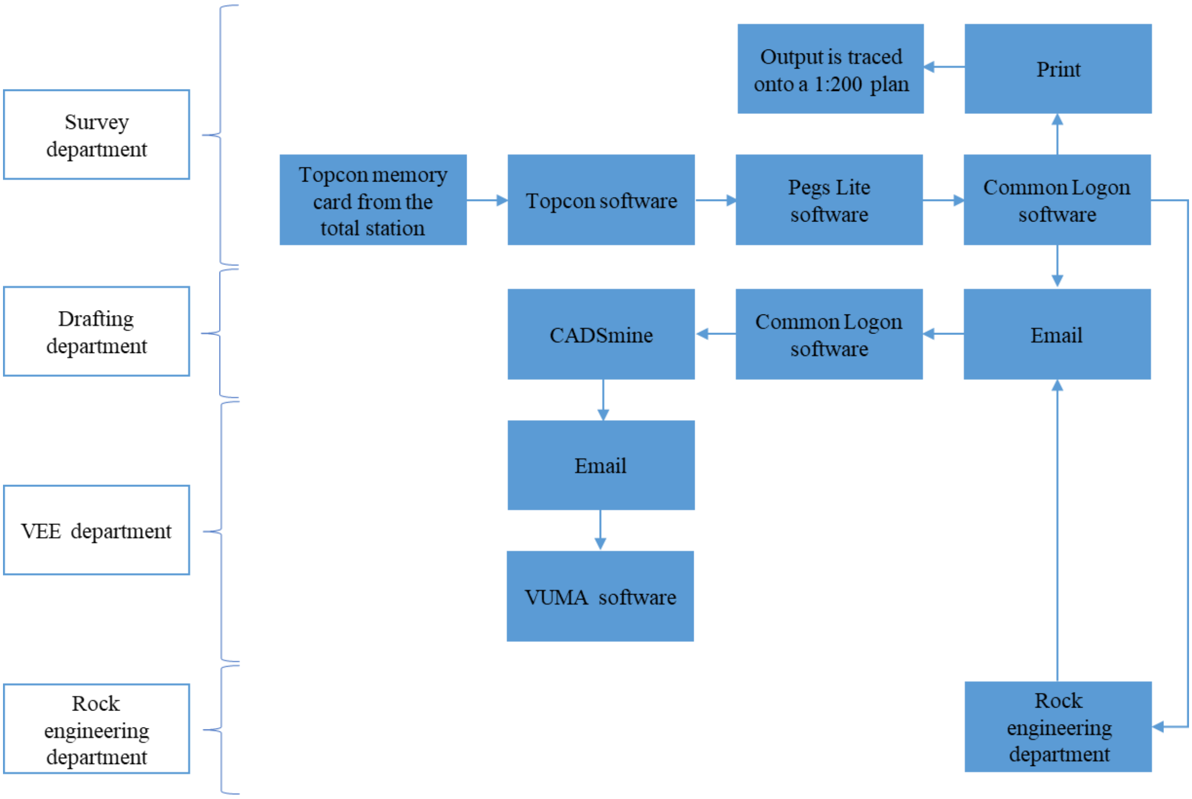


Figure 6.15: The flow of information between departments

It is shown that the survey, rock engineering, and VEE departments are linked to the drafting department, but are not directly linked to each other. The drafting department at the mine is responsible for ensuring that there is a digitised version of the entire mine plan. Therefore, it is essential that the different departments regularly update the drafting department of any changes that have occurred in the underground mine workings. Figure 6.15 also illustrates that the flow of information from one department to the other is through email, thus showing that there is no centralised environment where information is being shared. It also illustrates that the different departments are not connected as there is limited access to the information generated by the other departments.

According to BIM concepts, the BIM maturity level for Mine A is Level 0, meaning that the mine has low collaboration. Although the files are being shared on a digital platform, they are being shared as separate sources of information. The application of BIM concepts to the mine would assist with improving the BIM maturity level from Level 0 to Level 1, which involves partial collaboration. The subsequent section discusses the application of the BIM concept that has been identified as relevant for Mine A at this stage.

6.2 Application of BIM Concepts in the Underground Production Zone of Mine A

In BIM, a CDE is used, which is a common data environment where data is shared between various parties involved in a construction project. However, for the purposes of this research study, a central information environment (CIE) was used. This is because data and information will be shared between the various department on a centralised platform, as opposed to data and information being shared to individual departments directly. Each department will be responsible for the collection, cleaning and transformation of data into information that can be analysed and understood by other departments.

At BIM Level 1, the different departments will be using a CIE where information about the mine and its operation will be collected, managed, stored, and shared. BIM Level 1 involves the use of both 2D and 3D CAD drawings. Improving the BIM maturity level to Level 1 will assist with using information efficiently thus improving the communication and collaboration within the Technical Mining division. To ensure that there is a CIE where information can be shared between the various departments, it is essential to use an integration solution.

The CIE is a central information environment where information is stored, managed and accessed by the various departments on the mine. This means that if the CIE is used by all the divisions in the mine, then all the departments in the mine would be able to utilise it for managing and sharing information. However, for the purposes of this research study, the CIE will only include the departments in the Technical Mining division, as illustrated in Figure 6.16.

