

https://dspace.org/

Conceptualization of a mining information model (MIM) using real time information for smart decisio making: a smart economics approach

Javaid, Faiq

2018
https://hdl.handle.net/10539/27284

Downloaded from a DSpace repository. https://dspace.org/

CONCEPTUALIZATION OF A MINING INFORMATION MODEL (MIM) USING REAL TIME INFORMATION FOR SMART DECISION MAKING: A SMART ECONOMICS APPROACH

Faiq Javaid

A research report submitted to the Faculty of Engineering and Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Masters of Science in Engineering.

Johannesburg, 2018

DECLARATION

I declare that this thesis is my own, unaided work. Where use has been made of the work of others, it has been duly acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before in any form for any degree or examination in any other university.

Signed:

_____

Faiq Javaid
Student No. 1473030
Date: September 04, 2018

ABSTRACT

South Africa is a mineral resource-rich country with the largest concentrations of gold and platinum in the world. Yet the South African mining industry is facing an economic crisis. Some of the reasons for this crisis are: Low commodity prices, escalating production costs, depletion of economically ore grades, volatile currency, volatile exchange rates, difficulty to compete in the international markets, increased concerns of deteriorating relationships with mine-worker unions and the South African Government's Department of Mineral Resources (DMR) etc.

Thus there is a critical need to develop an information and decision-making system that will cater for modern-era needs. Such a system would need to optimize production cost, while properly linking it to current and expected market conditions to enable synchronised and timely decision-making. This can only be done via a framework that is supported by relevant and timely information. This will need to include the following mine and market data (in both current- and anticipated-forms): Production rates; assessment of what is going on underground; incident reporting; scheduling; costing; market updates; inventory management; life cycle management. And such a system, named Building Information Modelling (BIM), was developed for the construction industry. This indicates that development of a Mining Information Modelling (MIM) may also address above-mentioned aspects, allowing maximum production, optimal cost, less uncertainty and more efficiency – something that is difficult to attain via existing mining-software.

The purpose of this research was to investigate and present a conceptual framework for the development of MIM and a smart, real-time decision-making tool. The study reveals that MIM can be achieved via the combination of software from a number of providers, together with some additions. Ideally, the combination should cover the entire mining value chain. With MIM, a decision-making tool (with the support of MIM) can either be developed as a separate software or can be integrated with MIM. Such system will cater for modern-era needs, thereby enhancing mining capabilities without affecting job-creation.

ACKNOWLEDGEMENT

Profound gratitude and appreciation for the following individuals for their guidance, support and encouragement in making this study possible.

- My supervisor, Prof. Frederick Cawood (Director Wits Mining Institute, University of the Witwatersrand) for his precious academic support, guidance, trust and patience throughout this study.

- Wits Mining Institute and Sibanye-Stillwater for their financial support.

- Dr. Ali and Dr. Tariq for arranging this opportunity for me.

- Mr. Logan Nair and Mr. Marlon van Heerden for their valued guidance regarding current mine planning practices and related issues.

- Lindy, Sonja and Anzollete for their support during my research.

- Engr. Abbas Raza (Director, Softechniak Enterprises Pty. Ltd.) for his guidance about BIM and its practices.

- Engr. Arif and Engr. Javed Tipu for their immense moral support and guidance.

DEDICATION

To my caring parents for their support and sacrifice, my loving wife for her faith, dear brother and lovely sisters for supporting me and my teachers for their moral support and motivation.

TABLE OF CONTENTS

DECLARATION ..... **ii**

ABSTRACT ..... **iii**

ACKNOWLEDGEMENT ..... **iv**

DEDICATION ..... **v**

TABLE OF CONTENTS ..... **vi**

LIST OF FIGURES ..... **ix**

LIST OF TABLES ..... **xii**

LIST OF ABBREVIATIONS ..... **xii**

1 INTRODUCTION **1**

1.1 Overview 1

1.2 Economics-related problems in the mining industry 5

1.2.1 Commodity Prices 5

1.2.2 Currency exchange rates 8

1.3 Mining value chain 9

1.4 Building Information Modelling (BIM) 11

1.4.1 BIM in the project life cycle 13

1.4.2 BIM case studies 15

1.5 BIM to MIM (Mining Information Modelling) 16

1.6 Need of MIM 17

1.7 Research questions and objectives 17

1.8 Methodology 17

1.9 Facilities required 18

1.10 Research outline 18

1.11 Wits Mining Institute, Digital Mine and this research report 19

1.12 Conclusion 21

2 LITERATURE REVIEW 23
2.1 Overview 23
2.2 Internet of Things (IoT) 24
2.2.1 Benefits of IoT 26
2.2.2 Industries using IoT 27
2.3 Real-time – for the mining industry 28
2.4 Smart Economics 29
2.5 Costing for Smart Economics 30
2.6 Decision-making 35
2.7 Theory of Constraints (TOC) 36
2.8 Geographical Information System (GIS) 38
2.9 Similar research 40
2.9.1 Ernst and Young (EY) 40
2.9.2 International Business Machines (IBM) 41
2.9.3 Australia and Commonwealth Scientific and Industrial Research Organization (CSIRO) 42
2.9.4 China 44
2.9.5 South African Mining Extraction Research Development and Innovation (SAMERDI) 46
2.10 Anglo American Platinum Mogalakwena mine – A case study 48
2.11 Risks of non-implementing a MIM approach 54
2.11.1 The Mining industry, unemployment and worker unions 54
2.11.2 The Mining industry and the government 55
2.12 Literature findings 56
2.13 Conclusion 57
3 SOFTWARE CONSIDERATION FOR MIM 58
3.1 Overview 58

3.1.1 Optimisation software package 58
3.1.2 GeoFinance software package 61
3.1.3 Datamine 62
3.2 Comparison 63
3.2.1 MIM requirements 63
3.3 Conclusion 66
4 DEVELOPMENT OF AN INTELLIGENT DECISION-MAKING SYSTEM 67
4.1 Overview 67
4.2 Intelligent Decision-Making (IDM through MIM) 67
4.3 IDM – a case study 67
4.3.1 Resources – in general 70
4.3.2 Resources – in process 72
4.3.3 Product mix 74
4.3.4 Prices forecast 76
4.3.5 Capacity bottlenecks and Constraints 77
4.4 Illustration of an IDM process 78
4.5 Proposed architectures 84
4.5.1 Basic architecture of MIM 84
4.1.1 Architecture of IDM through MIM 86
4.5.2 MIM architecture across the mining value chain 90
4.5.3 Infrastructure and resource requirements for MIM, IoT and IDM through MIM 91
4.5.4 Infrastructure and architecture of Wits Mockup-mine 93
4.5.5 Action scenario 102
4.6 Wits Mockup-mine case studies – a step towards MIM 103
4.7 Conclusion 106

5 CONCLUSION AND RECOMMENDATION 107

5.1 Overview 107

5.2 Key findings of the research 107

5.3 Conclusions of the study 107

5.4 Research limitations 109

5.5 Recommendations and suggested future research 109

5.6 Wits Mockup-mine architecture with MIM 110

5.7 Conclusion 112

REFERENCES 113

APPENDICES 120

Appendix A 120

Appendix B: Table A Microsoft Excel formulas used to illustrate the example 2 (section 4.4 of chapter 4) in decision-making concept. 123

Appendix C: Table B Microsoft Excel formulas used to illustrate the example 2 (section 4.4 of chapter 4) in decision-making concept. 124

Appendix D: Table C Microsoft Excel formulas used to illustrate the example 3 (section 4.4 of chapter 4) in decision making concept. 125

LIST OF FIGURES

Figure 1.2 South African gold grade. After (Chamber of Mines of South Africa, 2017) 3

Figure 1.1 Cost of gold mining in South Africa. (Minxcon Group, 2017) 3

Figure 1.3 Annual average commodity prices After (World Bank, 2017) 6

Figure 1.4 Quarterly average commodity prices 6

Figure 1.5 Monthly average commodity prices 7

Figure 1.6 ZAR vs USD exchange rate After (South African Reserve Bank, 2017) 9

Figure 1.7 Mining value chain 10

Figure 1.8 BIM in a project lifecycle 12

Figure 1.9 The WMI way of research (Source: Author) 21

Figure 2.1 Simplest IoT architecture Source: After (Barrett, 2012) 25

Figure 2.2 Investment in IoT by different industries (Goerlich, 2016) 28

Figure 2.3 Activity Based Costing for Mineral Processing. After (Wentzel, 2012) 34

Figure 2.4 Decision making process Source: After (Ahmed, et al., 2014) 36

Figure 2.5 Example of constraints that can exist in the mining industry 37

Figure 2.6 GIS data layers and integration (Folger, 2009) 39

Figure 2.7 EY's Digital Navigator (Walker, et al., 2017) 41

Figure 2.8 Rio Tinto control room in Perth, Australia (Reed, 2014) 44

Figure 2.9 Operations monitoring and control center at Jinjie (Jianguo, 2015) ... 45

Figure 2.10 SAMERDI project timelines (Singh & Macfarlane, 2018) 48

Figure 2.11 Current location of mining at Mogalakwena (Source: Author) 49

Figure 2.12 Software used by Mogalakwena mine and their associated issues (Source: Author) 50

Figure 3.1 Building blocks of MineRP Optimization After (MineRP, n.d.) 59

Figure 3.2 MineRP GeoFinance building blocks After (MineRP, n.d.) 61

Figure 4.1 Information required for the decision (Source: Author)..... 69

Figure 4.2 General resources requirement for making the decision (Source: Author)..... 70

Figure 4.3 Resources to be considered required for processing phase (Source: Author)..... 73

Figure 4.4 Product mix for increased production (Source: Author) 75

Figure 4.5 Prices-forecast consideration for decision-making (Source: Author) . 77

Figure 4.6 Constraints to be considered for decision-making (Source: Author) .. 78

Figure 4.7 Basic architecture of MIM (Source: Author) 85

Figure 4.8 IDM through MIM architecture (Source: Author) 88

Figure 4.9 MIM architecture across the mining value chain (Source: Author) 89

Figure 4.10 How a shovel can be connected to IoT (Gomori, 2016)..... 92

Figure 4.11 Wits Mockup-mine (Source: Author)..... 94

Figure 4.12 Wits Mockup-mine lamp room, tunnel and stope (Source: Author) . 94

Figure 4.13 Vibra-Tech sensors Seismometer, extensometers and weather station (Source: Author) 95

Figure 4.14 Vibra-Tech live feed in WMI control room from different sensors (Source: Author) 96

Figure 4.15 Schauenburg's system in the Mockup-mine. Access control, PPE, Gas detection instruments, environmental sensors and S-link for location monitoring (Source: Author) 97

Figure 4.16 Schauenburg’s MIMACS software in control room. MIMACS asset management console and tracking agent. (Source: Author) 97

Figure 4.17 Minetec tracking and positioning system (Source: Author)..... 98

Figure 4.18 YoungBlood's production reporting system (Source: Author) 99

Figure 4.19 WMI control room (Source: Author) 100

Figure 4.20 Architecture of systems installed in the Mockup-mine (Source: WMI) 101

Figure 4.21 Dashboard-display of data sent from sensors housed in displayed sections of WMI's building which were converted to simulate different levels of a mine (Opiti, 2017)..... 104

Figure 4.22 WMI-IBM Intelligent Operations Center architecture (Source: WMI) 105

Figure 5.1 Architecture of Wits Mockup-mine with the addition of MIM and IDM through MIM (Source: WMI) 111

LIST OF TABLES

Table 3.1 MIM requirements in each phase of mining operation (Source: Author) 64

Table 3.2 Software capability from MineRP and Datamine (Source: Author)..... 65

Table 4.1 Decision making example 1 (Source: Author) 81

Table 4.2 Decision making example 2 (Source: Author) 82

Table 4.3 Decision making example 3 (Source: Author) 83

LIST OF ABBREVIATIONS

3D	3 dimensional

4D	4 dimensional
5D	5 dimensional
6D	6 dimensional
7D	7 dimensional
ABC	Activity Based Costing
AHS	Autonomous Haulage System
API	Application Programming Interface
AR	Augmented Reality
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building Information Modelling
BOQ	Bill of Quantities
CPS	Cyber Physical System
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organization
EPS	Enhanced Production Scheduler
DMR	Department of Mineral Resources
EY	Ernst and Young
GDI	Gas Detection Instruments
GDP	Gross Domestic Product
GIS	Geographical Information System

HG	High Grade
IBM	International Business Machines
IDM	Intelligent Decision-Making
IIOT	Industrial Internet of Things
IOT	Internet of Things
KPI	Key Performance Indicators
LG	Low Grade
LHD	Load, Haul and Dump
MG	Medium Grade
MIM	Mining Information Modelling
MIMACS	Mine Wide Integrated Monitoring and Control System
MVC	Mining Value Chain
NUM	National Union of Mine Workers
PPE	Personal Protective Equipment
RFI	Request for Information
RTIMS	Real Time Information Management System
SAAS	Software as a Service
SAMERDI	South African Mining Extraction Research Development and Innovation
SHEQ	Safety, Health, Environment and Quality
TOC	Theory of Constraints

VLG	Very Low Grade
VR	Virtual Reality
WMI	Wits Mining Institute

1 INTRODUCTION

The South African mining industry is currently experiencing economic challenges in spite of its extensive natural mineral resource base. Mining companies are facing difficulties in extracting the full potential of their mineral resources due to multiple factors. This chapter will briefly discuss these factors and how to address them.

1.1 Overview

South Africa is a mineral resource-rich country with the largest concentrations of gold and platinum in the world. This includes 80% of the world's platinum group metals, 80% of its manganese, 70% of its chrome, together with the world's largest gold deposits in what is named "The Witwatersrand Basin" (Chamber of Mines of South Africa, 2017). In terms of production, in 2016, South Africa produced approximately 141 metric tons of gold, 264 metric tons of platinum, 8.4 million carats of diamond, 0.3 million metric tons of coal, 16.3 million metric tons of chrome, 73.2 million metric tons of iron ore, and 15 million metric tons of manganese, together with job-provision to 0.46 million people (Chamber of Mines of South Africa, 2017). Yet the South African mining industry is facing an economic crisis. Some of the reasons for this crisis are:

- Low commodity prices;
- Escalating production costs;
- Reduced ore grades;
- Volatile currency;
- Volatile exchange rates;
- Difficulty to compete in the international markets; and
- Deteriorating relationships with mine-worker unions and the South African Government's Department of Mineral Resources (DMR) etc.

Of the above, lower commodity prices and volatile currency rates are primary factors. Indeed, an unforeseen combination between these two factors has aggravated the situation. This will be discussed in more detail in section 1.2.

However, it is important to note here that while global markets generally deal in United States Dollars (USD), South African Rand (ZAR) cost estimates and cash flows are generally prepared twice or at best, four times a year. Thus South African mine production is generally planned by keeping in view specific market price and cost estimates at a specific point in time. However, there is a significant time lag between the production date and selling date. Therefore, the varying price of the product and volatile exchange rate adversely affect the accuracy of mine valuation and decision-making criteria.

Another factor is that South African mining industry production rates have dropped significantly since 2007: Whereas diamond production was 15 million carats in 2007, this dropped to 10 million carats in 2017; Gold production dropped from 260 metric tons in 2007 to 140 metric tons in 2017; Similarly, platinum production dropped from 310 metric tons in 2007 to 250 metric tons in 2017 (Chamber of Mines of South Africa, 2017). Aggravating this are declining production levels and ore grades, together with fast-rising mining costs (Müller & Frimmel, 2010). Figure 1.1 shows cost of gold mining in South Africa and Figure 1.2 shows declining gold grade between 2004 and 2015[1].

[1] Limited data is available on South African gold grade.

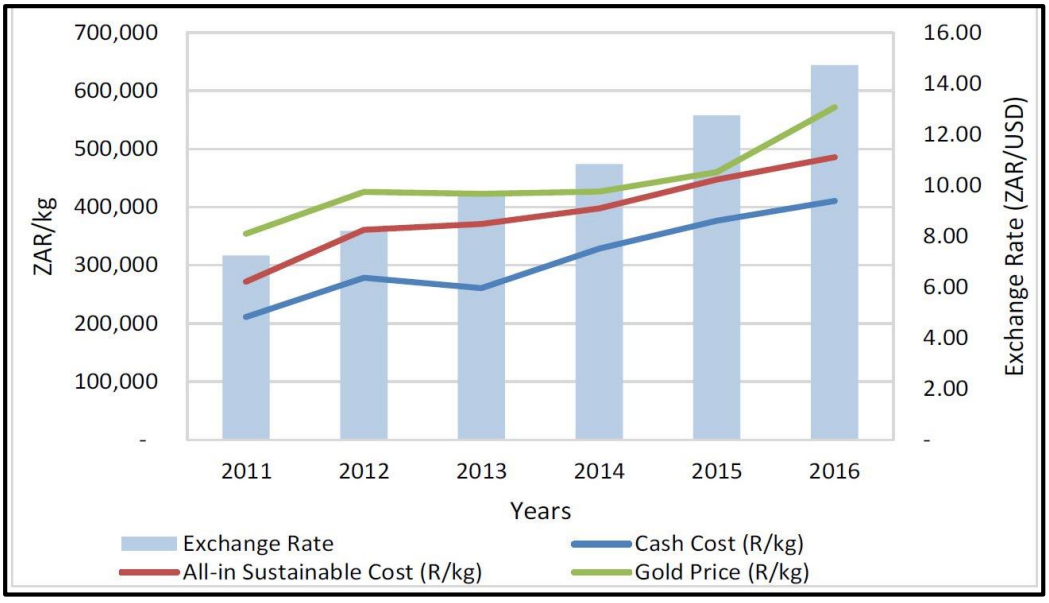


Figure 1.2 Cost of gold mining in South Africa.
(Minxcon Group, 2017)

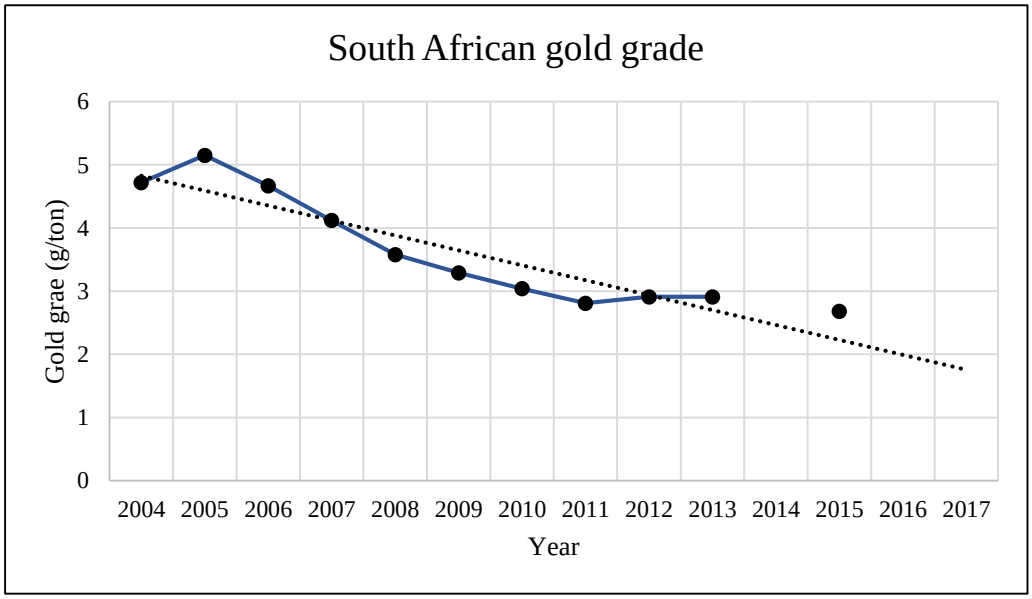


Figure 1.1 South African gold grade. After (Chamber of Mines of South Africa, 2017)

If conventional mining methods continue unchanged, the above statistics indicate that the South African gold industry will face further production-decline in coming years, followed by exhaustion of currently-economically-viable reserves by 2033 (Chamber of Mines of South Africa, 2017). This highlights the need to extract these reserves efficiently yet economically.