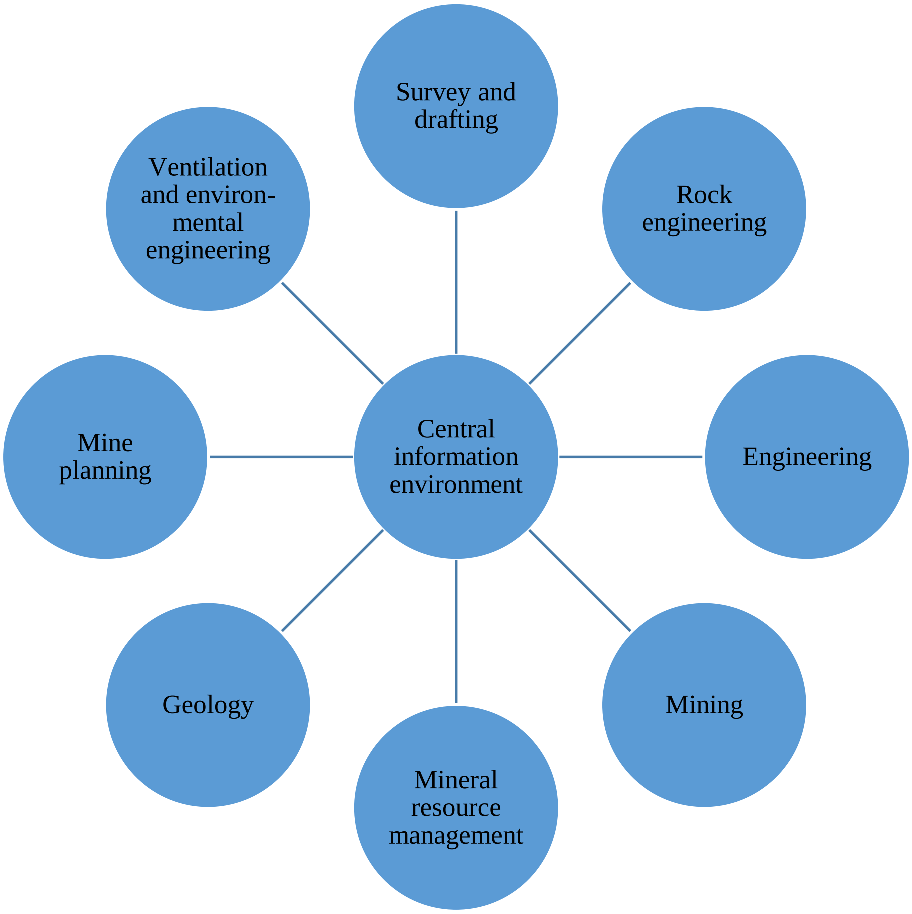


Figure 6.16: The CIE for the Technical Mining division

The different departments in the Technical Mining division that will be integrated through the CIE include drafting, survey, rock engineering, engineering, MRM, geology, mine planning, VEE and mining. Each department will be able to upload and retrieve information from the CIE. The information that can be retrieved is from any other departments. However, the information can only be edited or modified by the department that is responsible for creating and uploading the information. This ensures that there is data integrity. Although the different departments cannot edit each other's information, they are able to attach sticky notes to enquire about a piece of information that they do not understand or identify as missing. Having a CIE onto which each department can access all the information created in the department has the potential to improve the communication and collaboration between the different departments. This will ensure that each department has a common understanding of the operation and that information is easily accessible. Figure 6.17 illustrates the flow of information in the CIE for the departments in the Technical Mining division.

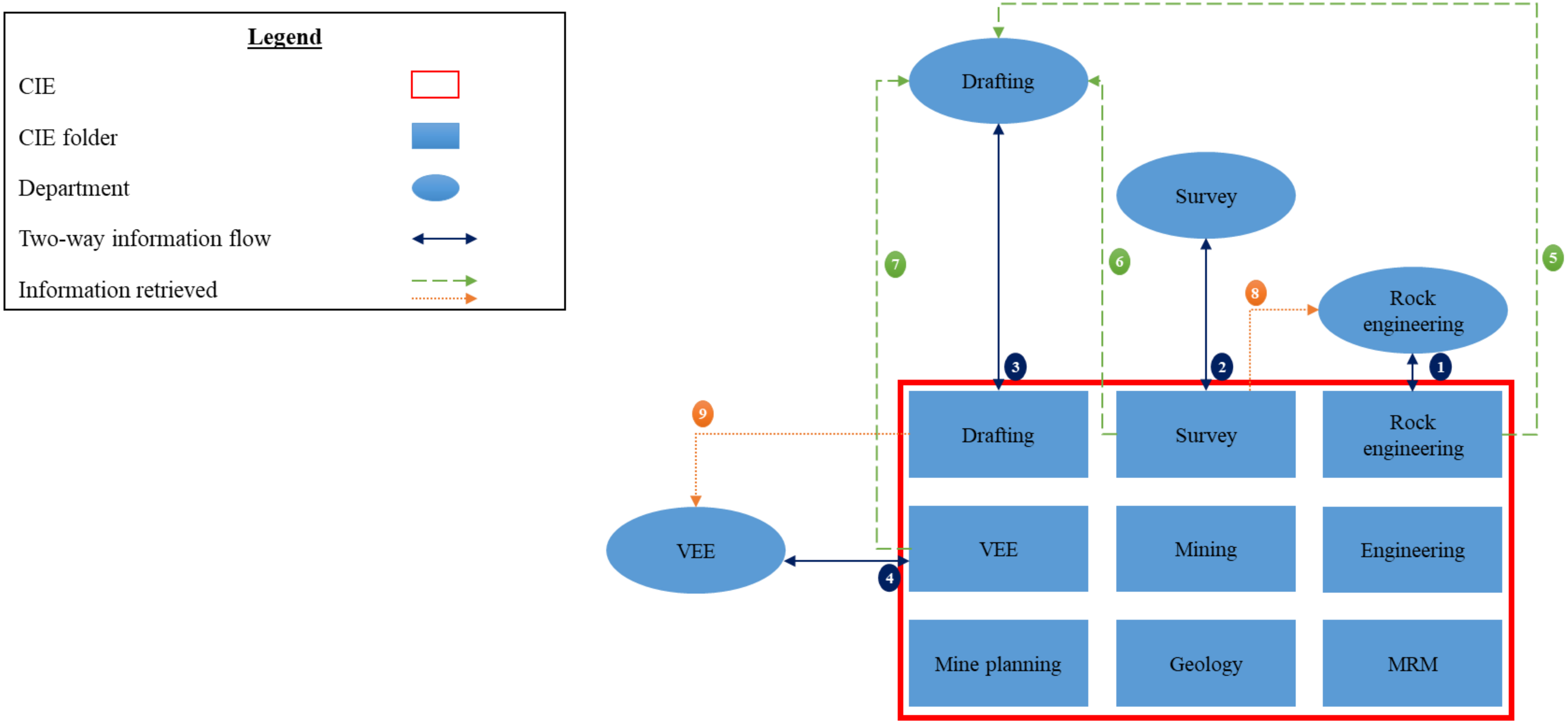


Figure 6.17: CIE information flow for selected departments

Figure 6.17 shows the following:

- Blue arrows (node 1, 2, 3 and 4) show that the rock engineering, survey, drafting, and VEE departments would be able to upload and retrieve information onto their respective department folders within the CIE. This would be a functionality that is available for all the departments that have folders in the CIE.
- Green arrows (node 5, 6 and 7) show the drafting department retrieving information from folders of various departments on the CIE. The drafting department would update the digital plans accordingly. Thereafter, the updated digital plans are uploaded onto the CIE under the drafting folder (blue arrow to node 3).
- Orange arrows (nodes 8 and 9) show the rock engineering and VEE departments retrieving information from the survey and drafting folders to update the plans, respectively.

The information that would be found within each folder of the CIE is shown in Figure 6.2 to Figure 6.9. The CIE in Figure 6.17 ensures that all the departments have access to all the information that is produced within the Technical Mining division. It allows for the access, management and storage of the information. To ensure information integrity, it is essential that the department that produced the information is the only department that has permission to edit the information. This means that the other departments can only view the information. However, sticky notes are available to facilitate communication between the different departments regarding the information on the CIE. Therefore, the CIE ensures that there is improved communication and collaboration, which better integrates the different departments.

The integration of the different departments on the mine will ensure that:

- When there is an emergency, the information for any department is easily accessible thus ensuring that there are less delays during an emergency;
- Clash detections are done to improve the integrity of the data produced;
- Any changes made are visible to all the departments, thus assisting with having all departments well-informed about the current status of the underground mine workings;
- Communication between the different departments is improved as notes can be attached to any changes made so that the different departments can have a better understanding of why the changes were made and be able to ask questions regarding any of the changes made; and

- The different departments are better prepared for monthly meetings between the different departments, thus assisting with improving the decision-making process.