It is important to understand that conventional mining methods are limited in their ability to economically exploit remaining mineral resources. Furthermore, energy and water constraints are causing electricity and water prices to rise rapidly. Therefore, the design of today's mines must address advanced risks, improved efficiencies and smarter applications (Braham, 2017). Mining operations in South Africa are also labour intensive. Closing a mine or reducing the lifetime of a mine may have severe impacts on jobs, local socio-economics and political stability. Thus there is a critical need to develop a system that will cater for modern-era needs, thereby enhancing mining capabilities without affecting job-creation.

Such a system would need to optimize production cost, while properly linking it to current and expected market conditions to enable synchronized and timely decision-making (discussion on costing, including Activity Based Costing will be presented in Chapter 2 - Literature review). This can only be done via a framework that is supported by relevant and timely information. However, for timely information, a large amount of real-time data from all phases of mining operation will be required. This will need to include the following mine and market data (in both current- and anticipated-forms): Production rates; assessment of what is going on underground; incident reporting; scheduling; costing; market updates; inventory management; and life cycle management[2]. Such a system would need to be specifically-designed to enable real-time decision-making on individual and combined aspects of the latter data.

And such a system, named Building Information Modelling (BIM), was developed for the construction industry. This has since proven to be effective and cost-efficient throughout the lifecycle of construction projects. This indicates that development of a Mining Information Modelling (MIM) system may also address above-mentioned aspects, allowing maximum production, optimal cost, less uncertainty and more efficiency – something that is difficult to attain via existing mining-software.

[2] This information will be necessary for MIM and IDM through MIM which will be discussed in detail in the later part of this research report.

Indeed, such a system is currently not available for the mining industry. The development of such a system will take time since multiple factors need to be considered and solved in order to reach the final stage of MIM. The purpose of this document's research is therefore to consider these factors, thus providing a head-start towards the development of MIM[3].

1.2 Economics-related problems in the mining industry

1.2.1 Commodity Prices

Section 1.1's overview introduced the fact that South African mine-planning is generally carried out six-monthly or quarterly using current commodity prices, and that this fails to cater for future price changes which may affect the complete planning process. Figures 1.3 to 1.5 show how commodity prices are changing.

[3] More information regarding this is available in the later part of this research report. Since MIM currently does not exist, practical examples are not available. However, various potential technological developments are discussed in chapter 2.

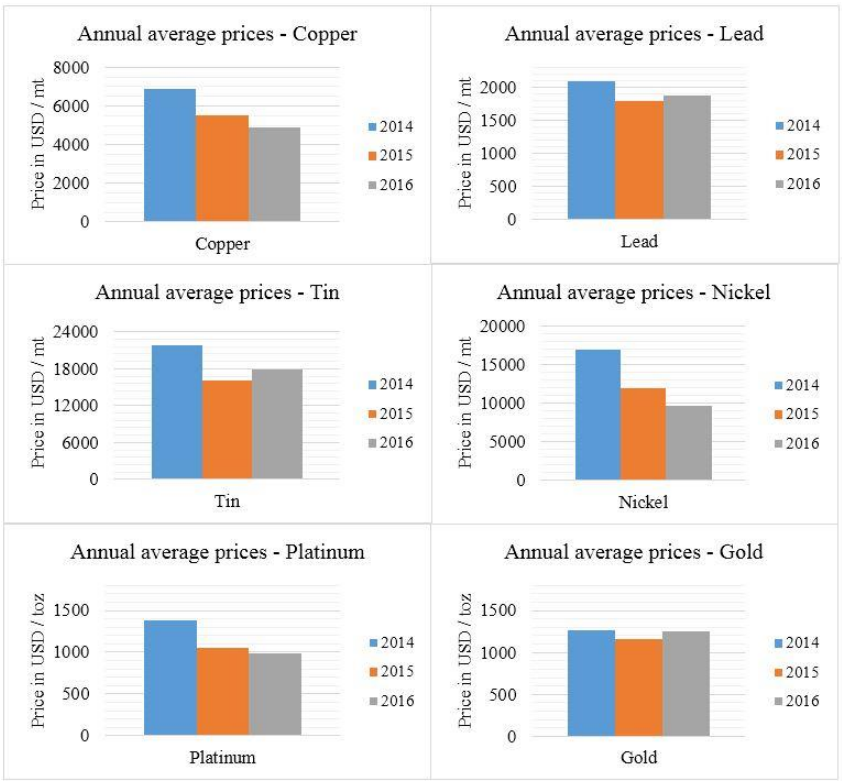


Figure 1.3 Annual average commodity prices
After *(World Bank, 2017)*

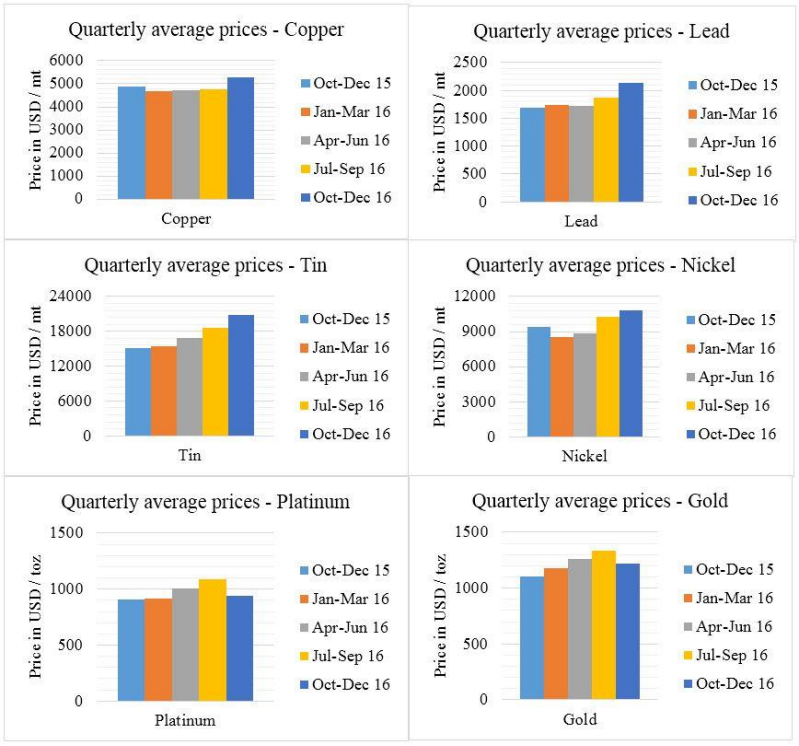


Figure 1.4 Quarterly average commodity prices
After (World Bank, 2017)

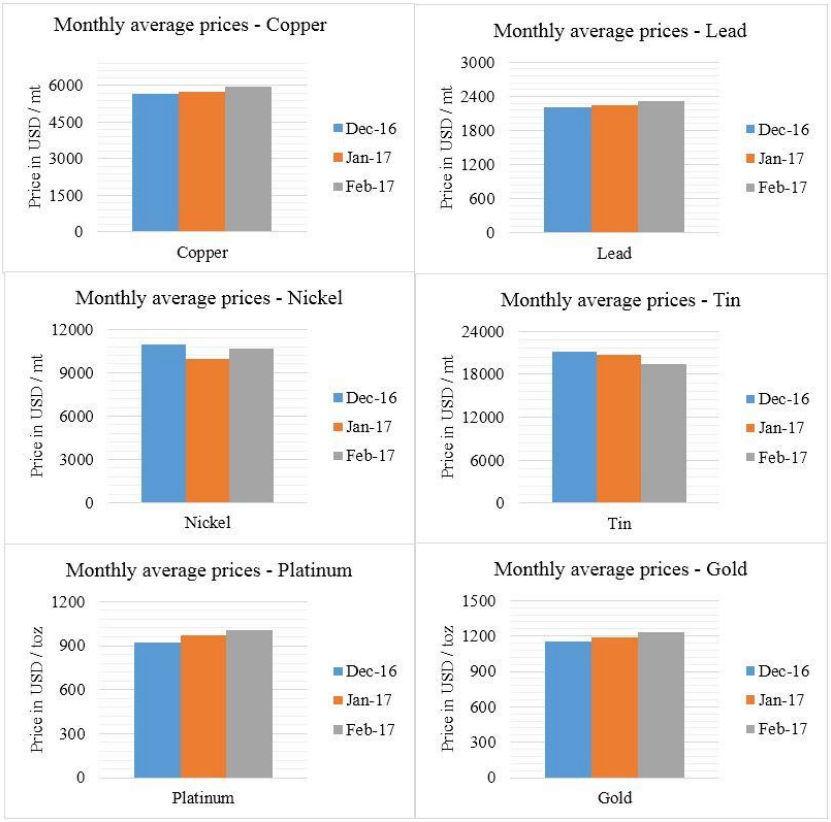


Figure 1.5 Monthly average commodity prices
After (World Bank, 2017)

Figure 1.3 reveals that average prices of commodities change significantly over a one-year period. For example, the price of platinum reduced from $1 384 per troy ounce in 2014 to $1 053 per troy ounce in 2015. South Africa produced 275.5 metric tons of platinum in 2015 (Chamber of Mines of South Africa, 2017). This implies that if the 2014 price and other factors had remained unchanged in 2015, the South African platinum industry could have earned R34.6 billion more in 2015 (i.e. 36.7% more than 2015's actual revenue). Furthermore, employees could have been remunerated R59.6 billion instead of R43.6 billion, and government might have received R0.98 billion instead of R0.72 billion in royalties.

A key factor to be considered in terms of mine planning based on current commodity prices, is that the time required to bring the commodity from mine to market differs between open pit and underground mines. In the case of underground mines, the period could be months. Figures 1.4 and 1.5 reveal considerable monthly and quarterly price-changes for most commodities. Such

changes are not favorable for mine planning therefore; alternative planning options could be considered in cases when latest prices fall. However, with a fixed overhead and fixed work force, mine-production cannot simply be turned on and off. Therefore, what is needed is working towards a system that will deal with real-time revenue and cost models, and enable mine managers to better understand changes and their impacts on mine productivity and ultimately, on profitability.

1.2.2 Currency exchange rates

Section 1.1 introduced a further complication to production planning, namely the fact that the South African Rand currency (ZAR) is volatile. Figure 1.6 shows the ZAR vs. USD exchange rate changing daily during the period 8 February 2017 to 20 March 2017. As may be seen, over a period of forty days, it dropped significantly from R13.5/$ to R12.6/$. Currently, there is no comprehensive way to determine currency forecast in such a way as to aid smart decisions. This document's research proposes linking of MIM to real-time currency exchange rates, together with forecasts that are based on both expected and determinable future events. This will, in turn, provide basis for considerably-improved mine planning.

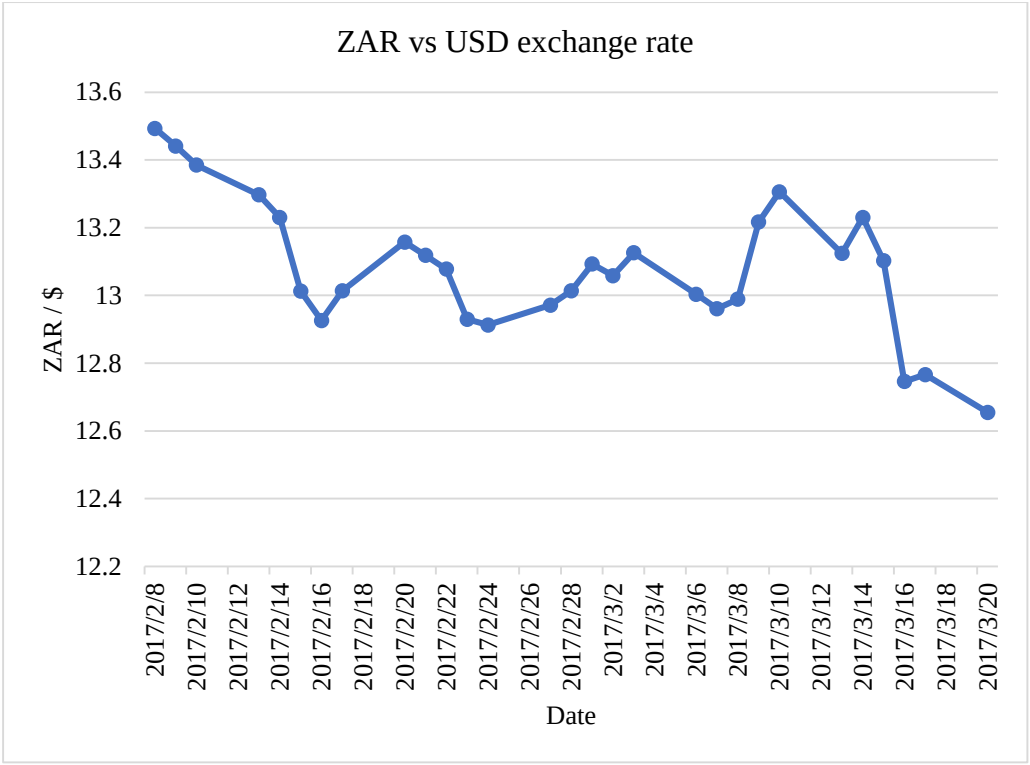


Figure 1.6 ZAR vs USD exchange rate
After (South African Reserve Bank, 2017)

1.3 Mining value chain

As shown in Figure 1.7, there are six phases in the mining value chain through which the final product is obtained. Undergirding this are mining laws and regulations which fall under the Mineral and Petroleum Resources Development Act, 2002 and Mineral and Petroleum Resources Development Amendment Act, 2009. These acts govern the issuance of mining rights and licenses, development of the mines, timelines and environmental aspects, etc.

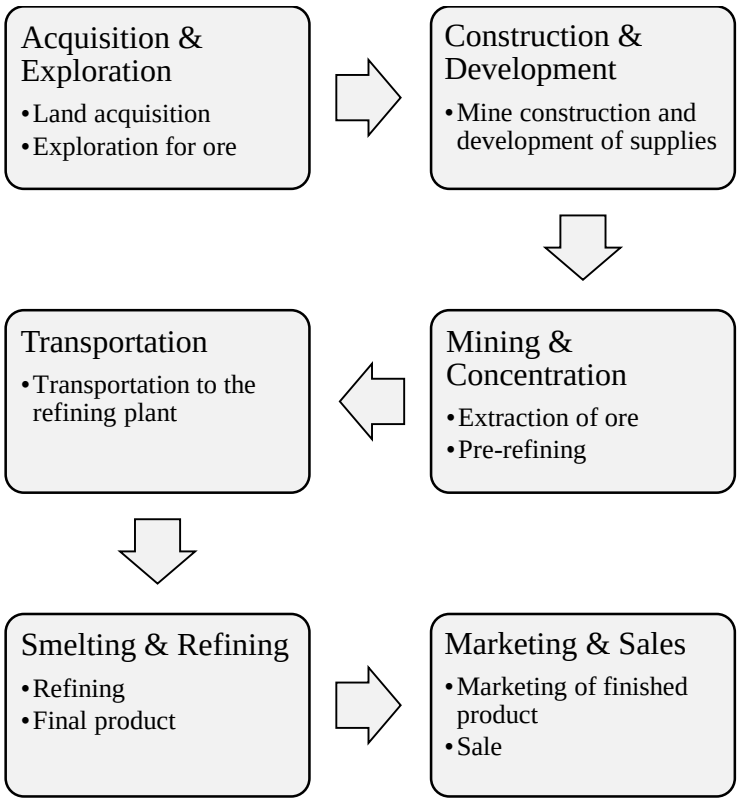


Figure 1.7 Mining value chain
After *(Guj, et al., 2017)*

Although this document's project primarily deals with Figure 1.7's Construction & Development and Mining & Concentration phases, a brief summary of other phases of the mining value chain with their timelines is presented below:

- **Acquisition & Exploration**

  In the first phase of the mining operation, land is acquired and exploration for the ore is carried out. Drilling and sampling is carried out and areas with high concentration of ore are highlighted. Per the Mineral and Petroleum Resources Development Amendment Act 2008 section 10 (b), the permission granted for this phase by the DMR is for 1 year.

- **Construction & Development**

  In the next phase, construction of the mine is started. Where required, shafts are sunk and further development to reach the ore is done. Basic facilities such as electricity, water supply, transportation system, ventilation system, etc. are

also installed during this phase. As stated by the Mineral and Petroleum Resources Development Act 2002 section 17 clause (6), this phase can continue for a maximum of 5 years. However, if there is a need of extension of period in this phase, section 18, clause (4) allows for a renewal for a period of 3 years.

- **Mining & Concentration**

  In Mining & *C*oncentration, the ore is extracted and initial separation from the waste is carried out. Whereas some mines then continue into the following phase, namely Transportation to concentration plants for Smelting & Refining, other South African mines execute their own Smelting & Refining. The duration of mining right, according to Mineral and Petroleum Resources Development Act 2002 section 23, clause (6), is 30 years. This can be renewed under certain conditions.

- **Transportation**

  The ore is then transported to the concentration plant through trucks, railways or ships for concentrating.

- **Smelting & Refining**

  In this phase, the ore is heated and melted and a final refined product is obtained.

- **Marketing & Sales**

  After refining and beneficiation, the final product is brought to the market and sold.

1.4 Building Information Modelling (BIM)

BIM is a technology and software used to create 3D planning models that helps architecture and construction engineers in proficient designing, planning, construction and management of buildings. It considers the spatial relationships, geographical information, quantities and qualities of elements, material and

equipment inventories, cost estimations, and project schedules, and enables team players to communicate, collaborate, simulate, optimize and operate the project throughout its lifecycle (Azhar, et al., 2008) and (Mihindu & Arayici, 2008).

Although BIM is an idea of the modern era, this word was first coined in 1992 (Nederveen & Tolman, 1992). Since then, BIM has improved substantially and its use is continuously increasing. The percentage of relevant professionals using BIM in the UK was estimated to be 13% in 2011, which has now increased to 54% (NBS, 2016). BIM can be used to create 3D, 4D, 5D, 6D and 7D models[4]. BIM in a project lifecycle is shown in Figure 1.8.

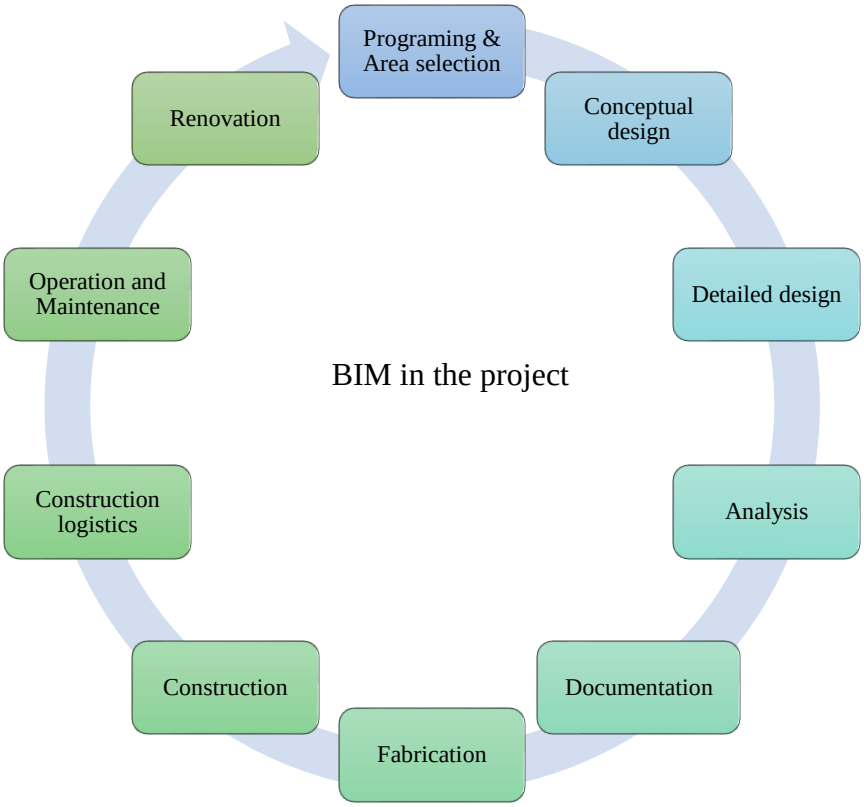


Figure 1.8 BIM in a project lifecycle
After *(Dispenza, 2010)*

[4]A 3D BIM model with schedule and time constraint is called 4D model and if the cost dimension is added, it becomes a 5D model (ASHRAE, 2009). 6D BIM modelling is about optimising the energy consumption of the building and 7D model helps in management of the lifecycle of the building along with other 6 dimensions (Elsafadi, 2016).

1.4.1 BIM in the project life cycle

BIM is essentially a comprehensive way of producing, using and sharing the data in a building life cycle. This involves all BIM stakeholders, including owners, architects, engineers, designers, contractors and facility managers (Hungu, 2013). One of the important benefits of BIM is the accuracy of geometrical representation of parts of the building in an integrated data atmosphere (CRC Construction Innovation, 2007). Integrated data is defined as data that is organised and taken unabridged so that the information coming from the preceding process may directly be used as input for the following processes without human intervention (ASHRAE, 2009). Figure 1.8's BIM project lifecycle components are explained below:

- **Programming and area selection**

  BIM helps in area selection, landscaping and terrain management. In an integrated BIM model, it is possible to shape the terrain according to the construction requirement and edit it until the most suitable model is obtained. BIM also assists understanding of environmental aspects concerning the building, such as sunlight direction, wind direction, weather conditions etc.

- **Conceptual design**

  BIM provides visualization of different ideas that are submitted. It shows whether the ideas are practical or not, and what changes will be required at this early stage.

- **Detailed design**

  In the detailed design, BIM helps in determining different structural properties of the building, such as strength of plinths and iron bars, gravity distribution, required capacity of equipment to be installed, etc.

- **Analysis**

  The detailed design is then analysed to ensure that all user requirements have been met. Analysis is also done to visualise conflicts between different parts or

installed equipment. Such conflicts, if identified, can thus be resolved prior to fabrication and installation.

- **Documentation**

  Documentation that is produced via BIM helps all stakeholders to better-understand the design. It also enables them to communicate with one another and discuss confusions in a more comprehensive way. A bill of quantities (BoQs) is also generated during this phase. BIM extracts information by breaking down the model into small parts so that the BoQs can be generated accurately, communicated properly and understood easily. (Consult Australia and Australian Institute of Architects, 2012).

- **Fabrication and Construction**

  During fabrication, drawings that were generated earlier are provided to the fabricator. BIM facilitates fabricator comprehension of the provided information through better (3D) visualization. During construction, there are often conflicts between involved parties. BIM facilitates resolution of such conflicts, thereby saving time and money.

- **Construction Logistics**

  BIM allows detailed project costing and scheduling from the beginning of the project. It calculates material and equipment that will be needed for the building and adds its costs to the budget. In this way, the purchase of surplus material is prevented. Also, BIM's real-time scheduling and progress updates enable the team players to work in their respective places timeously and without delays. If some part of the work is delayed for some reason, real-time progress reporting and scheduling enables team players to observe potential delays and reschedule activities accordingly.

- **Operations and Maintenance**

  After completion of construction, BIM assists operation and maintenance of the building. This includes BIM provision of complete data on installed equipment, including operator's manuals, dates of purchase, vendor lists, maintenance

schedules and warranty information. The single source of information in one package enables operations managers to manage all aspects of complete buildings and to correctly convey related information. The same feature enables operators to troubleshoot whenever there is an issue.

- **Renovation**

  During renovation, BIM data files can be retrieved and material or equipment that needs renovation or replacement may be arranged. Associated manuals and vendor lists enable responsible parties to execute such projects in the best way possible.

1.4.2 BIM case studies

The following case-studies (sourced from Autodesk Revit) highlight BIM benefits.

- Sundt Construction Inc., constructed Butler Water Reclamation Facility in Peoria, Arizona that started operation in 2008. The company saved 6000 hours on concrete rework and the use of BIM enabled the $135 million project to be completed in time. The stakeholders were able to clearly visualize the building and communicate effectively throughout the construction. During the project, there were 84% fewer requests for information (RFI) due to the interactive nature of BIM (Autodesk, 2009).

- Shanghai Tower Construction & Development Company Ltd. constructed Shanghai Tower in Shanghai, China. The building was inaugurated in 2015 with distinction of being one of the world's tallest and greenest buildings. The building contains 121 stories of transparent glass, 632-metre height and 5.7 million square meters of building space. Due to the use of BIM, the team encountered no conflicts during construction and reduced building material requirements by 32% (Autodesk, 2014).

1.5 BIM to MIM (Mining Information Modelling)

The above case studies reveal quantifiable benefits in using BIM. However, since BIM is a technology applied to construction rather than mining, bridging gaps between BIM and MIM will take time and effort. An aspect that could assist is Dundee Precious Metals mining company, who have implemented the concept of IoT (discussed in detail in section 2.2 of chapter 2) under which communication and data from a mine is transmitted real-time. Dundee installed 45kms of fiber optics in its mine and used Wi-Fi for communication. Improved communication and business intelligence using IoT enabled production-improvement from 0.5 million metric tons[5] annually to 1.8 million metric tons[5], and saved $2.5 million in operating costs (Prowse, 2014)[6]. This is just one part of applying modern-day technologies into one part of the mining operation. The value-add achieved by using IoT at the test site of Dundee Precious Metals mining company undergirds the impact it could make on the entire mining operation[7].

If a platform is developed that can capture real-time information, enable two-way communication, link to market prices, and assist smart-decisions, enormous improvement can be brought to the economics system of the mining industry. Benefits discussed above indicate that if it is developed for 21st century mines, it will become a game-changer that will take the mining industry from loss to profit.

Certainly, development of MIM and the process of its adoption by the mining industry will be time-consuming. It may take multiple man-years to combine multiple software packages to form MIM, or to develop complete new software as MIM. In either case, this should not be considered a bottleneck to working towards a real-time or a near-real-time information platform. The history of software

---

[5] Conversion factor applied (1 metric ton = 1.1 US tons).

[6] Real-time mine workers and equipment tracking, information regarding energy requirement and equipment maintenance requirement enabled Dundee to efficiently use their resources (thereby increasing production) and saving cost.

[7] "Entire mining operation" refers to any mining operation where MIM and IoT will be used. This may cover a single mining activity (e.g. extraction) or multiple activities in the mining value chain.

development repeatedly reveals “today’s impossibilities” becoming “today’s achievements”. Serious consideration of this is critical for ongoing success in future mining.

1.6 Need of MIM

In summary of above discussions: The mining industry is facing challenges, and one of those challenges is economic decision-making which needs to be more accurate, smart, quick and based on real-time information for the mine of 21st century. There is a possibility of connecting the mining industry to real-time information coming from the market on a continuous basis, so that necessary actions related to production and sales can be taken in real-time. However, there are constraints and cost aspects related to decision-making that need to be addressed while working towards MIM. These constraints and cost aspects are discussed in chapters 2 and 4, together with The Theory of Constraints.

1.7 Research questions and objectives

- Can real-time technology further improve mine optimisation?
- Is there a need for real-time economics in the mining industry?
- How can it be done?
- How will the upgraded system benefit mining stakeholders?

1.8 Methodology

A workshop with the Digital Mine group and industry experts was conducted to outline the research methodology and scope of the report. The proposed methodology is as stated below.

- **Study of current practices**

  Current mine planning and optimisation (for economics) methodologies in the mining industry will be studied. Case studies and reports from the mining industry will be studied and the data will be analysed.

- **Availability of software in the market**

  Software available in the market will be analysed to determine whether it is fully capable of taking the shape of MIM or whether it can be integrated as a part of the model. A software comparison will be done along with recommendations.

- **Conceptualization of the new system**

  After reviewing the current practices and software capabilities, a concept will be presented that will help understanding the problem with a possible solution.

1.9 Facilities required

The Wits Mining Institute (WMI) Digital Mine Laboratory has a facility of mock-up-mine in which different systems are installed for research purposes. This facility will be used during the research. For comparison and conceptualization of the MIM system, access to a database that contains market prices and software packages may be required.

1.10 Research outline

The research will be carried out as outlined below.

- **Current Chapter (i.e. Chapter 1 - Introduction)**

  In summary, the intent of the current chapter is as follows: It provides an introduction to the economics-related problems that the South African mining industry is facing. It explains BIM and how MIM will be helpful for the mining industry. It also explains the volatility in commodity prices and currency

exchange rates, and how they are affecting the South African Mining Industry. Furthermore, it illustrates why MIM is required, what are the research questions and objectives, and the research methodology to be followed for this research.

- **Chapter 2 - Literature review**

  This chapter explains current mine planning practices and identifies gaps in this process. A case study is used for identification of the gaps. The chapter also provides further understanding of IoT and Smart Economics, how these concepts can improve the mine planning process, and what countries like China and Australia and other institutions are contributing into this field.

- **Chapter 3 - Concept and methodology**

  Chapter three discusses software that is currently available in the market. It also identifies mining industry requirements and presents a comparison of what software enterprises are currently offering and how, and to what degree, this will meet mining industry needs.

- **Chapter 4 - Application of the concept**

  Chapter four explains how the new concept (MIM) will operate in the mining value chain and which MIM component will benefit which process. The chapter further explains the concept of 'decision-making aided by case-study'. The architecture of MIM and decision-making are also discussed in this chapter.

- **Chapter 5 - Conclusion and recommendations**

  This chapter extracts conclusions of the study. Considering the conclusions, recommendations are made for the future mine planning and optimization process.

1.11 Wits Mining Institute, Digital Mine and this research report

The Wits Mining Institute is one of the six 21st-century institutes of University of the Witwatersrand that is committed to achieve a zero-harm policy for miners. At

the same time, it is striving to enable the mines to achieve maximum production at optimal cost. The institute was established in 2012 with the name of Wits Mining Research Institute. The latter name was later changed to Wits Mining Institute to diversify the scope of research work. The institute currently focuses on underground mines with the following areas of research:

- Extension of surface technologies underground;
- Development of communication systems for the mines;
- Positioning, mapping and navigation;
- Real-time information management system;
- Smart decision-making;
- Remote access, visualization and inspection;
- Smart rock engineering (includes advanced numerical modelling of rock stresses to predict movement); and
- Risk mitigation.

Current research related to this document is aimed at developing a conceptual model for MIM, and will present an initial framework that will be combined with the other research topics of Digital Mine research group. The method of research in Wits Mining Institute is shown in Figure 1.9.

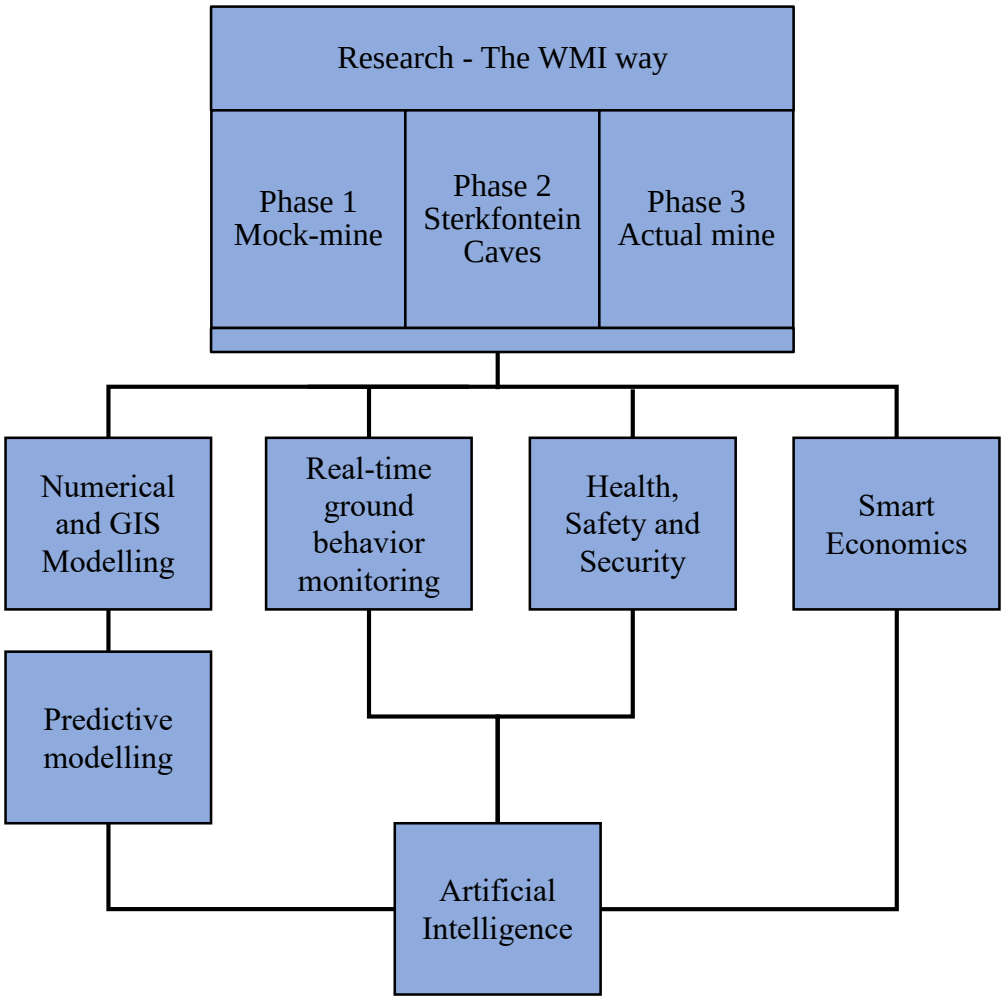


Figure 1.9 The WMI way of research
(Source: Author)

Research projects in Wits Mining Institute and Digital Mine are conducted in three phases. In the first phase, the project is prepared and tested in the Mock-up-mine. Following successful testing, it is moved to Sterkfontein Caves (which is a national heritage site) for further testing and examination. After successful testing in the two mining-like environments, the project is further matured to be applied in real-mining environments.

1.12 Conclusion

Chapter one provided an introduction of economic-related problems and the challenges that South African mining industry is facing. The chapter proposed that

the solution to these challenges lies in proper synchronisation of the mining industry with current market, using MIM. Chapter two will explain current mine-planning practices, together with a case-study that will identify gaps in the current practices. Included will be discussions on 21st-century concepts such as IoT and Smart Economics, together with what other countries and institutions are contributing towards solving issues.

2 LITERATURE REVIEW

This chapter provides understanding on terminologies associated with Internet of Things (IoT), decision-making and Smart Economics. The chapter also covers literature available on the topics and identifies gaps between what is currently available and what is required.

2.1 Overview

The recent history of mining in South Africa began in the 19th century. Since then, mining has supported significant elements of the country's economy. Initially, mineral extraction costs were not very high, the reason being that although mining techniques were not very advanced, the ore was relatively close to the surface and better in terms of grade. There was therefore not much need for optimisation. However, over time, ore closer to the surface was progressively depleted. Miners thus needed to be sent to greater and harsher depths at greater costs and lower ore grades. The effort and cost of extraction increased, decreasing the profit and necessitating the need for optimisation and integration of mining value chain.

Many South African industries were originally founded with the intent of supplying mines and their communities. Yet as technology advanced, some mining-industry aspects failed to progress at the same rate as some of the other industries. One of the most notable technological achievements in the history of mankind was reaching the moon in the late 1960s. Since then, technology has advanced into satellites, GPS, location monitoring and tracking, mobile communications, internet services, autonomous cars and drones. However, while many industries have included advanced technologies in their processes, the mining industry has been unable to apply some aspects (e.g. satellite positioning currently cannot operate in underground mining) and is struggling to find adequate formulae to optimise such processes in the mining value chain[8].

[8] This refers to economic and planning challenges that the mining industry is facing.

Most industries are now moving from working in silos to integrated and interactive systems. It is furthermore expected that the related information must be communicated and that this communication must be made accurately and in time. Moreover, software has been developed to enable modelling and pre-fabrication-testing to establish how products will behave in the real environment. Specific algorithms are now used by different industries to find out patterns of behaviour so that appropriate actions can be taken. For example, users' internet-surfing patterns are recorded and captured. Advertisements related to these patterns are then displayed to the user in such a way as to fit the user's best interest. The mining industry is still lagging, although several software packages are being used from exploration to final refined product and sales.

Some software companies are now offering integration of software and interoperability, but that is not sufficient for today's mining environment which requires much more for survival than just integration of software. For orebody extraction to be cost-effective and more profitable, concepts such as Internet of Things, Smart Economics, and Mining Information Modelling are required to establish what is inside the orebody and how its mining should be planned.

2.2 Internet of Things (IoT)

IoT is considered to be the third Information Technology wave after computers and internet (Yu-fang & Jin-xing, 2011). It is a concept where "Thing" is anything upon which a sensor can be installed to capture and transmit data. This data can then be collected by a computer, server, cloud, or smart-device in order to control or monitor. Monitoring and control could range from monitoring a patient's heartbeat to controlling a satellite or even a person sitting on a chair. Figure 2.1 shows a simple example of IoT, where information can be obtained from a sensor that is installed on a chair. This sensor can detect a person sitting down on the chair, with an RFID tag on the person providing identification. The same sensor is connected to the internet to provide live information. Such information can then be accessed from the software package on a laptop, iPad, or a cell phone. A typical example of using IoT in mining industry is Dundee Precious Metals Company (see section 1.5 of chapter 1).

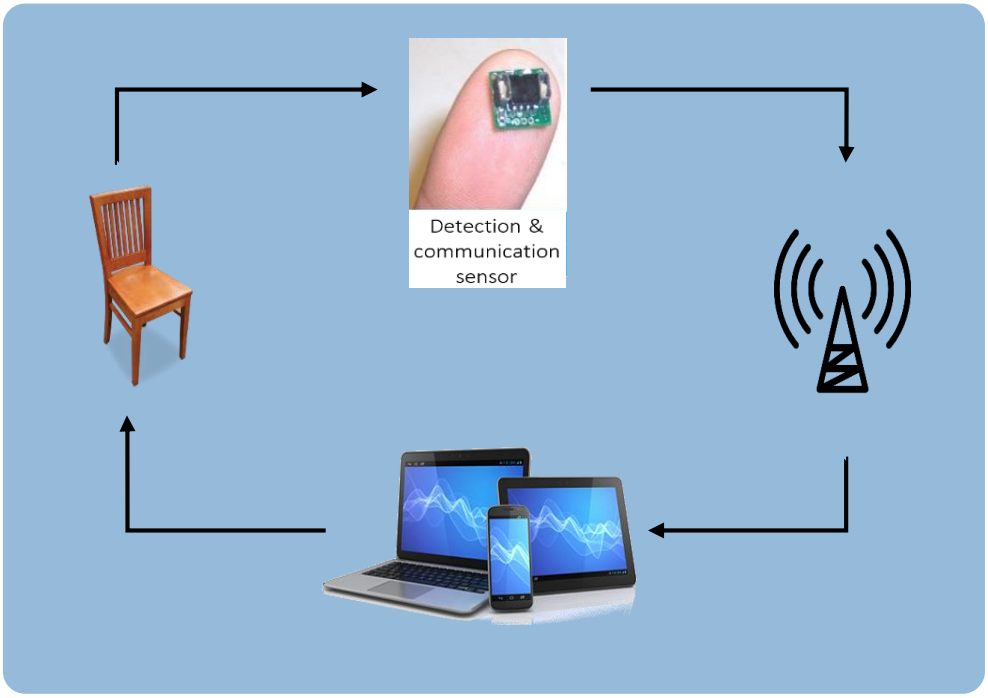


Figure 2.1 Simplest IoT architecture
Source: After *(Barrett, 2012)*

2.2.1 Benefits of IoT

The following are some of the benefits of using IoT (Merry, 2017)

- **Time saving**

IoT helps connecting equipment and devices and automatically generating data at one place. Furthermore, compared to manually-recorded data, IoT data is real-time and accurate. For example, many mines contain gas-detection devices which record gas-levels. If these devices are connected via IoT, the data will be transferred real-time to the control room or any other place where it is required. If these devices are not connected via IoT, alternate arrangements would need to be made, such as a person physically walking and collecting data from sensors, which would be time and resource-wasting.