Although information, instead of data, will be managed and shared on the CIE, it is essential to consider some of the data integration concepts to gain a better understanding of how the CIE can be created and managed.

6.3 Chapter Summary

The production zone was defined as the stoping area which is the part of the underground mine where the ore is extracted. The activities associated with the production zone were identified as drilling, charging, blasting, cleaning and supporting. Thereafter, the departments within the Technical Mining division were linked to the activities in the production zone. Although each department plays a role in each one of the activities, the departments that play the most significant roles were identified for each production zone activity. To identify a BIM concept that would be best suited for the production zone, it was essential to determine how information flows within the Technical Mining division and how the departments within Technical Mining are linked. The concept that was identified as best suited for the production zone was BIM maturity levels. The improvement of the BIM maturity level of the mine from BIM Level 0: low collaboration to BIM Level 1: partial collaboration would ensure that the information generated on the mine is used efficiently, thus improving the communication and collaboration between the different departments. The next chapter presents the BIM-based framework for a production zone of an underground mine.

7. BIM-BASED MINING FRAMEWORK

The purpose of the research study is to conceptualise a BIM-based framework for the production zone of an underground mine. Upon reviewing literature and considering the production zone activities and the Technical Mining divisions, a BIM-based framework that could improve the collaboration and communication for the production zone of an underground mine was conceptualised.

It has been noted that the integration of information on a mine has the potential to improve decision making by potentially 20% to 30% (Deloitte, 2018). Therefore, the current and proposed procedures for decision making are discussed in the subsequent section.

7.1 Monthly Meetings for the Technical Mining Division

On a monthly basis, the different departments in the Technical Mining division attend a meeting where each department is represented. The current procedure involves having isolated departments, with Figure 7.1 illustrating the current procedure. The arrows in Figure 7.1 illustrate the information brought to the meeting by a department. These individual arrows emphasise that the information is that which is known by that department in depth. For example, most of the information that the rock engineering department will be bringing to the meeting, will be new information on rock engineering to other departments. Therefore, the rock engineering department will have to present the information on rock engineering to the other departments to ensure that each attendee has a common understanding of any new information. Thereafter, solutions and decisions can be made by the meeting attendees.

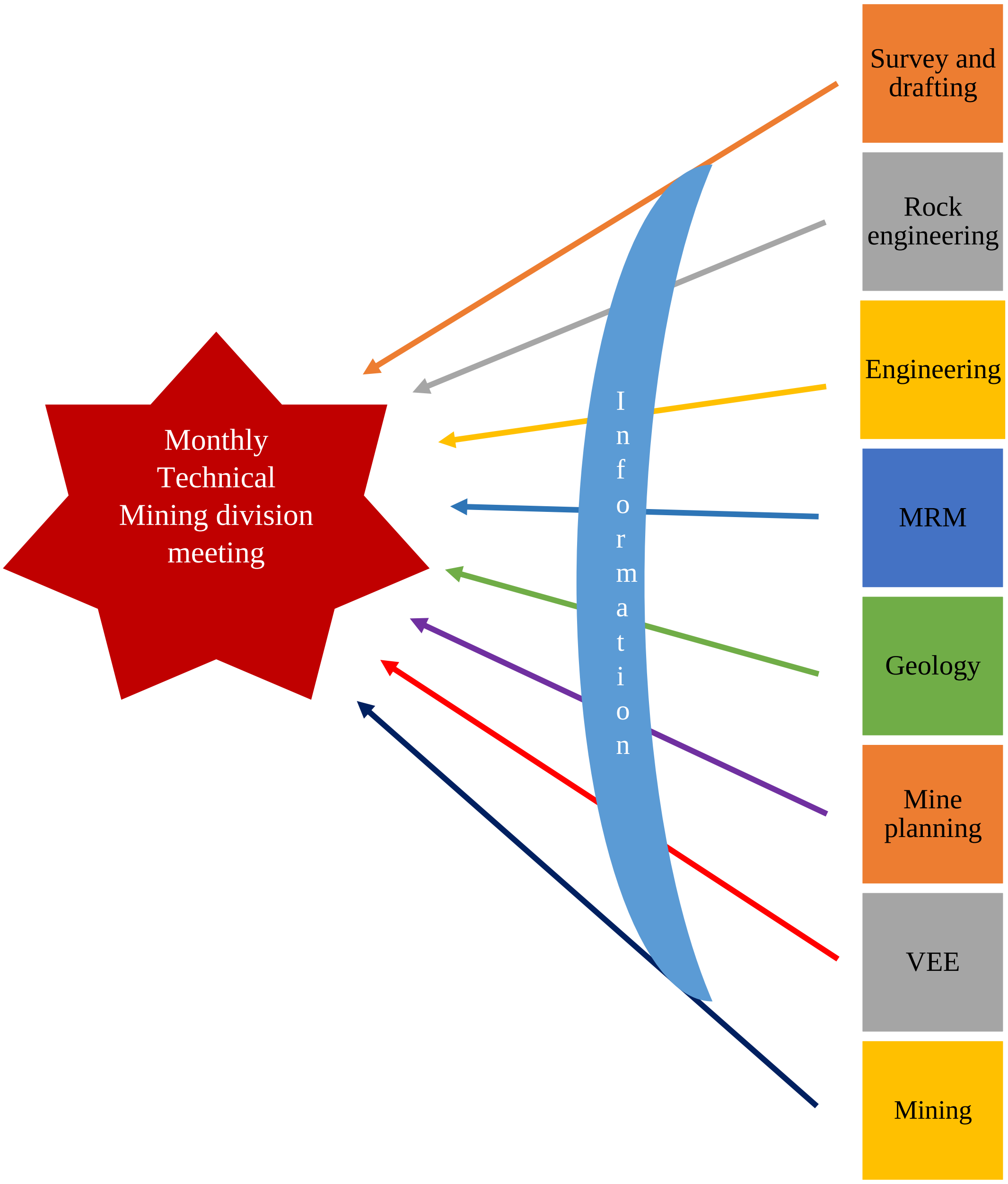


Figure 7.1: Current information flow for the monthly meetings

The steps leading to a decision being made by the departments during the monthly Technical Mining division meeting are illustrated in Figure 7.2.

Figure 7.2: Current procedure for decision-making

Having an isolated system results in longer meetings and insufficient time to address challenges and find the most effective solutions. This is because of each department having to provide an update, outline the challenges faced and propose solutions to the challenges. The decision-making step is essential as the decision made has a direct impact on the mining operation. Therefore, it is essential that there is a sufficient time set aside for decision making to ensure that the decision made provides the most efficient and effective solution to be implemented. Therefore, it is essential to consider a system that will ensure that there is more time set aside for decision making.

The proposed structure for information flow involves having integrated departments, as shown in Figure 7.3.

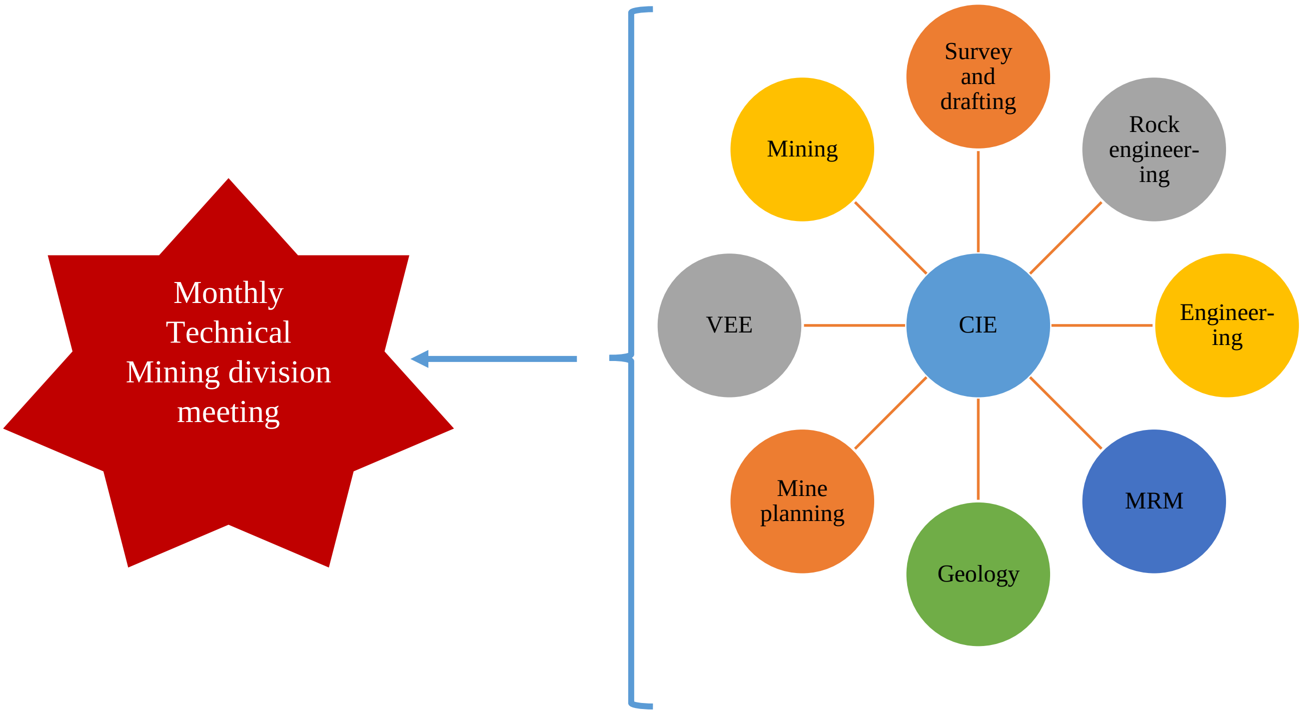


Figure 7.3: Proposed information flow for the monthly meetings

Figure 7.3 shows the implementation of the CIE whereby the information from each department is accessible through the CIE. Access to information does not translate to knowledge or understanding of the information. Therefore, as part of the CIE, there will be explanatory reports that will explain the information from the various departments. The departments will also be able to communicate by using a chat platform if there are any concerns or questions relating to the information on the CIE. The explanatory reports and the chat platform will aid in the understanding and efficient use of the information found on the CIE.

On the CIE, each department will upload the challenges faced and give a detailed outline of the proposed solutions. This will ensure that the other departments are aware of the challenges and understand the challenges and proposed solutions. Therefore, with the other departments having been familiarised with the challenges and proposed solutions, the other departments will have sufficient time to formulate questions and propose new solutions to the challenges. A collaborative system ensures that during the monthly meeting, the focus is on providing and discussing solutions to the challenges and deciding as to which is the most efficient and effective solution for implementation. The steps leading to a decision being made by the departments are illustrated in Figure 7.4.

Figure 7.4: Proposed procedure for decision-making

In the decision-making steps for the proposed procedure, the "update" step found in the current procedure for decision making has been reconfigured. The reconfiguration is because of having a CIE where information is readily available to each department. Thus, eliminating the need to update each department once a decision has been made. The proposed procedure for decision making also includes a CIE upload, whereby the proposed solutions are uploaded onto the CDE to keep the record of all proposed solutions.

When using the current procedure for decision making, the meetings are prolonged due to the updates given by each department and discussions around finding a solution. This results in, making the meetings focusing on understanding the challenges and solutions, and allocating less time to decision making. The proposed procedure for decision making ensures that there is more time dedicated to discussions and decision making, as each meeting attendee is up to date about the activities of every other department, the department’s challenges and the proposed solutions. Creating a CIE onto which the different departments can share, manage and store information, improves the way in which information is used and also improves the level of communication and collaboration on the mine. Thus, increasing the mines BIM maturity level from Level 0 to Level 1.

7.2 The BIM-based Framework for Mine A

The BIM-based framework for mining conceptualised in this research study is a framework that incorporates one or more of the BIM concepts and is applicable to the mining industry. The concept that was applicable to Mine A and thus considered for this research study is the BIM maturity level. The application of the BIM maturity level concept has the potential to improve the communication and collaboration on the mine by implementing a CIE onto which information can be shared, managed and stored. The implementation of the CIE also ensures that the Technical Mining division focuses more on potential solution discussions and decision making. Therefore, improving the decision-making process on the mine. The CIE also ensures that information is readily available and can be accessed timeously in the event of an emergency, thus reducing any delays. The implementation of the CIE is at the centre of the BIM-based framework because it is on the CIE where information is shared, managed and stored to improve the communication and collaboration on the mine thus improve the BIM maturity level of the mine. The five themes that are essential to the BIM-based framework are digitise, interoperability, bidirectional services, high performance and communication. The five themes were selected after considering the needs of the CIE and reviewing literature about data integration. Figure 7.5 illustrates the BIM-based framework for mining. Each theme represented in the BIM-based framework for mining is further discussed in the subsequent subsections.