- **Improved safety**

Real-time data-communication of dangers and hazards such as rock movement ensure improved safety. For example, if a support pillar is weakening and there is a chance of it collapsing, sensors can communicate it to the mine control room so that safety precautions can be taken. Similarly, if the braking system of a haulage truck has failed, IoT can transfer this information to the control room in real-time. Furthermore, it can inform people working around about the truck and stop its engine to avoid accident.

IoT is also used to keep track of the miners' locations. Systems are currently available which can track the location of a miner to an accuracy of a metre or less. Similarly, smart-helmets and mobile gas-detection instruments contain systems which use IoT for two-way communication. Such communication includes emergency messages to and from the mine control room and distress calls. Both capabilities are installed Wits Mining Institute's Mock-up-mine (see chapter 4 section 4.5.5 for discussions).

- **Maintenance**

IoT assists predictive maintenance by communicating information from vital parts of the equipment. For example, if there is excessive fuel usage in a mine-generator, a sensor will read and communicate the information to the control room. Included in the communication will be repair instructions, saving money and shut-down time of the equipment. Semi-autonomous and autonomous vehicles working in the mine can also be connected to the mine control room through IoT. Not only maintenance-related data, but also vital signs such as engine temperature, fuel levels etc., can then be communicated in real-time.

- **Energy and cost**

With IoT, more data can be gathered from equipment in the mine and then analysed. For example, mine-ventilation is potentially resource-consuming. Thus excessive ventilation can add substantial energy-usage and costs. This can be alleviated by connecting sensors to ventilation fans via IoT, and then communicating information to the control room so that necessary action (such as ventilation on demand) can be taken accordingly.

2.2.2 Industries using IoT

IoT is used in many industries, including agriculture. It could be argued that agriculture is a simple industry which therefore does not require advanced technology. However, farmers are using IoT platforms to obtain data, access their devices remotely and to obtain statistics on production and feed of their cattle. This is enabling the farmers to optimize their processes and earn more. Studies show that IoT-usage has caused average-yield-per-acre to increase by 1.75%, energy-cost to decrease by 30%, and water-consumption to decrease by 8%, and that the number of agriculture-aiding devices connected via IoT is expected to increase at a rate of 20% annually and rise to 75 million by 2020 (Meola, 2016).

Other industries using IoT include manufacturing, healthcare, transportation, retail and wholesale. Figure 2.2 shows IoT investments made by different industries in 2015. From smart homes to smart cities, IoT is becoming an essential part of personal life and business management. Its use and benefits are expected to continue increasing significantly over time.

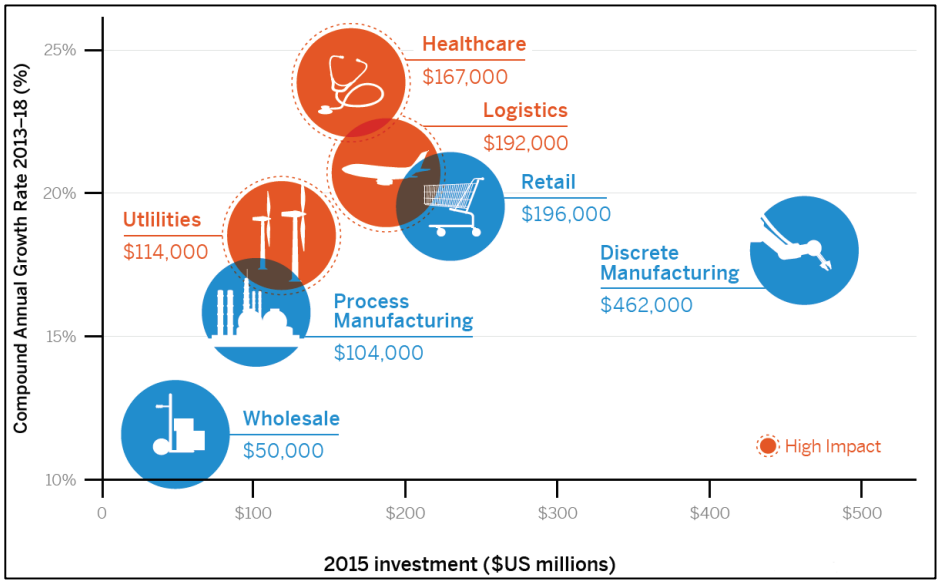


Figure 2.2 Investment in IoT by different industries (Goerlich, 2016)

2.3 Real-time – for the mining industry

The meaning of the words "real-time" holds different understandings in different areas of the mining industry. However, in industries such as aviation, real-time or real-time-information means data which is communicated at the same time as the incident or process is taking place. However, the timeline of real-time varies from system to system. Some examples of this variability are mentioned below:

- Radar system: few milliseconds;
- Chemical reaction: few seconds to hours;
- Weather forecasts: hours.

Real-time information in the mining industry requires to be well-defined. In some areas of the mining industry, real-time is considered to be the moment when the process is taking place, such as data of rock movement. Yet in other areas such as production, a delay of some hours may be referred to as real-time. Different meanings of real-time could also be related to the fact that real-time systems are still evolving in the mining industry. The industry is still in a transition of moving from conventional mining into fully-automated mechanised-mining-systems which usually require flow of information in real-time (at the same time). Therefore, there is a need of identifying the proper use of "real-time" for the Mining Industry.

2.4 Smart Economics

As introduced in chapter 1, mine planning for optimised cash-flows is generally done in advance for the next 3 or 6 months. Yet given the length of such timelines, forecast-factors that influenced the planning could change prior to actual execution dates. In volatile economies such as South Africa's, the effect of this could be more prominent. This necessitates need for an approach that enables real-time forecasting and decision-making. In this context, Smart Economics and Smart Decision-Making use digital and real-time information and allow the flexibility of making real-time planning.

The idea behind planning through Smart Economics and Smart decision-making is to connect the planning process with internet either through IoT or through any other platform such as MIM. Real-time information covering commodity prices and change in currency exchange rates from the market and their forecasts is then continuously fed into the system. If price-change then necessitates review of the production schedule, this can be done using Smart Economics. (However, constraints related to particular decisions would need to be considered – see Theory of Constraints and Decision-Making Process discussions in the later part of this report). In Smart Economics, the decision-making process is embedded in the system, and a dashboard shows current details relevant to making real-time decisions.

The Smart Economics concept therefore has the potential to bring change in the mine planning and optimisation process. Reduction and removal of uncertainty from the mining value chain through smart decision-making based on the real-time information will enable the mine planners to avoid loss due to uncertainty. It is expected that Smart Economics will provide full benefit to the mining industry once MIM is in place (it should be noted that many of these benefits are dependent on MIM).

- **Benefits of Smart Economics**
  - Smart Economics will help in using real-time values of currency exchange rate and commodity prices, optimising the profit and reducing the chances of losses;
  - Real-time economics information will optimise production planning; and,
  - Operational and strategic decisions made using real-time information will be significantly more accurate than decisions made in an uncertain situation[9]; and,

2.5 Costing for Smart Economics

Cost is explained by (Arumugam, 2012) as "The system of accounts which systematically and accurately records every expenditure in order to determine the cost of a product after knowing the different expenses incurred in various departments". There are several types of costs. However, two major types are explained below:

- **Fixed cost**

  Fixed cost (such as management-staff salaries, rents etc.) do not usually vary with production.

[9] The benefits of Smart Economics may vary in different stages of the mining operation.

- **Variable cost**

  Variable cost (such as cost of raw material, maintenance, repairs etc.) varies with increased or decreased production levels.

There are various methods of costing such as, Traditional Costing, Job Costing, Batch Costing, Process Costing and Activity Based Costing (ABC) etc. (Pristine, 2017). These costing methods are explained below:

- **Traditional costing**

  Traditional costing method generally assigns the overall cost to the total number of units produced. This often results in incorrect allocation of cost per individual unit. Consider the following example: A mining operation has two shafts (Shaft A and Shaft B). In Shaft A, the mining face is nearer to the shaft, whereas in Shaft B, miners have to travel to some distance to reach the face, thereby consuming time and other resources such as vehicles, fuel etc. The Shaft A's mining cost should therefore be less than that of Shaft B. However, the traditional costing method will apply the same cost to products coming from both the Shafts A and B, which will be incorrect.

- **Job Costing**

  In this method, the cost is assigned on the basis of work-order or job. Each job has its own requirement and specifications hence, different costs. Generally, this type of costing method is used for repairing and construction works.

- **Batch Costing**

  Batch costing is generally used by manufacturing industries such as garment and spare-parts manufacturers. In this method, the cost applies to a batch consisting of multiple identical units. Example: 100 units of a specific bolt were produced in a batch, with cost of production applying to the batch and not to individual units (unit-cost can be calculated by dividing the batch cost by the number of units produced).

- **Process Costing**

  This type of costing assigns cost to each individual process. It is used in cases where products go through multiple processes before finished product is obtained. The total costs of all the processes then become the total cost of the final product.

- **Activity Based Costing (ABC)**

  ABC assigns cost to individual tasks involved in any process (unlike Traditional Costing which assigns overall cost to all the activities). The benefit of ABC is that responsible parties can keep track of the most and least expensive activities involved in any process, together with the value-add of each activity. If the value being added and cost are not in the required proportion, the responsible parties can review the process and make necessary changes. For the mining industry, ABC is a better way of costing as compared to Traditional Costing (Lind, 2001). The steps to be followed for ABC are as follows (Drury, 2012):

  - Identifying activities in a process;
  - Assigning costs to each activity;
  - Selecting appropriate cost-drivers; and
  - Assigning the cost of activities to products (total cost of the process).

  Figure 2.3 shows a simple model of ABC for one of the processes in the mining value chain, i.e. "Mineral Processing". Generally, Mineral Processing consists of six stages called "activities" (these activities can be different for different mining operations). Each activity has a separate cost driver10 (e.g. the cost driver of last activity in the Figure 2.3, named "Disposal", could be "tonnage", namely weight of material which is to be transported to the tailings). Each activity will have a separate cost. The

[10] Cost driver is a factor that impacts the cost of any activity.

final cost of the whole process can be obtained by adding the costs of individual activities.

The concept of Smart Economics in this study also requires an ABC model which can calculate the costs of processes involved in a mining operation (by breaking down the processes into activities). The reason for suggesting ABC is that it is already smart and near to what is required by Smart Economics. The ABC linked to Smart Economics should have the capability to calculate the costs based on real-time information coming from the mining operation as well as the latest costs associated to each activity.

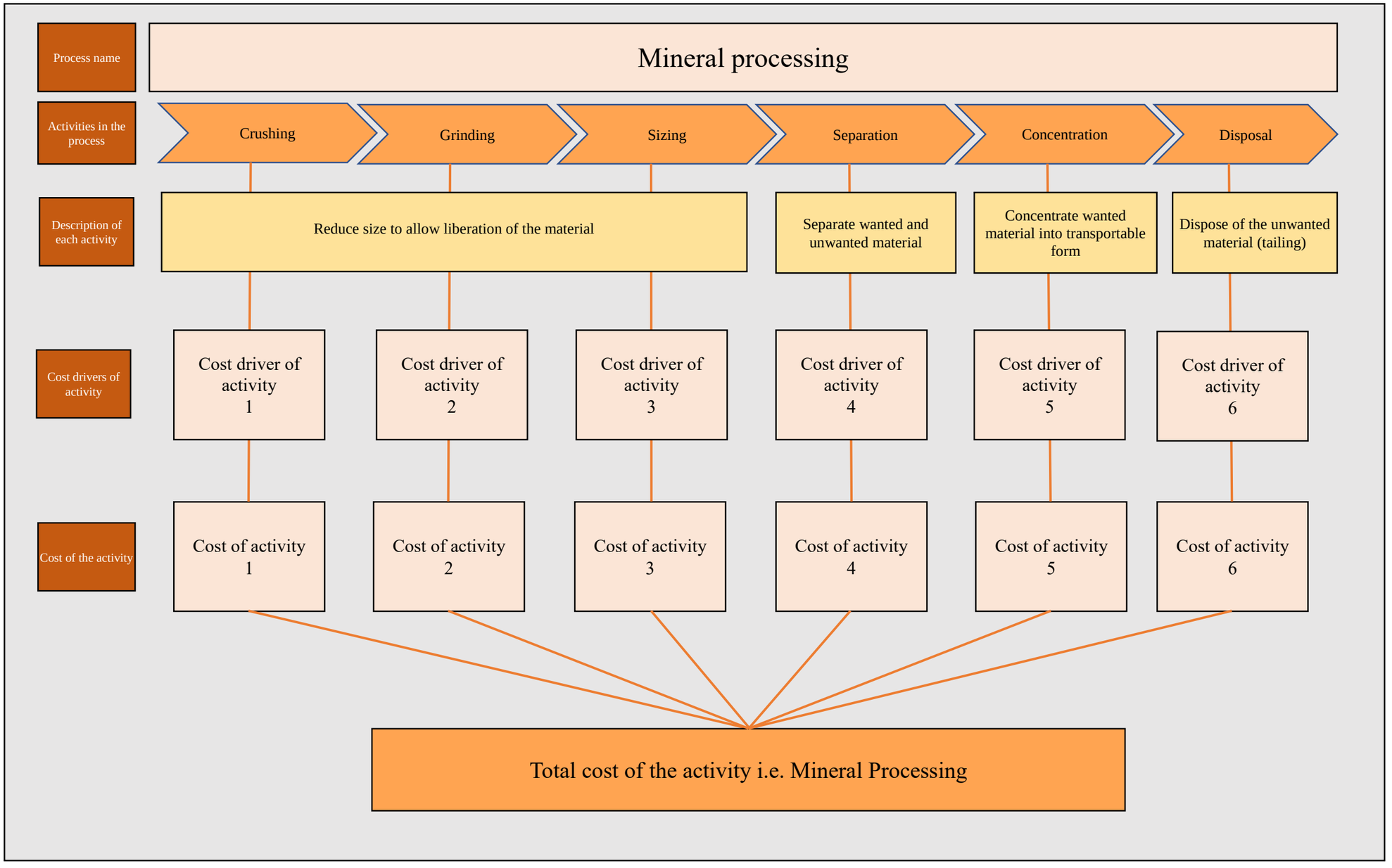


Figure 2.3 Activity Based Costing for Mineral Processing. After *(Wentzel, 2012)*

2.6 Decision-making

Decision-making may be defined as a process of analysing relevant solutions for a given problem, and then selecting the most appropriate one. In the routine life, there are multiple decisions that a person has to make. Whether taking small or big decisions, decision-making process is always intentionally or unintentionally working in a person's brain. However, professional and organisational decisions are often comparatively challenging to make and more brain-storming is required before taking such decisions.

There are three types of decisions at organisation or professional level as cited by (Srivastava & Teo, 2004) from (Anthony, 1965), namely Operational decisions, Tactical decisions and Strategic decisions. Operational decisions are generally short-term, based on what is currently happening, with the decision-making person being close to the problem. Tactical decisions are based on data coming from day-to-day operations and are generally concerned with how available resources can be used. Strategic decisions are long-term and organisational-based. The level of risk in Strategic decisions is often high, hence these are made by top management of organisations.

A decision-making model was proposed by (Ahmed, et al., 2014), as shown in Figure 2.4. According to this model, the first step in the decision-making process is assessment of the situation. After assessment, facts must be gathered and analysed. Following the latter two steps, the decision-making person should have enough information concerning the situation. This allows the person to identify alternatives and establish decision criteria, on the basis of which the decision is to be taken. In the next step, the alternatives are evaluated using the established decision criteria. Again, the best alternative must be selected and then finally, review of the decision has to be made. A similar kind of approach can be used in Smart Economics and Smart Decision-making processes – but in a much better and quicker way using real-time information.

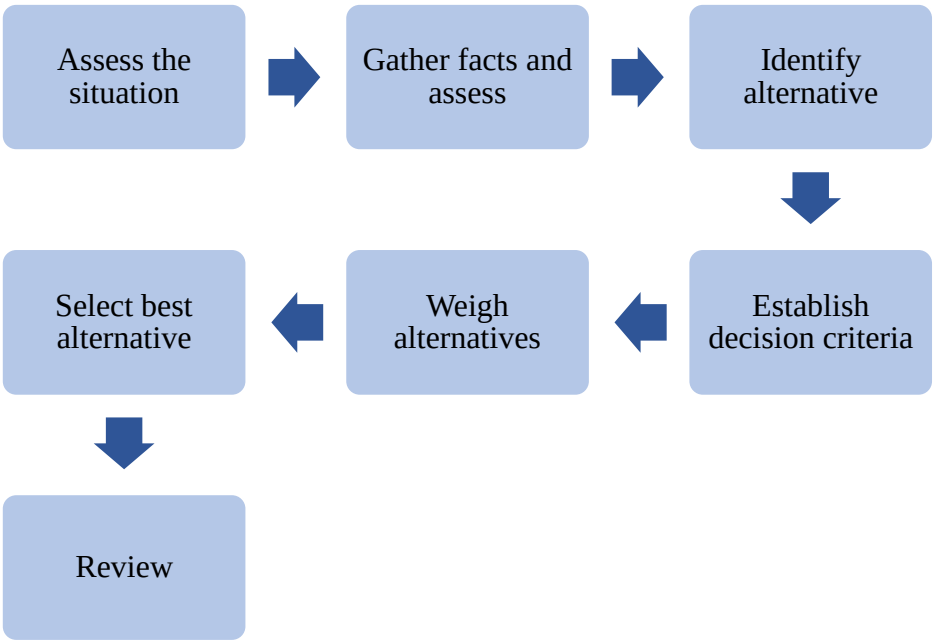


Figure 2.4 Decision making process
Source: After *(Ahmed, et al., 2014)*

2.7 Theory of Constraints (TOC)

TOC assesses constraints present in a system and how to deal with them such that they do not become a bottleneck. (Cox & Schleier, 2010) explains it as "TOC says that constraints (anything that limits a system from achieving a higher performance versus its goal) determine the performance of a system and TOC provides methods for efficiently and effectively utilising these constraints". According to the TOC, every system must have at least one constraint or else it will be able to produce an infinite number of units[11]. There are different types of constraints depending upon the industry. For example, manufacturing companies may have constraints related to plant-input-capacity or raw-material; mining companies may have constraints related to extraction or plant-capacity or market-demand; etc. Some constraints that a mining company may face are depicted in the Figure 2.5.

[11] Units refer to what is produced in a process. This varies from industry to industry, such as for petroleum industry, it can be litres, and for mining industry it may be metric tons etc.

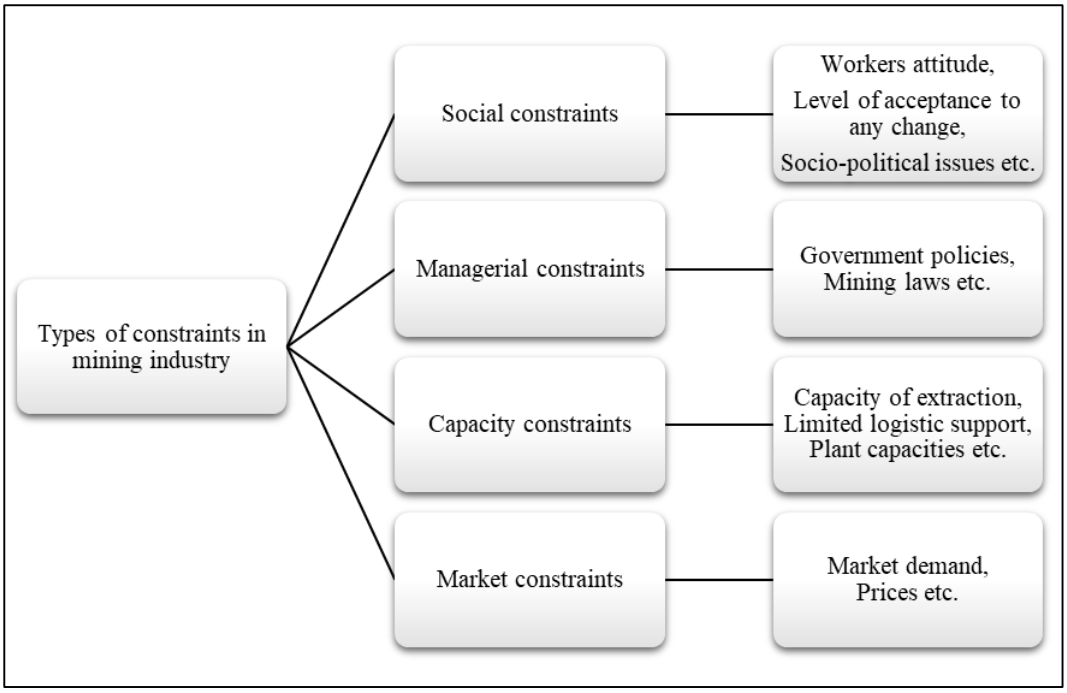


Figure 2.5 Example of constraints that can exist in the mining industry

Five steps were identified by (Goldratt & Cox, 2004) to effectively deal with the constraints present in any system. These steps are explained below (Kettering University, 2016):

- **Identification of constraint**

  This step involves the identification of the constraint in the system. This will be the "weakest link in the chain" and can either be a physical constraint such as machine-capacity, or it can be related to the policy framework of the organization.