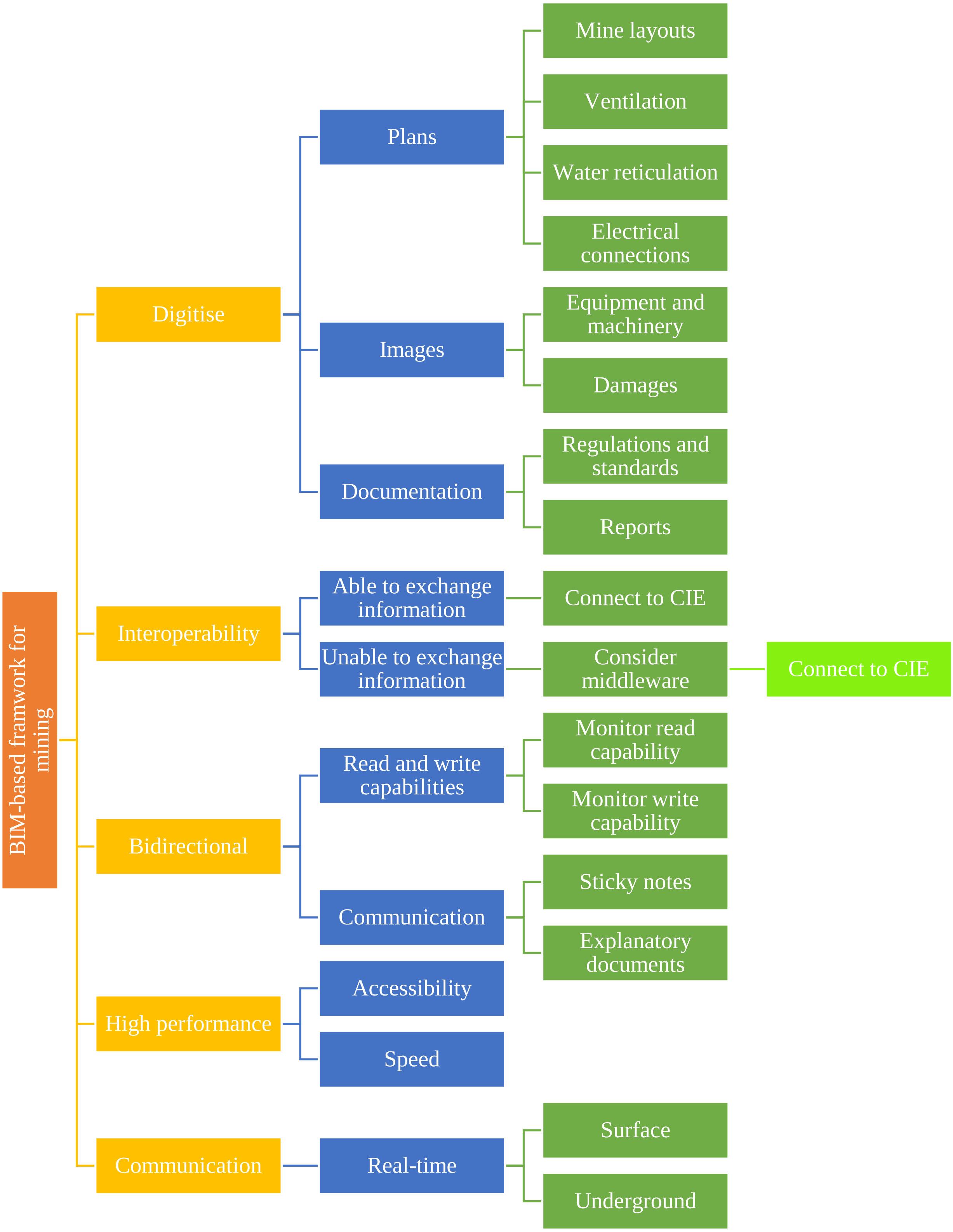


Figure 7.5: BIM-based framework for mining

7.2.1 Digitise

The digitise theme involves having a digital copy of the plans, images and documentation as illustrated in Figure 7.6.

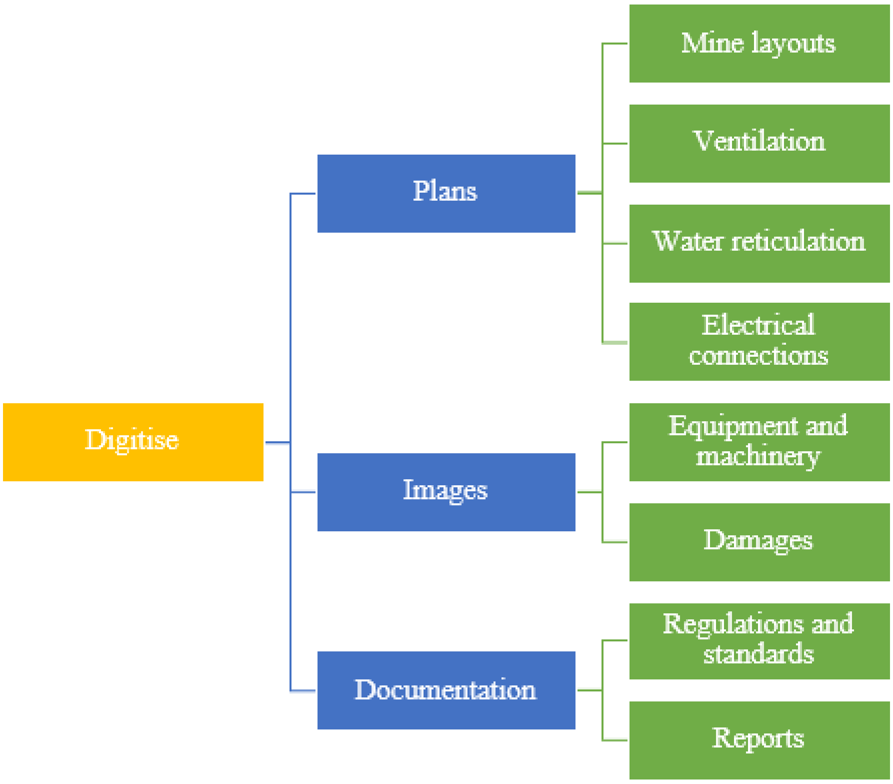


Figure 7.6: Theme 1 - digitise

The CIE is a digital tool therefore the information on it must be in a digital format. This means that all the mine plans, images, and documents must be in a digital format to make the sharing, managing and storing of information on the CIE possible. If the information is not digitised, it can be scanned, just as in the case of previously printed reports where the digital copy has been misplaced. The scanning will be conducted using the scan-to-BIM concept. However, the plans must be redrawn so that the plans can be updated on a regular basis when changes need to be made. Some of plans include, but are not limited to, the mine layouts, ventilation, water reticulation and electrical connections plans. Images of the equipment and machinery can be taken and uploaded on the CIE so that they can be attached to the equipment and machinery specifications. Images of damages that occur in the underground work environment can be taken and uploaded so that there is a record of the damages and the intensity of the damage can be analysed. Documentation includes regulations that must be followed by the mine, mine standards, and reports that are generated by the different departments on the mine. Having digitised documentation allows for a paper trail of all the information generated by the mine.

7.2.2 Interoperability

The interoperability theme involves the ability and inability of the software to exchange information as illustrated in Figure 7.7.