- **Decide how to exploit this constraint**

  The next step is to make a decision on how to deal with this constraint. At this stage, in order to avoid expensive upgrades and time-consuming changes in the system, it is sometimes (according to the constraint and the system) decided to utilize the equipment or the system at its full capacity so that the constraint can be addressed.

- **Subordinate everything else to the above decision**

  At this step, the focus is kept on the decision made to deal with this constraint. All the remaining factors are kept aside or more specifically, adjusted according to the constraint which is being addressed.

- **Elevate the system constraints**

  Necessary actions to eliminate the constraint is taken at this step. Major changes are carried out in the system to eliminate the constraint.

- **Repeat if any constraint is broken**

  The last step involves the review of the previous steps. The whole process is reviewed in this step to make sure that the whole system is working fine and that addressing one constraint does not affect the system or create another constraint.

TOC is extensively used in improvement and optimisation of systems. It also supports decision-making processes. The Smart Decision-Making process explained in chapter 4 also needs TOC embedded in the process so that it can support the process using real-time information. Yet currently, it seems difficult to have TOC embedded in the process while simultaneously working on its own. However, it can be made possible through the development of MIM.

2.8 Geographical Information System (GIS)

GIS is explained by (Folger, 2009) as, "A digital database in which information is stored by its spatial coordinate system, which allows for data input, storage, retrieval, management, transformation, analysis, reporting, and other activities". It also helps in analysing the patterns and relationship between variables and aids decision-making. Typical benefits of GIS include better decision-making, better communication due to visualization, and improved efficiency.

Figure 2.6 shows the data layers of GIS and their integration, where the first layer of information is street data (i.e. map). The second layer provides information on buildings on the map. The third layer provides data on vegetation in the area.

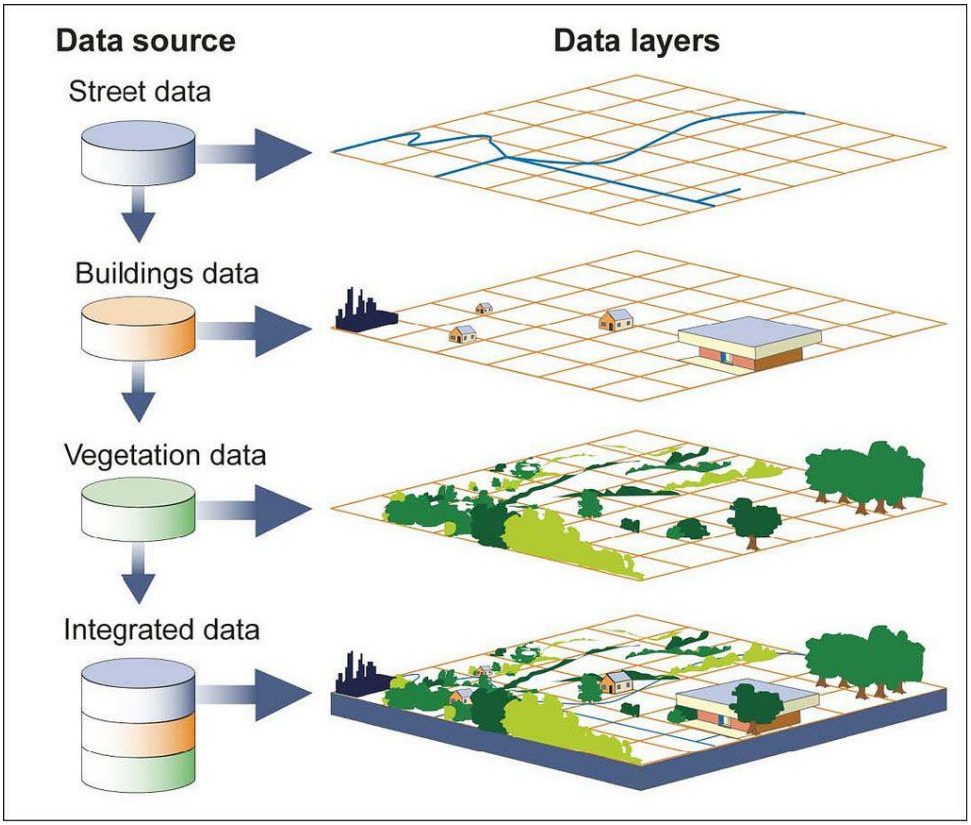


Figure 2.6 GIS data layers and integration *(Folger, 2009)*

The fourth data layer integrates the above three data layers in order to aid understanding of how the individual layers affect and relate to one another. Various things can be done with the help of this information, such as installation of street lights, construction of sanitation systems, and other development projects.

The objective of the above discussions is to assess whether GIS can also be used to serve the purpose of MIM. As seen in Figure 2.6, combining data layers provides complete information about the area. Similarly, for the mining operation, data can be spatially arranged to provide information about the mining operation. However, this would only provide pictographic information of the mining operation. Other aspects such as mine planning and scheduling, budgeting and costing etc. will need to be done using applicable software. Thus GIS will be of limited help, not fully working towards a MIM for the mining industry.

2.9 Similar research

Research work in the similar domain is being conducted in terms of optimization using digital systems and IoT. Some prominent work is mentioned in the following paragraphs.

2.9.1 Ernst and Young (EY)

Ernst and Young (EY) is a global accounting firm that provides consultancy services to multiple industries, including mining and metals, oil and gas, power, consumer products, media and communication, etc. EY has their own research groups for innovation and new technology. In a research survey, EY conducted a webcast poll on digitisation in the mining industry involving 700 participants. The result of the poll shows that 84% of the participants are already considering or planning to consider "digital" as a part of their daily operations. In another survey, conducted to assess where the digitisation of the mine falls in the agenda of mining professionals, it was found that 31% of the participants are already using it while only 15% participants are not considering it at all (Walker, et al., 2017). However, although "digitisation" has a bright future and can change the future of mining, there are still impediments in its implementation, such as lack of high-level support, wrong perception of cost, cultural difficulties, and misunderstood maturity-level of digital systems.

To bridge this gap and avail future opportunities in the mining industry, EY and its member firms have developed a tool named Digital Navigator (Walker, et al., 2017) – see figure 2.7. This tool enables EY to assess what digitisation is already in place in an organization, what would be required, and the current "digital" maturity level of the client organisation. Through this assessment, EY then produce a road-map for digitisation, keeping in view the organisation's capabilities, investments and strategy. Digital Navigator can thus assist the mining industry to move from conventional methods into complete digital mining, therefore addressing both current and future needs while contributing to MIM development.

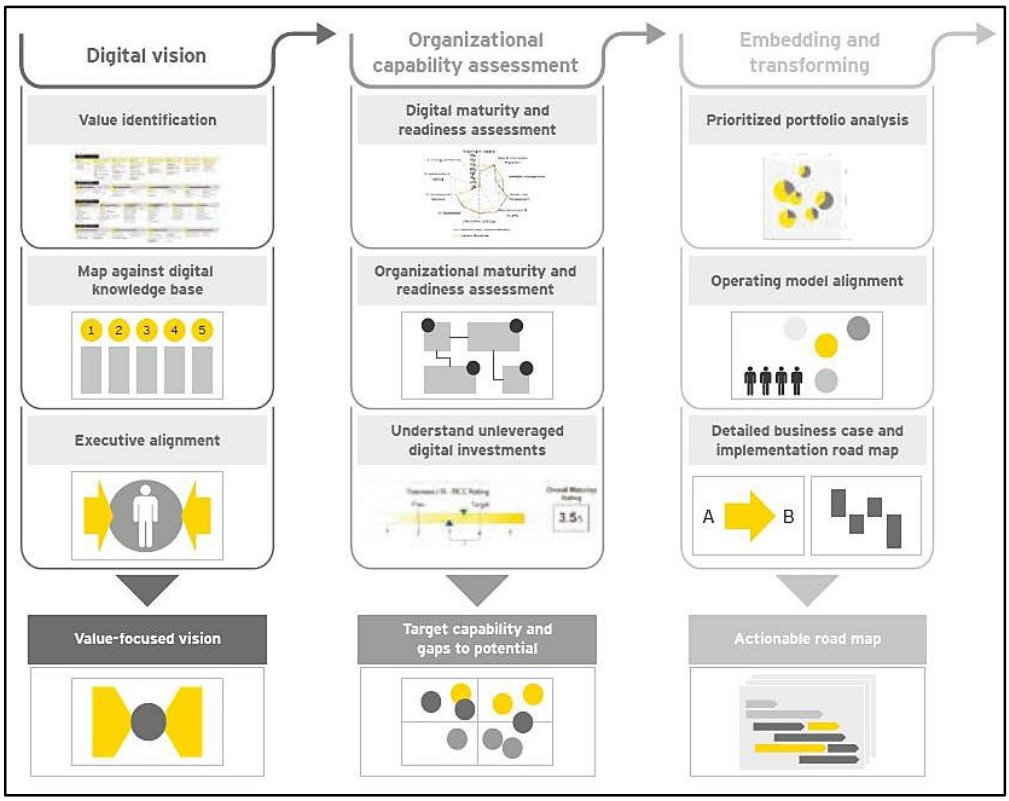


Figure 2.7 EY's Digital Navigator *(Walker, et al., 2017)*

2.9.2 International Business Machines (IBM)

IBM is a global and leading manufacturer of computers and computer-devices with extensive expertise in hardware and modern-day technological innovations. An interesting aspect is that IBM has been working on data analytics for several years. This is particularly relevant in context of IBM's provision of business solutions to multiple industries, including mining and metals, automotive, agriculture, asset management, smart cities, health and medical care, environment, construction, cyber security, manufacturing and robotics.

IBM has developed a tool named Watson (High, 2012), which consists of a set of "Application Programming Interfaces" (APIs) and "Software As A Service" (SAAS). The basic purpose of Watson is to collect data, analyse and observe patterns, and predict future behaviour. In the mining environment, Watson can help in many ways, such as gathering data from underground loaders, drawing and understanding patterns, and predicting the maintenance schedule. It can also suggest how mine production can be optimised to provide more advantage with less

maintenance. In Smart Economics, Watson may gather prices from the market, predict future trends, and provide suggestions on how to optimise mine production according to commodity prices and currency exchange rates.

2.9.3 Australia and Commonwealth Scientific and Industrial Research Organization (CSIRO)

CSIRO Australia is working on future digital mining and has developed the following projects. Although these projects are small-scale and are not directly related to MIM, they provide an understanding on how CSIRO is addressing 21st-century mining challenges, thereby working towards digital mining and saving resources.

- **Optimisation of transportation**

  Rio Tinto in Australia owns the largest private railway network (over 1500 kilometres) and covers 14 mines. This transportation system transports high-grade and low-grade ore separately – either to live stockpiles which are a part of the production line, or to bulk stockpiles. The challenge in this project was to optimise this complex transportation system, thereby ensuring that the correct ore-type goes to the correct place. Planning of such originally took 5 to 6 hours and was carried out manually. There were almost 80 000 variables and 50 000 to 60 000 constraints involved in the planning process. To simplify this complex process, CSIRO worked with Rio Tinto and developed software for optimisation. As a result, planning was reduced to 15 minutes, and the efficiency of transportation increased by 0.5 million metric tons (CSIRO, 2016).

- **Fast grade drill hole analysis**

  In this project, the challenge was to reduce the cost of diamond drilling. CSIRO, along with their partners, invented a tool named FastGrade for bore-hole analysis in real-time. This tool generates neutrons along the drill hole and data is captured and logged with the help of these neutrons. As an outcome of

this project, the client saved more than $10 million USD in 2014-15 (CSIRO, 2016).[12]

- **Rapid Ore Sorting**

  The world's high-grade ore deposits are depleting continuously. New deposits are comparatively lower in quality, which sometimes makes the extraction non-feasible. To solve this problem, CSIRO has developed a sensor-based system for large-scale ore sorting. The sensor uses radio pulses to assess the ore grade and this is done along the production conveyor in consecutive sections. Ore carried by each section of the conveyor can either be sent for production or can be rejected according to the data received from the sensor. The trial of this technology was done successfully and it is expected that it could improve the productivity by 20%. It is also expected that with the help of this technology, annual carbon dioxide emission will be decreased by 33 000 metric tons, and water consumption will be reduced by 15% (CSIRO, 2016).[12]

- **Rio Tinto in Australia**

  In 2008, Rio Tinto in Australia launched a program called "Mine of the Future" (Rio Tinto, n.d.). The aim of the program was to find advanced ways of extracting ore from underground orebodies at greater depths with improved safety. Under this program, an operations centre was established through which an entire operation could be monitored, from one location, in real time. Combined with this was real-time information-flow, which enabled Rio Tinto to optimise the entire operation, from mining through to maintenance and logistics. Figure 2.8 shows the control centre of Rio Tinto in Perth, Australia.

[12] Although these projects are not directly related to MIM, they are saving costs— which is the ultimate goal of MIM and Smart Economics. The reason for listing these projects in this research report is that they identify how small technologies can save considerable resources. This, in turn, identifies huge impacts that can be made while working towards MIM and Smart Economics.



Figure 2.8 Rio Tinto control room in Perth, Australia *(Reed, 2014)*

In the same operation, Rio Tinto installed Autonomous Haulage Systems (AHS), making Rio Tinto the world's largest autonomous-haulage-truck operator, with 69 trucks in the fleet. AHS improved productivity, efficiency and safety in the logistics operation. In 2008, Rio Tinto also tested an autonomous drilling system, which aims to replace conventional drilling. In the railway system, Rio Tinto used AutoHaul technology, through which locomotives were made autonomous. AutoHaul increased the capacity of the logistics operation without investing in additional trains. In 2015, these trains were successfully tested and controlled through the control centre. This enabled Rio Tinto to apply for regulatory approvals in 2016 (Rio Tinto, n.d.). Rio Tinto's control room (shown in the Figure 2.8) provides an example of MIM potential, where real-time information from all areas of the operation flows into the control room and makes decision-making easier, thereby optimising the operation and saving cost.

2.9.4 China

China is one of the countries of the world that is seriously considering digitisation of the mining industry. This digitisation is not only being considered in the private sector but also in government-run mines. The impetus is initiatives to make mines technologically more advanced and safer to work in. The government of China

made it compulsory for the coal mining industry to implement state-of-the-art, coal-mining safety systems. This initiative is a part of their 12th five-year plan (2011-2015) in which mines are required to address their problems with the collaboration of universities. The seriousness of Chinese government can be assessed from the fact that the government closed approximately 4800 small coal mines due to dangerous working conditions (Chadwick, 2007).

China Shendong Energy Company is China's largest coal producer. The company automated their mining, excavation and transportation processes in such a way that it enabled one person to control multiple systems such as ventilation, transportation and power supply. Figure 2.9 shows the operations monitoring and control centre of Shendong's Jinjie coal mine.

Thus in 2005, the production of raw coal of Shendong coal mines was 90.7 million metric tons[13], with a production efficiency of about 11 500 metric tons[13] per worker per year, and an efficiency per worker per working day of about 108 metric tons[13]. Furthermore, for Halagou coal mine of Shendong, the production efficiency was 170 metric tons[13] per worker per working day, the latter being approximately 4.5 times the average of coal mines in USA at that time (Wu & Che, 2008).



Figure 2.9 Operations monitoring and control center at Jinjie *(Jianguo, 2015)*

[13] Conversion factor applied (1 metric ton = 1.1 US tons).

More than a decade ago, the importance of using advanced tools in mining was realised and its implementation resulted in enormous impact on production. At that time, there was no access to IoT, and Digital Mine was an emerging concept. Today, IoT sensor-based systems, far better communication, and multiple software solutions are available. Use and implementation of technologies collectively can result in huge benefits for the mining industry of South Africa and the rest of the world.

2.9.5 South African Mining Extraction Research Development and Innovation (SAMERDI)

"South African Mining Extraction Research Development and Innovation" (SAMERDI) is a joint initiative of South Africa's "Council for Scientific and Industrial Research" (CSIR) and the South African mining industry. It has its roots in the Mining Phakisa process. CSIR is a research-based organisation, with one of its initiatives being improvement and betterment of the mining industry in South Africa. "Real Time Information Management System*"* (RTIMS) is a project under SAMERDI in which the capabilities of the mining industry for real-time information will be enhanced. The idea is to have maximum certainty at every point of the mining operation, from mine-face to board-room. The following fifteen work packages will be executed during this program:

- RTIMS landscape and enterprise architecture;
- Industrial Internet of Things (IIoT);
- Underground communication systems for sensors, actuators, real time control, monitoring and vision systems;
- Deployment of stope communications, positioning and strategies for when the stope moves;
- Positioning systems (visual and electromagnetic);
- Definition of scenarios for RTIMS deployment based on mine types versus mine lifetimes;
- Use-cases and literature review for selected use cases;

- Determination of a research test site for communications, testing and to define adaptable platform requirements;
- Data science architectures and reference implementations;
- Modelling, simulation and visualization requirements;
- "Cyber Physical System" (CPS) control, monitoring, management and alarms;
- Build / integrate demo RTIMS components;
- Test RTIMS and selected use-cases in underground site;
- Liaison and logistics for RTIMS; and
- Project management of these work packages.

All these work packages are directly related to real-time information which is transmitted to a central server and from there, displayed on a common platform for better visualisation and enhanced control. Figure 2.10 shows the timelines of SAMERDI projects aimed at developing a "modernised mine". This research report falls under Figure 2.10's RTIMS thematic area. In summary therefore: The goal of this report, RTIMS and other thematic areas depicted in Figure 2.10, is a modernised mine with all necessary information communicate real-time for decision-making and other purposes.