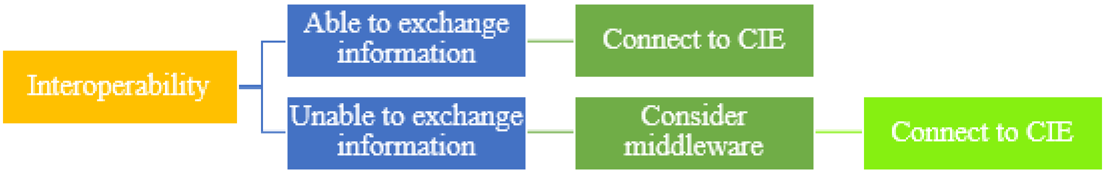


Figure 7.7: Theme 2 - interoperability

In the event where the software can exchange information with other software from a different software vendor, the department can be directly connected to the CIE to exchange information. Therefore, an interoperable software is categorised under open BIM. In the event where the software is unable to exchange information with other software from a different software vendor, then an integration tool such as middleware needs to be used. The middleware connects the different software in such a way that they can be connected to a centralised environment. Once the systems are connected through middleware, the department can be connected to the CIE so that the information generated by the department can be uploaded and retrieved from the CIE. This type of software would be considered as a software that is not interoperable and would be categorised under closed BIM as discussed in see Section 3.2.

7.2.3 Bidirectional

The bidirectional theme ensures that the information on the CIE can be viewed and edited, also known as, read and write, respectively. The bidirectional capability also caters to the communication aspect of the CIE as illustrated in Figure 7.8.

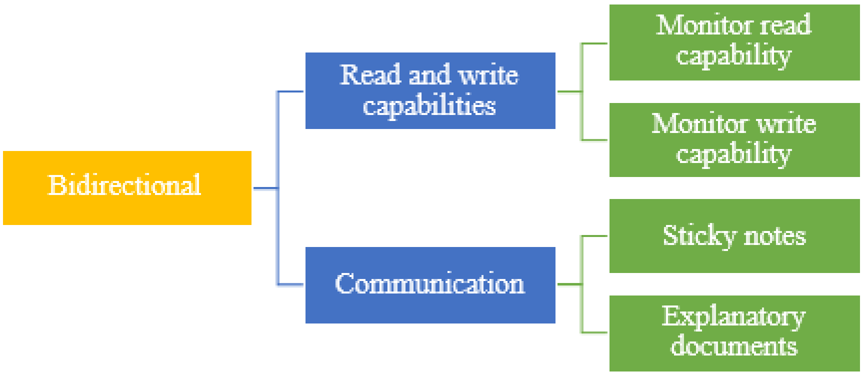


Figure 7.8: Theme 3 – bidirectional

It is essential that the read and write capabilities of the CIE be monitored such that the department that uploads the information is the only department that can write or edit the information. While the other departments can only read or view the information. Monitoring the read and write capabilities in this manner protects the integrity of the information. The departments that can only view the information can communicate on the CDE by using sticky notes. The sticky notes can be attached to any document or diagram to seek clarification or communicate any ideas. The department that can edit the information can upload explanatory documents that are attached to the plans, images and diagrams. The explanatory documents will assist the other departments with understanding the information being communicated.

7.2.4 High performance

The high-performance theme involves having a CIE that is easily accessible at a high speed, as illustrated in Figure 7.9.

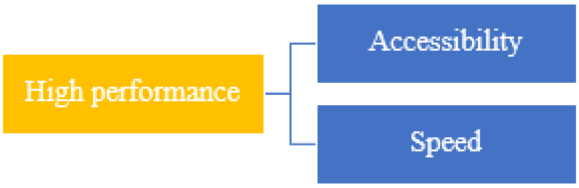


Figure 7.9: Theme 4 - high performance

It is essential that the CIE is easily accessible to the different departments so as to ensure that in the event of an emergency, the information can be retrieved from a folder of as specific department. This will ensure that there are minimal delays. It is also essential that the information can be retrieved relatively quickly to reduce the waiting periods. The CIE should ensure that the information that is uploaded and retrieved is done so at an appropriately high speed.

7.2.5 Communication

The communication theme involves having real-time two-way communication between the teams in the production zone and the departments in the Technical Mining division, as illustrated in Figure 7.10.

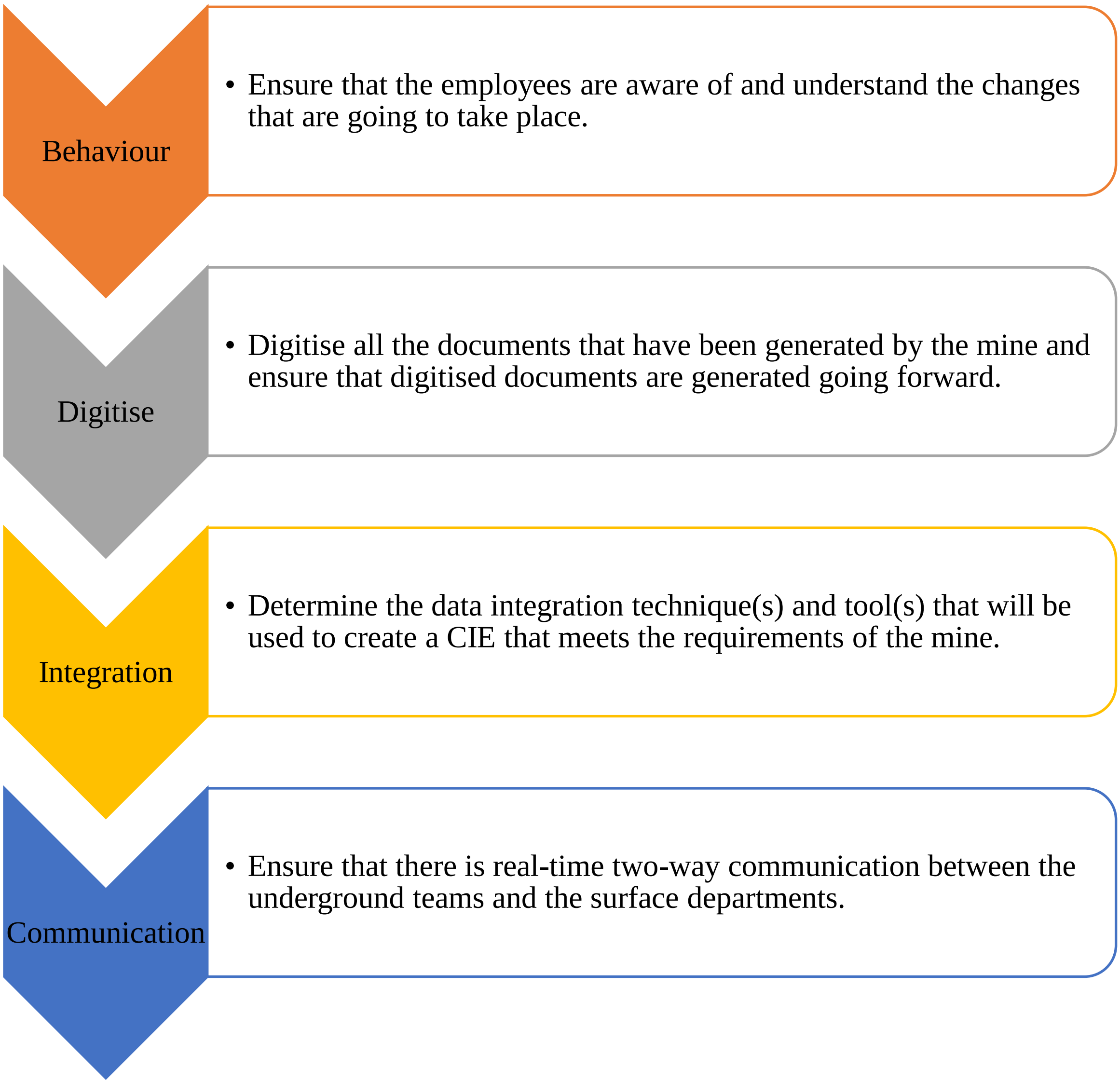
Figure 7.10: Theme 5 - communication

The issues faced in the production zone need to be communicated to the Technical Mining division based on surface in a timely manner especially in the case of an underground emergency. It is also essential that the decisions that are made by the departments in the Technical Mining division can be communicated to underground workers in real-time. The real-time two-way communication will ensure that action is taken timeously by all affected parties.