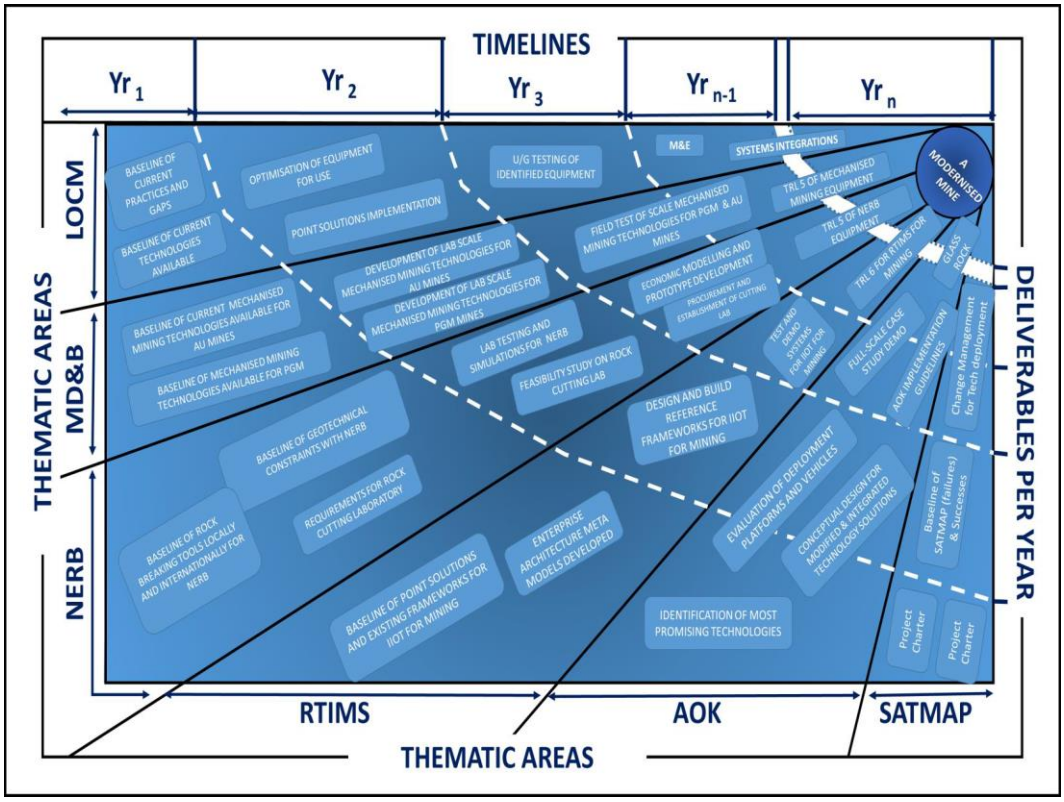


Figure 2.10 SAMERDI project timelines *(Singh & Macfarlane, 2018)*

2.10 Anglo American Platinum Mogalakwena mine – A case study

Mogalakwena platinum mine is situated in Waterberg district of Limpopo province, South Africa. The mine was established in 1993 and is owned and operated by Anglo American Platinum. It is the largest open-pit platinum mine in the world (Anglo American Platinum, 2015). While the major product of the mine is platinum, it also produces nickel, gold, palladium, rhodium, iridium and ruthenium. The production of the mine was increased by 3% due to strong plant recoveries in the first quarter of 2017, and is reported to be 111 900 ounces of Platinum Group Metals (PGM). The value chain of Mogalakwena mine includes extraction of ore, processing, smelting and sales. The product is sold per client-requirements of metal type and grade. The grades are divided into 3 categories namely High grade (HG), medium grade (MG), low grade (LG) and very low grade (VLG). Different proportions of the ore are mixed and blended to achieve the desired quality of the required product. VLG is generally stock-piled to be used after the life of mine.

Figure 2.11 shows the current location of blasting and extraction at Mogalakwena mine.



Figure 2.11 Current location of mining at Mogalakwena (Source: Author)

The mine uses different software packages for different purposes. No single software package is available that is able to cater for all of the mine's needs. Thus information developed in one software package needs to be fed into other packages, thereby wasting time and resources. For example, the software package used for designing is Datamine, and for scheduling is Comet. If an integrated software package is developed for scheduling and designing, there would be no need of importing data from one to the other. This would save time and be more interactive to the user. Figure 2.12 below shows software used by Mogalakwena mine and related issues:

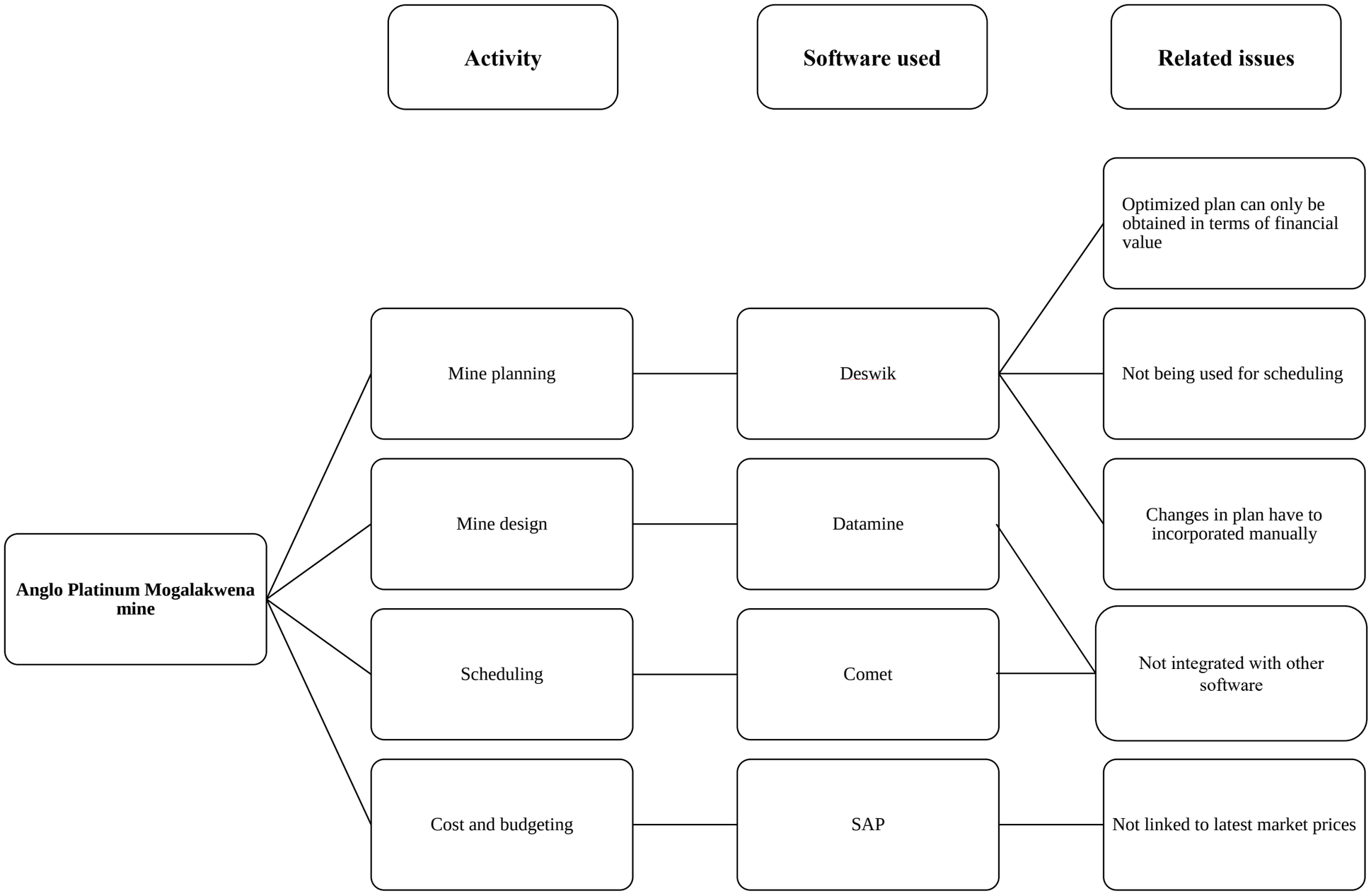


Figure 2.12 Software used by Mogalakwena mine and their associated issues (Source: Author)

Deswik software is used for mine planning purposes[14] at Mogalakwena mine, but not for scheduling. Time is therefore also wasted in having to run more than one software package to create an optimised mine plan (Deswik for mine planning and Comet for scheduling). Furthermore, changes in the plans are manually incorporated in the system. This wastes considerable amount of time, resources and is also prone to human error. Moreover, the optimised plan obtained from the software is improved in terms of financial value only. The reason is that the software considers financial planning information for optimisation, and not for overall mine planning[15].

Deswik is also not linked to current market for prices, so it cannot consider market trends and currency exchange rates. Thus, although Deswik is capable of processing multiple years of planning, market prices must be fed manually into the software. The forecast of prices is therefore also manually fed into the software and is only considered while doing planning. Production therefore cannot easily be optimised according to forecast-prices of the market. Another issue in using multiple software packages is added training costs.

For budgeting and costing, SAP[16] is used. However, figures generated in the software are presented to the chief mine planner in the form of spread sheets, and this is done only once a year. Costing and cash flows are therefore only prepared once a year with no planning being done during other parts of the year. One of the reasons for this is that the planning process consumes so much time that repetition is not feasible. The time consumption is also a built-in weakness of the software's capability and the capacity of the system that is being used.

[14] Author is not at the mine; limited information was provided by the mine.

[15] The purpose of this case study was to analyse the software being used in mine planning phase and their associated challenges. Construction industry is using BIM (as all-inclusive one package) which is proved to be substantially beneficial (as discussed in chapter 1). This research is at the initial stage of working towards MIM therefore, it seems difficult to have all-inclusive one package. But with continued research and bridging the gaps, MIM can be achieved.

[16] SAP is an enterprise resource planning software developed by SAP SE.

Besides the above-mentioned issues, some aspects of proper infrastructure-planning may be lacking. Poorly-planned infrastructure may therefore impact the production cycle and affect the output of individuals working in the mine. For example, high voltage cables for electric shovels run alongside the haulage route (these cables are rolled and unrolled by a specialised vehicle). During operation, if a truck on the haulage route accidently changes its path and runs over the cable, there may be following consequences:

- Worker-safety compromise;
- Loss of expensive cable; and
- Loss of production hours since shovels will not be able to work without power.

Furthermore, at Mogalakwena mine, stockpiles have increased with the passage of time. With the growing size of the mine, there is now a requirement of moving these stockpiles away from the mine. The relocating of these stockpiles will now cost the mine additional resources in the form of time and money. If the extension of the mine had been anticipated earlier, there might not have been a need to dump these stockpiles[17].

This case study strongly suggests that a single software package should deal with all the requirements, including mine planning and design, scheduling, cost and budgeting etc. Although it seems difficult at this stage, this should not be a barrier to working towards MIM. At this early juncture when the mining industry is still working towards "Modernised mine" (as mentioned by CSIRO), an all-inclusive software package may seem like the idea of driverless trucks, which, a short while ago, seemed an impossible dream, yet today is being used by Rio-Tinto in its Australian operations (Vella, 2013). Also, without BIM, which is all-inclusive package, the construction industry might also have had trouble figuring out best practices for optimisation. But since the development of BIM, its benefits to the

[17] Quantifying the loss is difficult due to the limited information available from the mine. However, if the mine had anticipated extending the mine and had therefore dumped the stockpiles further away, further transportation would certainly have increased cost. However, this additional cost would have been far less than the current cost of relocation which necessitates other activities such as loading etc.

construction industry are being made obvious by case studies mentioned in chapter 1.

Thus similarly to BIM in construction industry, MIM will not only reduce mine planning time but it will also make it easier to interact and communicate along different stages and departments of a mining operation. For the platinum industry, the market is constrained and limited. Thus it is unlikely that the mine could earn more by simply increasing production, since this could saturate the platinum market. Mines therefore need to produce only what is required by the market – taking into account the lead-time during the mine planning phase. However, as indicated in earlier discussions, process optimisation could increase savings and profits. Such optimisation will be simpler for open-pit mines than underground mines, the reason being that open-pit mine operations are less complex than underground mine operations.

Thus more optimisation will be required for underground mines, where miners face harsh environments, difficult transportation systems and multiple health and safety issues. Furthermore, a great deal of time is wasted in travelling from shaft to face. Infrastructure planning is also difficult in underground mines: Water, electricity, transportation system, etc. need to be there and should be in perfect condition. The planning for such must therefore be done in advance. Thus usage of intelligent software will assist accuracy and speedy adjustment if new factors appear. Obvious benefits of MIM include:

- Mines will be able explore their full potential;
- Wastage of resources due to inadequate planning will be controlled; and
- MIM will help the mines in long term operations and sustainability.

2.11 Risks of non-implementing a MIM approach

2.11.1 The Mining industry, unemployment and worker unions

Concepts like MIM and Smart Economics are supposed to optimise the mining operation thereby enabling the mines to cut down costs and earn more. The survival of mining industry without these concepts will be hard. If the mining industry does not grow, there will be serious consequences such as unemployment. The unemployment rate in South Africa was reported to be 27.3% in 2016 (which was the highest in 12 years), with an estimated youth-unemployment rate of 50%, and an estimated Gini coefficient[18] of 0.69 (World Bank, 2017). The latter Gini coefficient shows that there is a situation of inequality in the society. (In the 1900s when the situation of inequality was widespread, mine workers union was established in 1910 to safeguard the rights of mine workers (Bhorat, et al., 2014). The purpose of creating worker unions was to negotiate better wages and other basic rights.

Negotiations worsen when worker demands are high and mine management is unable to fulfil them. This situation sometimes leads to strikes which cause production losses for the mine. In 1987, mine workers demanded 30% increase in wage along with their other demands for the year 1987-1988 (Davenport, 2013). These demands were not accepted by the Chamber of Mines. The National Union of Mine Workers (NUM) then initiated a strike on 9th August, 1987 which continued for almost 3 weeks. During this strike, 9 workers were killed, nearly 500 were injured, and 1.3 million working days were lost, which was significant (Davenport, 2013).

Such situations are unwanted and create problems for both mine management and workers. Yet with the mining industry not growing, incidents may increase together with associated affects upon labour-sending areas. These concerns should

[18] Gini coefficient measures income inequality in a society, where Gini coefficient 0 means least inequality and 1 means most.

therefore provide further impetus to shifting from conventional tools to MIM and Smart Economics.

2.11.2 The Mining industry and the government

Another risk of not considering MIM approach is that the government may start losing taxes and royalties if the mines are not profitable. Also, mines will find it difficult to invest in new mines if the existing mines are not profitable. In 2015, the South African mining industry contributed R286 billion towards Gross Domestic Product (GDP), namely 7.1% of total GDP (Chamber of Mines of South Africa, 2017). The South African economy is already in crises therefore another setback may worsen it, suffocating job retention and new-job creation.

While considering the economics of the mine, it is also important to consider potential costs of non-compliance to government regulations. Mines are required to annually report their level of compliance with the Mining Charter (Department of Mineral Resources, 2016). The Mine Health and Safety Act of 1996 also states in section 2 (1), clause (c) that mines are supposed to submit a report on health and safety conditions of the mine. Periodic visits to mines are conducted by mine inspectors to ensure the level of compliance. Mines may be charged with heavy penalties if they are found to be noncompliant. In the worst case, a section of the mine or the whole mine might get closed over noncompliance. Such a situation will have adverse effect on the economic planning of the mine. Considering health and safety issues, such as proper mine-ventilation, is required for working-areas of the mine[19]. If the ventilation is not according to requirements, the Mine Health and Safety Inspector may impose Section 54[20] of Mine Health and Safety Act. Under this act, the Inspector has authority to halt mining operation in that area of the mine.

---

[19] Although health and safety issues are not directly related to optimisation of a mine, they affect the economic planning of the mine. Hence, this example is presented to understand how MIM will also help in health and safety issues.

[20] The Section 54 of the Mine Health and Safety Act 1996 states that "If an inspector believes that any occurrence, practice or condition at a mine endangers or may endanger the health or safety of any person at the mine, the inspector may give any instruction necessary to protect the health or safety of persons at the mine" (Department of Mineral Resources South Africa, 1996).

Obviously, this will affect mine planning, production and profits, which will subsequently cause the government to also lose revenue. Since it is expected that MIM will ensure that ventilation requirements of an area are according to mine design, not only will it protect the safety of employees, but it will, in turn, save the mine from non-compliance thereby protecting both government and the mine from associated revenue losses.

2.12 Literature findings

In mine planning and optimisation, most institutions and companies are generally working on optimising one or two processes – which is not enough. Such is also the case with real-time information. Most of research in the latter area is being done in specific areas, such as collection of the data of truck loads from in-situ to stockpile. It is good to have real-time information at any point in the mine as long as value is added with this information. But this information is not helpful until there is analysis on this data and a smart decision-making process follows this analysis.

In open-pit mines, the major focus of optimisation is generally the transportation system. Yet if the transportation system is optimised completely, and there is a constraint in other processes such as stockpiling or processing, optimisation of only one process may not provide much advantage: As stated by a famous proverb, “A chain is only as strong as its weakest link”. Thus the efficiency of a whole mining operation may be limited to its weakest process.

The gap found during this literature review is that not much attention is being paid to how to optimize the whole mining operation and how to bring the complete mining operation into one software package. Smart Decision-making using real-time information is also a gap which must be addressed for processes that will benefit from real-time information.

2.13 Conclusion

Chapter 2 provided insight into current mine-planning and optimisation practices. The chapter also discussed available literature on the topic, including information on what others are contributing to optimisation using modern technologies. Finally, chapter 2 identified the gap between current practices and the requirement. The next chapter will cover the concept on how this gap can be bridged.

3 SOFTWARE CONSIDERATION FOR MIM

This chapter identifies suitable software options for MIM. Two leading software providers in South Africa are considered for this purpose and their software capability is explained, followed by a comparison. Using BIM as a basis, the chapter then analyses gaps between the software and proposed MIM and draws a conclusion.

3.1 Overview

Implementation of MIM in the mining industry is recommended for continued profitability and cost-effectiveness in 21st-century mining. One approach to attaining the model would be to use BIM learnings as a basis for developing new software for mining. A second approach would be to use a customised combination of existing software packages. The resultant model could then be linked with IoT for smart decision-making.

The second approach may be more attractive for a number of reasons. One reason is that marketplace-usage of existing software generally forces suppliers to correct faults and make it more reliable. Another reason is that additional costs of new software may not attract many users of existing software. This research report therefore reviews software available from two leading software enterprises in South Africa, namely MineRP and Datamine[21]. This review will assist assessment of gaps between what is available and what is required for MIM.

3.1.1 Optimisation software package

The Optimisation software package is a combination of eight subset packages (referred to as building blocks), namely: SpatialDB, SpatialDash, SpatialAnalyzer,

[21] Review and comparison is based on the claims of the respective companies.

MineRP CAD, Mine2-4D, EPS, IBM ILOG and IBM CPLEX, as shown in Figure 3.1 and discussed below.

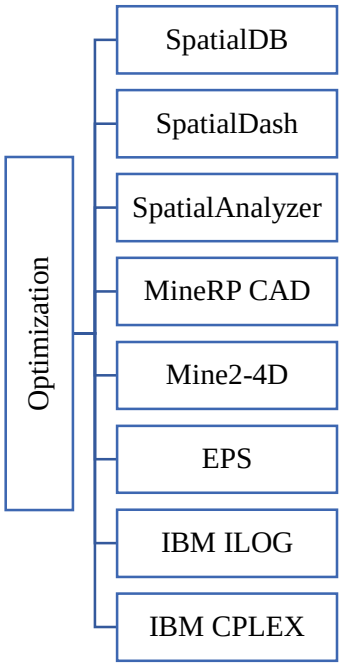


Figure 3.1 Building blocks of MineRP Optimization
After *(MineRP, n.d.)*

- **SpatialDB**

  SpatialDB is a data storage platform which enables the user to use and store data. The integrated nature of SpatialDB allows storage of scientific as well as technical data-sets. It also permits the users to use data for either a single mine or for a global operation.

- **SpatialDash**

  SpatialDash is a dashboard application for the visualisation of Key Performance Indicators (KPIs). It allows all the data to be viewed spatially at one location.

- **SpatialAnalyzer**

  SpatialAnalyzer is a web-based application used for visualization and analysis of spatially-related data. It also allows 3D animations of the data for better visualisation.

- **MineRP CAD**

  MineRP CAD is a Computer Aided Design tool which serves as building block for Optimisation solution. Along with CAD capabilities, added advantage of this tool is that it provides integrated view to all data sets. It also interacts directly with SpatialDB for multidisciplinary data sharing.

- **Mine2-4D**

  Mine2-4D is a mine planning and scheduling software. It allows mining engineers to plan, schedule and visualise complex designs of the mine. It can be integrated with MineRP's EPS and EPSViz scheduling-software to split the design and schedule into activities for better planning. Due to database based nature, design changes are identified automatically and processed. This feature significantly speeds up the process. Furthermore, scenario-based planning and scheduling eases the obtaining of optimised schedules. Mine2-4D also allows integration with other software packages which mitigates need for conversion of data from one format into other.

- **Enhanced Production Scheduler (EPS)**

  EPS enables mine planners to prepare and update schedules while simultaneously considering the design and visualisation. Data from external sources can also be imported and exported via this software. In EPS, tasks are created and managed as rate or duration-driven. The resources are either termed as equipment or labour, and are assigned to activities. The progress of these activities in terms of percentage can be recorded. Basic financial plan through revenue and cost can be generated, and track of both can be kept over time.