An implementation strategy for the BIM-based framework is an essential aspect of the framework, as it considers how the mine will implement some, if not all, the concepts outlined in the BIM-based framework. The implementation strategy is discussed in the subsequent section.

7.3 Implementation Strategy

An implementation strategy shows how the BIM-based framework can be implemented in the Technical Mining division to ensure that there is a change in the way in which information flows. The implementation strategy considers the themes of the BIM-based framework and the requirements of the mine. Figure 7.11 illustrates the implementation strategy for the BIM-based framework. Each step in the implementation strategy is described in the subsequent subsections



- Ensure that the employees are aware of and understand the changes that are going to take place.

- Digitise all the documents that have been generated by the mine and ensure that digitised documents are generated going forward.

- Determine the data integration technique(s) and tool(s) that will be used to create a CIE that meets the requirements of the mine.

- Ensure that there is real-time two-way communication between the underground teams and the surface departments.

Figure 7.11: Implementation strategy

7.3.1 Behaviour

The first step is to change the behaviour on the mine in terms of the employees' view of the implementation of digital technologies. It is essential that the employees understand that the CIE is meant to assist with information integrity, decision making, relatively easy access, and keep all the employees up to date. The current procedure on the mine involves low collaboration where information is being sent through email with the departments not being able to stay up to date with what is happening in the other departments. Therefore, it is essential that each employee understands the impact that the CIE will have on how information flows. Although some employees might feel that the CIE will be used as a means to determine whether the work that they are producing is correct, up to date and continuously being worked on, it is essential that employees understand the purpose of the CIE. The CIE will be used as a platform to ensure that the information is accurate and true, and that all employees know what is happening in the mine without having to visit that department.

7.3.2 Digitise

The information will be on a digital platform therefore it is essential that all the documents that are produced by the mine are in a digital format. These documents include, but are not limited to, mine layouts, ventilation, water reticulation, and electricity plans, drawings and images. The documents that are in a paper format can be scanned and uploaded onto the CIE as scanned documents. However, the layouts, plans and drawings would have to be redrawn on a CAD environment to ensure relative ease when updating the layouts, plans and drawings when needed.

7.3.3 Integration

When considering the integration, it is essential to consider the techniques and tools that will be used. The techniques and tools should consider interoperability, bidirectional services, and high performance. An integration technique must first be determined before the integration tool can be determined. After considering the advantages and disadvantages of the data integration techniques, middleware and data warehousing were identified as the suitable data integration techniques for the mine. Data warehousing is also preferred by many businesses due to the flexibility and ease associated with storing, managing and viewing the data in a centralised location (Haider, 2019). Although, one of the disadvantages of data warehousing technology is that it would become obsolete in the near future, it has been noted that the data warehousing technology is being developed in such a way that the data warehouse no longer needs to be on-premise and can be on a cloud (Bui, 2017). Middleware is a data integration technique that caters to interoperability as middleware structures the different data sets in such a way that the data is in a format that can be uploaded onto the CIE (Talend, n.d.).

Upon considering some of the integration tools, Oracle Data Integrator Enterprise Edition was identified as the best integration tool for the mine. Oracle Data Integrator Enterprise Edition allows for the movement and transformation of data at a high performance. Data can be integrated on-premise or on the cloud. It is an integration tool that has an interface that is easy to use and has the capability to improve productivity. It is a fully integrated tool that consists of Oracle Fusion Middleware, Oracle GoldenGate, Oracle Database, Oracle Big Data Appliance and Exadata. These additional tools assist with integration (Oracle, 2016). The Oracle Data Service Integrator is also a recommended data integration tool as it has the bidirectional capability that would ensure that the information on the CIE can be viewed and edited (Oracle, n.d.). The integration tools developed by Oracle are the recommended integration tools for the mine as the Oracle integration tools take into consideration some of the themes of the BIM-based framework for mining.

7.3.4 Communication

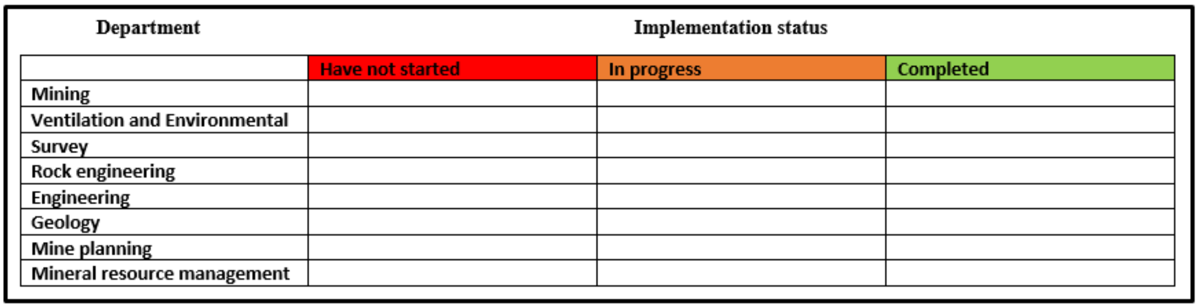
The CIE will be used as a platform that will assist with communication and collaboration, thus improving the decision-making process on the mine. It is essential that when decisions are made regarding the production zone, the decisions can be communicated to the underground mine workings. Therefore, it is essential that there is a real-time two-way communication system that connects the underground mine workings to the surface environment to communicate decisions made by the Technical Mining division to the underground mine workings timeously, especially in the case of an emergency. It is also essential that the underground workers can communicate with the departments on surface. Establishing a reliable two-way communication system that is linked directly to the CIE can be suggested a further research topic.

The Technical Mining division will have a status board that will indicate the status of implementation for each department. Figure 7.12 shows an example of the dashboard steps for a given instruction.

Figure 7.12: Dashboard steps for a given instruction

On the dashboard, a department, mine level, and stoping area (stope) will be selected. Thereafter, a list of instructions will appear. Upon selecting a particular instruction, the status of the instruction will be displayed. There will be three statuses, namely, have not started, in progress and completed. If the instruction is represented by the have not started status, a reason must be provided as to why the instruction has not been executed yet. If the instruction is represented by the in-progress status, a due date for completion must be provided, and if the instruction is represented by the completed status, a date on which the instruction was completed must be provided. The Technical Mining division will also have a dashboard, which summarises the most recent implementation statuses for each instruction per department. An example of the implementation status board is shown in Table 7.1.