- **IBM ILOG**

  IBM ILOG is utilised by MineRP for decision management and optimisation, and is capable of providing supply-chain management solutions.

- **IBM CPLEX**

  IBM CPLEX is used in the Optimisation package to solve mathematical problems as well as to improve efficiency and cost-reduction via mathematical modelling.

MineRP's Optimisation solution package essentially contains most of the tools that are required for MIM. Missing tools are related to financial planning, infrastructure planning and geological modelling (however MineRP can provide CADSmine for geological modelling). In addition, a tool will be required to connect the whole package with IoT. This will assist obtaining real-time information concerning mining operation and market trends.

3.1.2 GeoFinance software package

MineRP developed GeoFinance which integrates multiple software packages into a financial modelling tool. GeoFinance uses SAP, IBM AMP, SpatialDB, SpatialDash, SpatialAnalyzer and MineRP CAD (the latter three packages are also components of MineRP's Optimisation package). The building blocks of GeoFinance are shown in Figure 3.2.

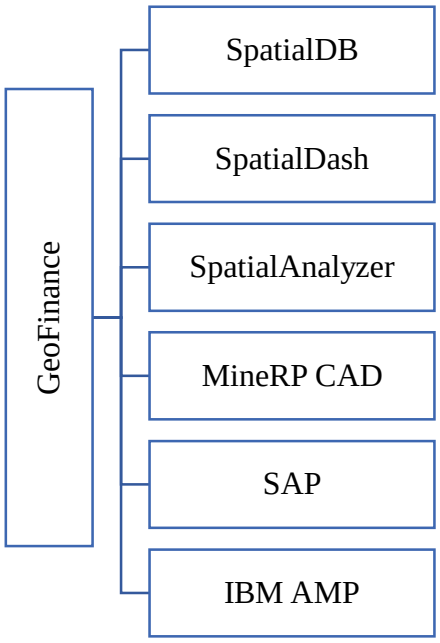


Figure 3.2 MineRP GeoFinance building blocks
After *(MineRP, n.d.)*

3.1.3 Datamine

Datamine is a mining software provider for almost the complete mining value chain, ranging from exploration to mine planning and financial modelling. An analysis of the software available from Datamine is presented below.

- **Exploration**

  For exploration, Datamine offers three software packages named Discover, Discover 3D and Discover PA. Discover is GIS-based mapping package for exploration purposes, Discover 3D provides 3D visualisation, and Discover PA enables analysis of geotechnical data.

- **Resource modelling**

  Datamine offers StudioEM, StudioRM, Strat3D and Ore Controller for resource modelling. Ore Controller is used to classify ore through block modelling. Information obtained through this software can be provided directly to shovel operators in order to control extraction. This feature can reduce the work load of geologists in the field. Datamine also offers Advance Geostatistics for resource valuation.

- **Mine design**

  Studio OP and Studio UG are offered by Datamine for opencast and underground mine design respectively. Both options are capable of scheduling using the design prepared in the software.

- **Open pit mine planning**

  For open pit mine planning, Datamine offers NPV Scheduler, which can be used for pit optimisation, cut-off grade optimisation, haulage optimisation and stockpile management.

- **Underground mine planning**

  Studio 5D planner is underground-mine-planning software which can be used with EPS for Gantt charts. An added advantage is that changes made in the

design are automatically added to the Gantt chart without need for manual inputs.

- **Financial modelling**

  At date of this research, Datamine offered NPVone for financial modelling and project evaluation (NPVone is a cloud-based tool which enables multiple users from essentially any location to access and use it). However, Datamine subsequently discontinued supply of NPVone, which will affect this research report's overall evaluation of Datamine products. However, comments and evaluation have been retained in case Datamine reintroduces the product in the same or different form.

3.2 Comparison

3.2.1 MIM requirements

Using BIM as a basis, this section provides a gap analysis between currently-available software and proposed MIM requirements. Table 3.1 presents the requirement for MIM in each phase of the mining value chain. Explanation of these requirements is given in the following paragraphs.

- Acquisition and exploration: In the first phase of a mining operation, data related to exploration will be required.
- Construction and development: This phase will require mine design, construction scheduling, inventory management and construction progress reporting.
- Mining and construction, Transportation, and Smelting and Refining: In these three phases, data related to planning and scheduling along with infrastructure planning and inventory management will be required. Infrastructure planning and inventory management will be required throughout the operation on real-time basis.

- Financial modelling is required throughout all phases of a mining operation, beginning with Acquisition and exploration and continuing to Marketing and Sales.

Table 3.1 MIM requirements in each phase of mining operation (Source: Author)

	Phases in mining operation					
Requirements in a mining operation as compared to BIM	Acquisition and exploration	Construction and development	Mining and concentration	Transportation	Smelting and refining	Marketing and sales
Exploration data	✓					
Mine design		✓				
Planning	✓	✓	✓	✓	✓	
Scheduling	✓	✓	✓	✓	✓	
Infrastructure planning	✓	✓	✓	✓	✓	
Inventory management	✓	✓	✓	✓	✓	
Financial modelling	✓					

3.2.2 Software capability

Table 3.2 provides a comparison between MIM requirements (see table 3.1) and what is available in Mine RP and Datamine software. As may be seen, both companies provide software for almost the complete mining value chain. However, MineRP has an added advantage of providing software-integration (per section 3.2.3 discussions, MineRP's GeoFinance and Optimisation applications integrate multiple software packages). Table 3.2's conclusion row therefore suggests that

MineRP is closer to what is required for MIM. If infrastructure-planning and IoT decision-making are added, MineRP[22] may begin to take the shape of MIM.

Table 3.2 Software capability[23] from MineRP and Datamine (Source: Author)

Requirement	**MineRP**			**Datamine**		
	Available	Not available	Application[24] (OC/UG/UGT/UGMM/UGBP)	Available	Not available	Application[24] (OC/UG/UGT/UGMM/UGBP)
Exploration	✓		-	✓		-
Mine design	✓		OC/UGT/UGMM/UGBP	✓		OC/UGT/UGMM/UGBP
Planning	✓		OC/UGT/UGMM/UGBP	✓		OC/UGT/UGMM/UGBP
Scheduling	✓		OC/UGT/UGMM/UGBP	✓		OC/UGMM/UGT/UBP
Financial modelling	✓		OC/UGT/UGMM/UGBP		✓	-
Infrastructure planning		✓	-		✓	-
Inventory management		✓	-		✓	-
Integration with other software	✓		-		✓	-
Conclusion (software closer to MIM)	✓			×		

- Opencast: OC;
- Underground tabular: UGT;
- Underground massive mining: UGMM;
- Underground bord and pillar: UGBP.

[22] In another two studies conducted by (Genc & Musingwini, 2016) and (Genc, et al., 2016), software from MineRP is explained to be covering most of the areas of the mining value chain.

[23] Software-capability mentioned in the table is according to information provided by the software company.

[24] The "Application" column presents the software capability for different mining methods. The information available in this column is according to the details provided by the software company.

3.3 Conclusion

Chapter 3 presented a review of the available software, together with suggestions on which software may be used to develop MIM. Once complete information about the mining operation is available, there will be a need of smart, intelligent and real-time decision-making. The latter decision-making process and its operation are explained in the following chapter.

4 DEVELOPMENT OF AN INTELLIGENT DECISION-MAKING SYSTEM

This chapter discusses the process of Intelligent Decision-Making (IDM). A case study is considered to explain this concept. The chapter also explains the architecture of MIM in general, architecture of MIM across the mining value chain, and architecture of IDM. The infrastructure requirements at mines for implementation of MIM and IDM are also discussed in the chapter. Wits Mockup-mine is considered as an example for understanding the infrastructure requirements.

4.1 Overview

Mining Information Model can be developed by the integration of multiple software components as discussed in section 3.2 of chapter 3. Such a model can be used to develop a decision-making tool. Besides economic decision-making, this tool can be used for other decisions as well, therefore is named as "Intelligent Decision-Making through MIM" (IDM through MIM).

4.2 Intelligent Decision-Making (IDM through MIM)

Decisions that are fast, accurate and based on real-time information are termed Intelligent Decisions, and the associated process is called Intelligent Decision-Making. This study's example-decision is related to economics of a mine. Economic decision-making is a subset of Strategic decisions (which are explained in section 2.4 of chapter 2), and is a complex process involving risks and uncertainties. The decision-making method presented in this study provides significant advantages: It provides more certainty to economic decisions; it brings decision-making persons closer to problems, thereby enabling speedy attention to short-term issues rather than just long-term objectives. Economic decision-making under such a process can therefore become operational and not just strategic.

4.3 IDM – a case study

To describe the process of IDM, the following economic decision-making question is considered: "Can short-term profitability be increased by increasing the

production". There could be two possible consequences after taking this decision: Either the profit of the mine will increase by the increased production (production would also need to be considered by IDM), or it may not. To assess the two possibilities, the decision-making process needs to consider all the parameters involved. Before taking this decision, uncertainties related to this decision must be addressed.

To reduce uncertainty, the information required for this decision is broken down into categories and sub-categories. The five major categories of information are shown in Figure 4.1 and their explanation is given in following paragraphs.

- Resources – in general;
- Resources – in process;
- Product mix;
- Prices forecast; and
- Capacity bottlenecks and Constraints.

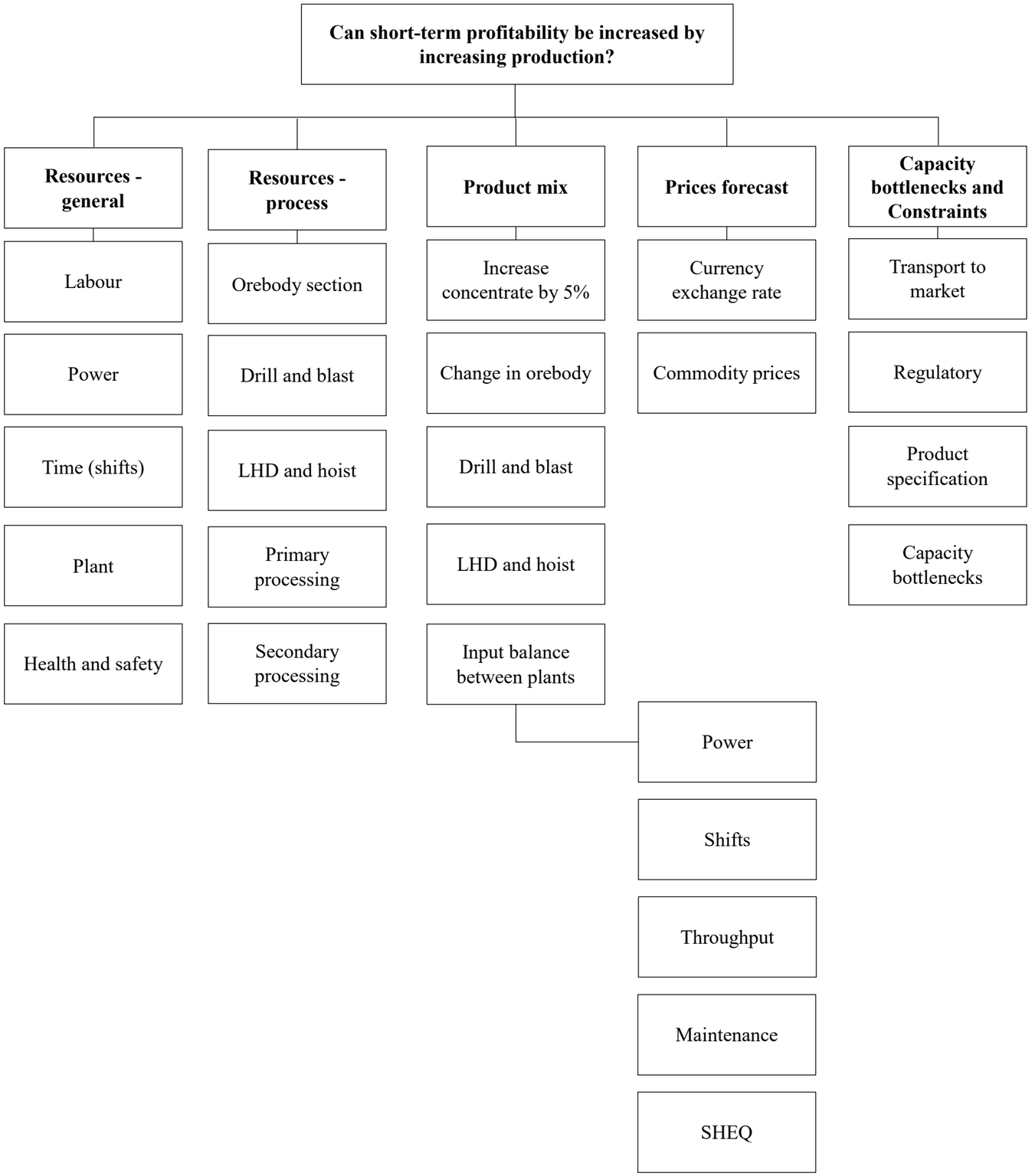


Figure 4.1 Information required for the decision
(Source: Author)

4.3.1 Resources – in general

"Resources – in general" are the basic resources that a mine should have in order to successfully run an operation. To increase production, escalation in these resources may be required. As highlighted in Figure 4.2, these resources include labour, power, time (in terms of labour shift), plant capacity and health and safety.

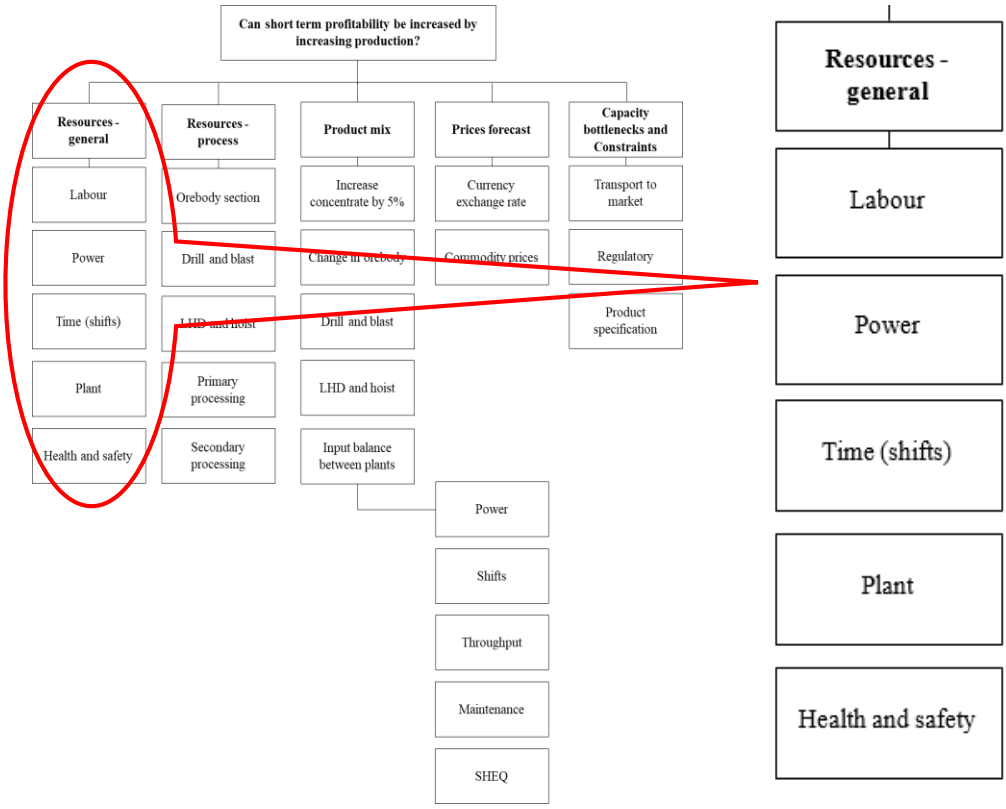


Figure 4.2 General resources requirement for making the decision
(Source: Author)

- **Labour**

  The labour and manpower capacity of the mine is analysed in this decision-making process component. To increase production, additional manpower may be suggested. If sufficient labour is available, the decision-making process will move to analysis of the next variable.

- **Time (shifts)**

  Timing and shifts are potential labour constraints: If the labour is already working three shifts per day, it will be difficult to manage the decision of increased production. However, if there are two shifts, it may be easy to add an extra shift through proper planning and scheduling. Another alternative could be optimising the existing shifts plan. In either case, analysis of alternatives is required.

- **Electric power**

  There may be some power-usage limitations in the mining operation. Increasing production may increase power consumption, hence it must be analysed before the decision is made.

- **Plant capacity or shaft capacity**

  Plant capacity is another important aspect to be considered before increasing production. If plant capacity is insufficient or if the plant is already running at full-capacity, decision to increase production may not be feasible. Application of TOC can assist the decision-making process in such cases. Also, design of the mine may provide information regarding plant and shaft capacity. Plant and shaft capacity is an extensive subject thus separate research will be required to properly cover it. Such research would need to include contents and equipment in the plant and shaft. The following are some general considerations; however, analysis should not be limited to these only:

  - Crushing and milling capacity of the plant;
  - Drying and smelting capacity;
  - Refining capacity of base metals and precious metals;
  - Personnel and equipment-carrying-capacity of the shaft; and
  - Ore transfer capacity from underground to the surface etc.

- **Health and Safety**

  Increasing the production may place extra loads on labour and staff. Their health and safety must therefore be considered in the decision-making process since noncompliance to health and safety may lead to penalties.

4.3.2 Resources – in process

Increasing production will increase the amount of ore to be processed in the processing plants. This may require additional resources for the processing, which may, in turn, add further constraints. Resource-processes (also shown in Figure 4.3) include:

- Orebody section;
- Drill and blast;
- Load, haul and dump (LHD) and hoist;
- Primary processing; and
- Secondary processing.

Details of these resource-processes are discussed in following paragraphs.

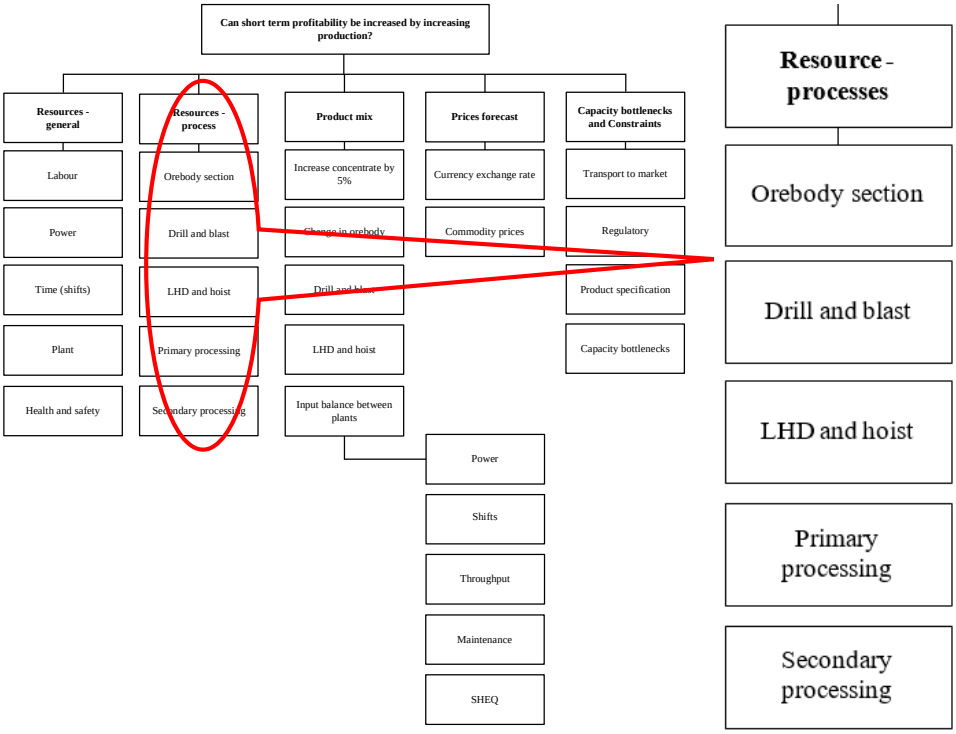


Figure 4.3 Resources to be considered required for processing phase

- **Orebody section**

  To increase production, it is important to assess whether the existing orebody-section is sufficient, or if more extraction locations need to be added. Such information would be provided by MIM and fed into the decision-making process. Included would be MIM information regarding development of new extraction site (sourced from the MIM mine plan and mine design) and flexibility of the orebody (i.e. whether the orebody allows multiple or different mining sites to extract higher or lower ore-grades according to the requirement).