Table 7.1: Implementation status board



Department	Implementation status		
	Have not started	In progress	Completed
Mining			
Ventilation and Environmental			
Survey			
Rock engineering			
Engineering			
Geology			
Mine planning			
Mineral resource management			

The implementation statuses available include have not started, in progress, and complete. When highlighting a particular status, it is essential that each department briefly states the steps that have not been started, are in progress, or have been completed. The implementation status board will assist with tracking the progress of the implementation strategy by the Technical Mining division.

7.4 Chapter Summary

Various decisions are made on a mine daily, however, for the purpose of this research study, the monthly Technical Mining division meeting was considered as the point of focus for the decisions made by the Technical Mining division. The current procedure was described as an isolated system which results in longer meetings and less time for discussions and decision making. The proposed procedure was described as a collaborative system whereby the meetings are more focused on discussions, decision making and ensuring that everyone in the Technical Mining division is kept abreast. In conceptualising the BIM-based framework the five factors considered were digitise, interoperability, bidirectional, high performance and communication. The factors ensure that all the information on the CIE is digitised, exchangeable, can be viewed and editable, is easily accessible at a high speed and encourages two-way communication. The recommended implementation strategy that ensures that the BIM-based framework can be successfully implemented includes a change in behaviour, digitising the documents on the mine, integration techniques and tools, and real-time two-way communication. The next chapter presents the conclusions and recommendations for this research study.

8. CONCLUSIONS AND RECOMMENDATIONS

Mining is an essential player in many countries globally, with Asia-Pacific being the largest ROM contributor. From the South African context, the mining industry contributed 7% to the GDP in 2019 and 17% through supply chains. Although the mining industry plays a significant role in the South African economy, it is faced with various challenges. Some of these challenges include, inter alia, market volatility, commodity price downturns, having a deeper understanding of the resource base, improving productivity and maintenance, optimising the flow of material and equipment, and improving safety. There are several trends that have been noted as being able to assist with the survival of mining companies. Some of these trends include big data and mining, the geopolitics of mining, transitioning to a low-carbon economy, access to resources, modern mining workforces, new ways to finance mining and as social contract for mining. It has also been noted that digital technologies have the potential to solve some of the challenges that the mining industry is facing.

The purpose of this research study was to identify a digital technology that has the potential to assist with solving a challenge that is currently being faced by the mining industry. Various mining companies are investing in digital technologies such as AI to efficiently use the data that are generated. The efficient use of the data has the potential to improve the decision-making process across the MVC. In the journey of implementing digital technologies in the mining industry, it is essential to consolidate data that are in isolation.

Although, the mining industry faces various challenges, one of the challenges that was the focus of this research study was the inefficient use of the data and information generated by the mine. The inefficient use of the data and information is a result of mining companies struggling to access complete and accurate data timeously. The digital technology that was identified to solve this challenge was BIM, a digital technology used in the AEC industry. BIM is a process that ensures high efficiency and collaboration between the various parties involved in a project. The objectives of this research study were to understand the different departments in the Technical Mining division, analyse BIM and conceptualise a BIM-based framework for mining. One of the limitations of the study was that one mine was considered for the research study and within that mine only four departments were able to grant access to required data. Other departments could not grant access due to confidentiality related challenges. The data and information for the research study were collected from Mine A and the key findings for the research study are discussed in the subsequent section.

8.1 Key Findings

The key findings for this research study are as follows:

- Mine A does not have a centralised information environment where the information is shared with the various departments to ensure data integrity. The departments in the Technical Mining division share information via email and from a BIM perspective, Mine A is considered to have a BIM maturity level of 0 as there is low collaboration between the departments;
- Mine A has the ability to transition from BIM maturity level 0 to BIM maturity level 1 whereby there would be partial collaboration through a CIE for the integration of information from the various departments in the Technical Mining division;
- The CIE will assist with ensuring the information from the various Technical Mining departments is accessible to all relevant departments and that there are explanatory reports and a chat platform to aid in understanding the information retrieved from the CIE; and
- Mine A has monthly meeting for the Technical Mining division. The CIE will assist in ensuring that each attendee of the meeting has had access to the information on the CIE relating to any challenges or benefits for each department. This will ensure that the meetings are focused on decision-making rather than going through the information in detail.

8.2 Conclusion of the Study

The implementation of partial collaboration on the mine will significantly improve the information integrity, ensuring that the information is easily accessible and readily available. Furthermore, it will improve the communication and collaboration between the different departments in the Technical Mining division. A schematic that illustrated the CIE and how information would be exchanged was developed. Within the CIE, each department would have a folder onto which they can upload information to and retrieve information from. Although, all the departments have access to the information, not all the departments can edit the information. Only the department that is responsible for the information can edit it. Monitoring the reading and writing of the information would ensure that the information remains true and accurate.

The BIM-based framework for mining was designed firstly, to improve the communication and collaboration in the production zone of an underground mine, and lastly, to prepare the mine for the implementation of the other BIM concepts which have the potential to significantly improve the mine processes and decision making. The BIM-based framework has four themes, namely, digitise, interoperability, bidirectional, high performance, and communication. These themes were identified as essential themes for improving the communication and collaboration on the mine.

Since the CIE is a digital technology, it is essential that the data generated by the mine be digitised to be uploaded on the CIE. The interoperability ensures that the different software packages that the mine uses can connect and communicate with each other, even though they are created by different software vendors. The bidirectional services ensure that the information can be accessed by the different departments and edited by the department that is responsible for the information. The high-performance theme focuses on ensuring that the information can be provided at a high speed, can be easily accessed and can be used to improve the decision-making process on the mine. Mine A is on a digital journey with one of the focus areas being the integration of data. Therefore, this research study is considered as one that may be useful in improving the communication and collaboration on Mine A. Subsequently, improving the decision-making process on the mine through the efficient use of information.

8.3 Recommendations

The recommendations of this research study include:

- Using the middleware and data warehousing integration techniques. A combination of the two integration techniques caters for flexibility and ease of storing, managing, exchanging and viewing the information;
- A combination of the Oracle Data Integrator Enterprise Edition and Oracle Data Service Integrator is recommended for the mine. This combination caters to the four themes identified in the BIM-based framework for mining; and
- Although the information will be on the CIE, a backup for the information should always be kept.

8.4 Further Research

Communication is one of the themes for the BIM-based framework as the decisions made on surface must be communicated to the underground workings and the underground workings must be able to communicate to the workers on surface in a timely manner. Therefore, it is essential that there is a real-time two-way communication system that is reliable and suitable for deep to ultra-deep level underground mines. It would be essential that the real-time two-way communication system links directly to CIE so that there is a live feed of the communication. During the period of this research study, a two-way communication system did not exist at Mine A. Therefore, further research will be required to design a framework that will ensure a two-way communication system that links directly to the CIE on Mine A.

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