- **Drill and blast**

  Drill and blast patterns will be considered to see if they can remain the same or if they need to be changed in order to increase the production.

- **LHD and hoist**

  Load, haul and dump relates to the transportation of the mined-ore from the mine to the stockpile or the processing plant. Hoists or winders are generally used for conveyers to transport the ore. All such aspects of the transportation capacity of the mine need to be analysed to assess whether there is sufficient capability to cater for increased production.

- **Primary processing**

  After extraction, the ore goes for primary processing. Processing-plant capacity must be sufficient to fulfil increased needs.

- **Secondary processing**

  As with primary processing, plant capacity must be sufficient to cater for assessed increases in secondary-processing.

4.3.3 Product mix

The mixture of the product needs to be considered in this stage of the decision-making process (Figure 4.4 illustrates this stage). In this case study, an assumption is made to increase the concentrate by 5%. Aspects that need to be considered under this assumption are: orebody; drill and blast patterns; LHDs and hoisting; input balances between plants. Although the latter are considered and explained in sections 4.3.1 and 4.3.2, it is vital to also consider them separately for product mix phase.

Furthermore, it is important to maintain "input balances between plants" so that any process within the processing plant does not become a bottleneck for the whole process. As highlighted in Figure 4.4, aspects to be considered in this are:

- Power requirements of the plant;
- Working shifts;
- Throughput of plants;
- Labour;
- Maintenance of plants;

- Time of running the plants; and
- Safety, health, environment and quality.

Paragraphs following Figure 4.4 further explain these aspects.

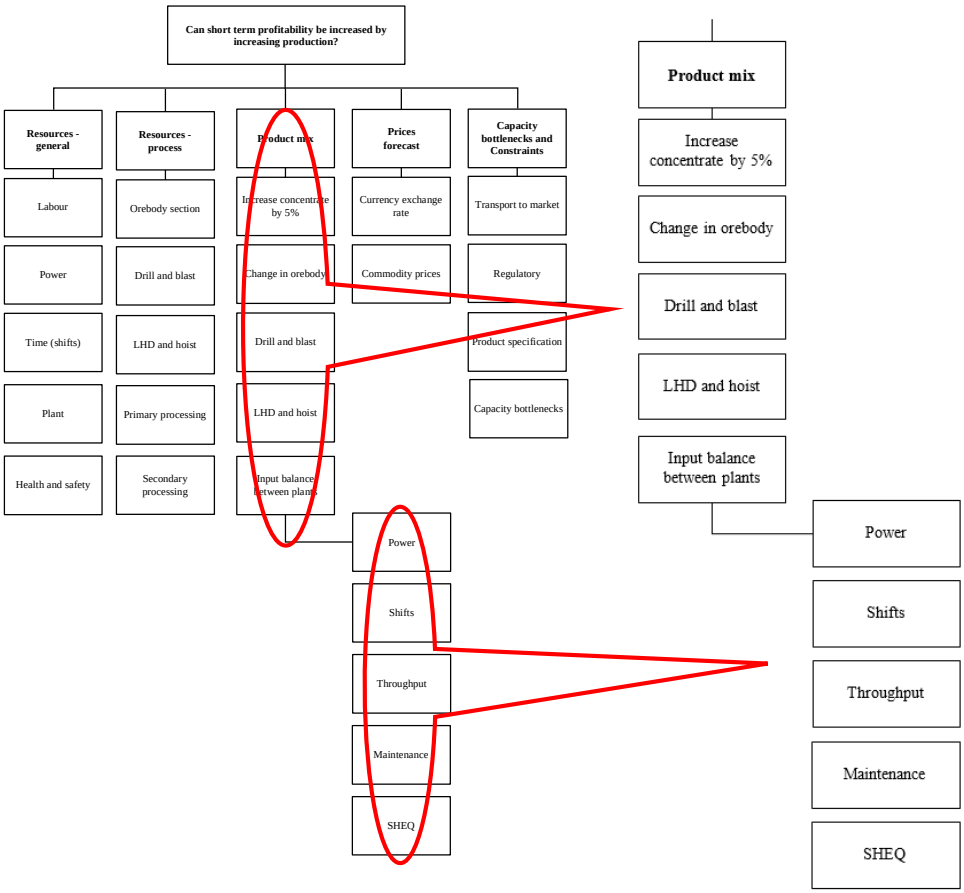


Figure 4.4 Product mix for increased production
(Source: Author)

- **Power requirements**

  The measure and cost of power required to process each metric-ton of ore must be considered in estimating the cost of additional production.

- **Working shifts**

  The average labour-cost of each person per shift must be known to enable evaluation of additional shift-costs. If such costs adversely affect expected profits, intelligent decision will be required.

- **Throughput of plants**

  Throughput of plants refers to how much material the processing plant can process in a specified time-frame. If this is not sufficient to fulfil projected production increases, the plant may need to be upgraded. The cost of this must be considered in the decision-making process (ABC model discussed in section 2.5 can be used for this purpose). Furthermore, plant-throughput is also related to the overall production time-horizon dictated by the decision: The plant capacity must be sufficient to process all the extra ore within the given time frame.

- **Maintenance**

  The maintenance requirements of the plant must also be considered in the process. Such requirements should include: assessment whether additional maintenance personnel are needed, time and costs needed to maintain additional equipment obtained to process higher volumes; reduced intervals between scheduled maintenance of existing equipment caused by increased volumes; increased shut-down of existing equipment for maintenance caused by increased volumes; etc. If the latter factors inhibit maintenance or related cost is too high, the decision-making process must consider it accordingly.

- **Safety, health, environment and quality (SHEQ)**

  SHEQ is important as it may not be affected through increased production.

4.3.4 Prices forecast

The next information to be considered in the decision-making process is prices-forecast as shown in Figure 4.5. Commodity-price information will be received by the system through IoT. The system will analyse this information and decide (on the basis of forecast) whether increase in production will increase profit or otherwise. Production costs will also have to be considered and analysed in tandem with analysis of prices. This can be done using ABC models discussed in section 2.5 of chapter 2.

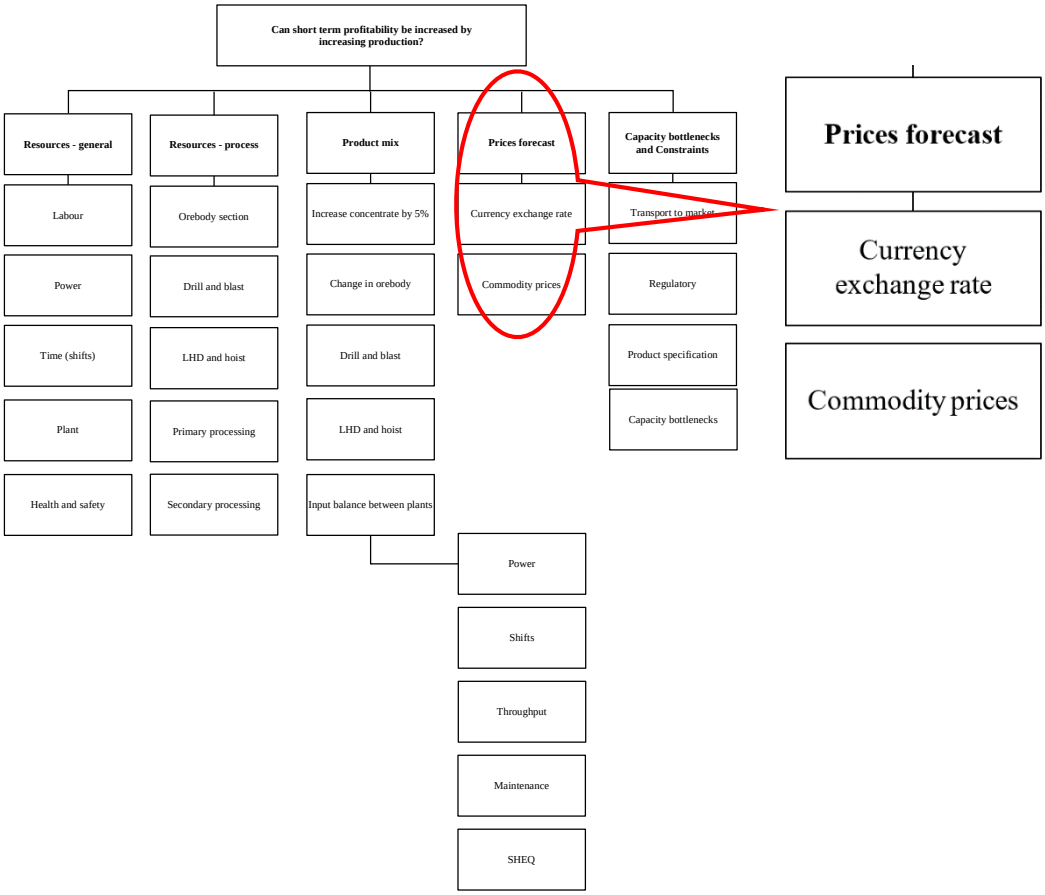


Figure 4.5 Prices-forecast consideration for decision-making
(Source: Author)

4.3.5 Capacity bottlenecks and Constraints

The following are some of the constraints that may affect the decision of increasing production as highlighted in Figure 4.6.

- Transportation of final product to the market;
- Regulatory; and
- Product specification.

“Transportation final product to the market” includes transport-related issues such as material quantity, shape, size, etc.

Regulatory relates to issues regarding governmental framework under which the mine is operating. For example, regulatory framework may not allow the mine to increase production. Regulatory information will be made-available via MIM.

The decision-making process will also analyse the impact of a decision in terms of product specification.

Also, capacity-bottlenecks will need to be considered in the complete process of decision-making. As such, the process will not allow a decision to be taken unless there is a possibility of removing the bottleneck while considering associated costs and benefits via TOC and ABC models.

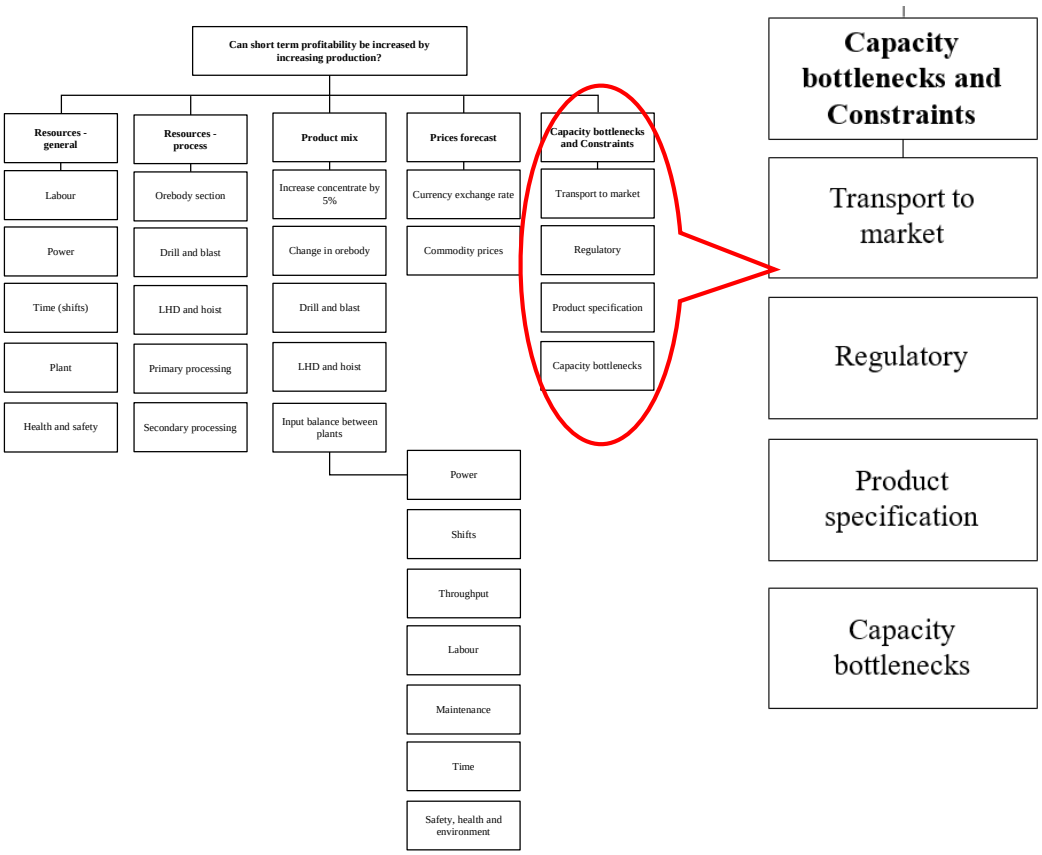


Figure 4.6 Constraints to be considered for decision-making
(Source: Author)

4.4 Illustration of an IDM process

Information discussed in section 4.3 will come from MIM and IoT. This will then feed into the decision-making process, which will analyse all the information and

variables. For this purpose, either dedicated software can be used, or the decision-making process can be developed within MIM. In this study, Microsoft Excel "if-else" statements have been used to illustrate the concept (see details in the following paragraph and in Appendices B, C and D). For materialisation of the concept, detailed coding can be developed to improve the process.

The IDM scenarios are shown in Tables 4.1, 4.2 and 4.3. In each of these tables, four columns (adopted from the IDM case study in section 4.3) hold the following information: "Required information", "Sub category I", "Sub category II" and "Sub category III". Each sub-category is followed by a column labelled "Status", where "1" indicates availability and "0" indicates unavailability of the resource in the preceding column. The latter columns are followed by: "Can be arranged" (1 indicating that an unavailable requirement can be arranged); "Cannot be arranged" (1 indicating that what is unavailable also cannot be arranged); "Possible" and "Not possible" (showing the possibility of the task indicated by the category). As introduced earlier, analysis of the latter 1 and 0 options via Excel's "if-else" has been used to illustrate the IDM concept (see Appendices B, C and D).

Tables 4.1, 4.2 and 4.3 provide three examples in which different scenarios are illustrated. Each scenario provides a decision, based on the availability of what is required:

- **Example 1**

Table 4.1 contains the simplest decision-making example, where all requirements are met. The decision-process therefore continues unhindered from one factor to the next. It finally shows a green indicator, which means that all the requirements are met and profit can be increased by increasing production, therefore a positive decision may be taken.

- **Example 2**

Table 4.2's decision-making process assesses similar information to table 4.1. However, when it reaches "LHD and hoist" in row 14, the Status shows that it is not available to support the current decision. However, the next column indicates

that “LHD and hoist” can be arranged. All other factors are positive thus the table shows a green indicator which means a positive decision can be taken.

- **Example 3**

Table 4.3 shows that LHD and hoist are not available but they can be arranged. However, required “maintenance” of the equipment for extra working hours is a problem and cannot be arranged. It is therefore marked as “0” in the Status column and “1” in the “cannot be arranged” column. Thus, owing to unavailability of required maintenance, the decision-making process stops and shows red in the indicator.

Table 4.1 Decision making example 1 (Source: Author)

Scenario 1											
Sr. No.	**Required information**	**Sub category-I**	**Status**	**Sub category-II**	**Status**	**Sub category-II**	**Status**	**Can be arranged**	**Cannot be arranged**	**Possible**	**Not possible**
1	**Resource - processes**	Orebody	1							1	
2		Drill and blast	1							1	
3		LHD	1							1	
4		Hoist	1							1	
5		Primary processing	1							1	
6		Secondary processing	1							1	
7	**Resource - general**	Labour	1							1	
8		Power	1							1	
9		Time (Shifts)	1							1	
10		Plant	1							1	
11		Health and safety	1							1	
12	**Product mix**	**Increase concentrate - 5%**		Change in orebody	1					1	
13				Drill and blast	1					1	
14				LHD and hoist	1					1	
15				**Input balance in plants**		Power	1			1	
16						Shift	1			1	
17						Throughput	1			1	
18						Labour	1			1	
19						Maintenance	1			1	
20						Time	1			1	
21						SHEQ	1			1	
22	**Prices forecast**	Currency exchange rate	1							1	
23		Commodity prices	1							1	
24	**Capacity bottlenecks and Constraints**	Transport to market	1							1	
25		Regulatory	1							1	
26		Product specification	1							1	
27		Capacity bottlenecks	1							1	
Decision											

Table 4.2 Decision making example 2 (Source: Author)

Scenario 2											
Sr. No.	**Required information**	**Sub category-I**	**Status**	**Sub category-II**	**Status**	**Sub category-II**	**Status**	**Can be arranged**	**Cannot be arranged**	**Possible**	**Not possible**
1	**Resource - processes**	Orebody	1							1	
2		Drill and blast	1							1	
3		LHD	1							1	
4		Hoist	1							1	
5		Primary processing	1							1	
6		Secondary processing	1							1	
7	**Resource - general**	Labour	1							1	
8		Power	1							1	
9		Time (Shifts)	1							1	
10		Plant	1							1	
11		Health and safety	1							1	
12	**Product mix**	**Increase concentrate - 5%**		Change in orebody	1					1	
13				Drill and blast	1					1	
14				LHD and hoist	0			1		1	
15				**Input balance in plants**		Power	1			1	
16						Shift	1			1	
17						Throughput	1			1	
18						Labour	1			1	
19						Maintenance	1			1	
20						Time	1			1	
21						SHEQ	1			1	
22	**Prices forecast**	Currency exchange rate	1							1	
23		Commodity prices	1							1	
24	**Capacity bottlenecks and Constraints**	Transport to market	1							1	
25		Regulatory	1							1	
26		Product specification	1							1	
27		Capacity bottlenecks	1							1	
Decision											

Table 4.3 Decision making example 3 (Source: Author)

Scenario 3											
Sr. No.	**Required information**	**Sub category-I**	**Status**	**Sub category-II**	**Status**	**Sub category-II**	**Status**	**Can be arranged**	**Cannot be arranged**	**Possible**	**Not possible**
1	**Resource - processes**	Orebody	1							1	
2		Drill and blast	1							1	
3		LHD	1							1	
4		Hoist	1							1	
5		Primary processing	1							1	
6		Secondary processing	1							1	
7	**Resource - general**	Labour	1							1	
8		Power	1							1	
9		Time (Shifts)	1							1	
10		Plant	1							1	
11		Health and safety	1							1	
12	**Product mix**	**Increase concentrate - 5%**		Change in orebody	1					1	
13				Drill and blast	1					1	
14				LHD and hoist	0			1		1	
15				**Input balance in plants**		Power	1			1	
16						Shift	1			1	
17						Throughput	1			1	
18						Labour	1			1	
19						Maintenance	0		1	0	1
20						Time	1			1	
21						SHEQ	1			1	
22	**Prices forecast**	Currency exchange rate	1							1	
23		Commodity prices	1							1	
24	**Capacity bottlenecks and Constraints**	Transport to market	1							1	
25		Regulatory	1							1	
26		Product specification	1							1	
27		Capacity bottlenecks	1							1	
Decision											

4.5 Proposed architectures

IDM and MIM development will require clearly-defined architecture based on mining-industry requirements. Following discussions cover three conceptual architectures. In addition, the discussions aid understanding of MIM functionality and IDM interaction through MIM across various stages of a mining value chain. The three architectures are as follows:

- Basic architecture of MIM;
- Architecture of IDM; and
- Architecture of MIM across the mining value chain (MVC).

4.5.1 Basic architecture of MIM

The proposed basic architecture of MIM is shown in Figure 4.7, and consists of four components:

- Mining value chain;
- IoT connectors;
- Server; and
- MIM.

As may be seen in Figure 4.7, the entire mining value chain is connected to IoT connectors, which are, in turn, connected to a central server or data cloud for data collection and storage (either a centralised server or a data cloud can be used for this purpose). MIM is connected to this server/cloud, enabling information to be obtained per requirements.

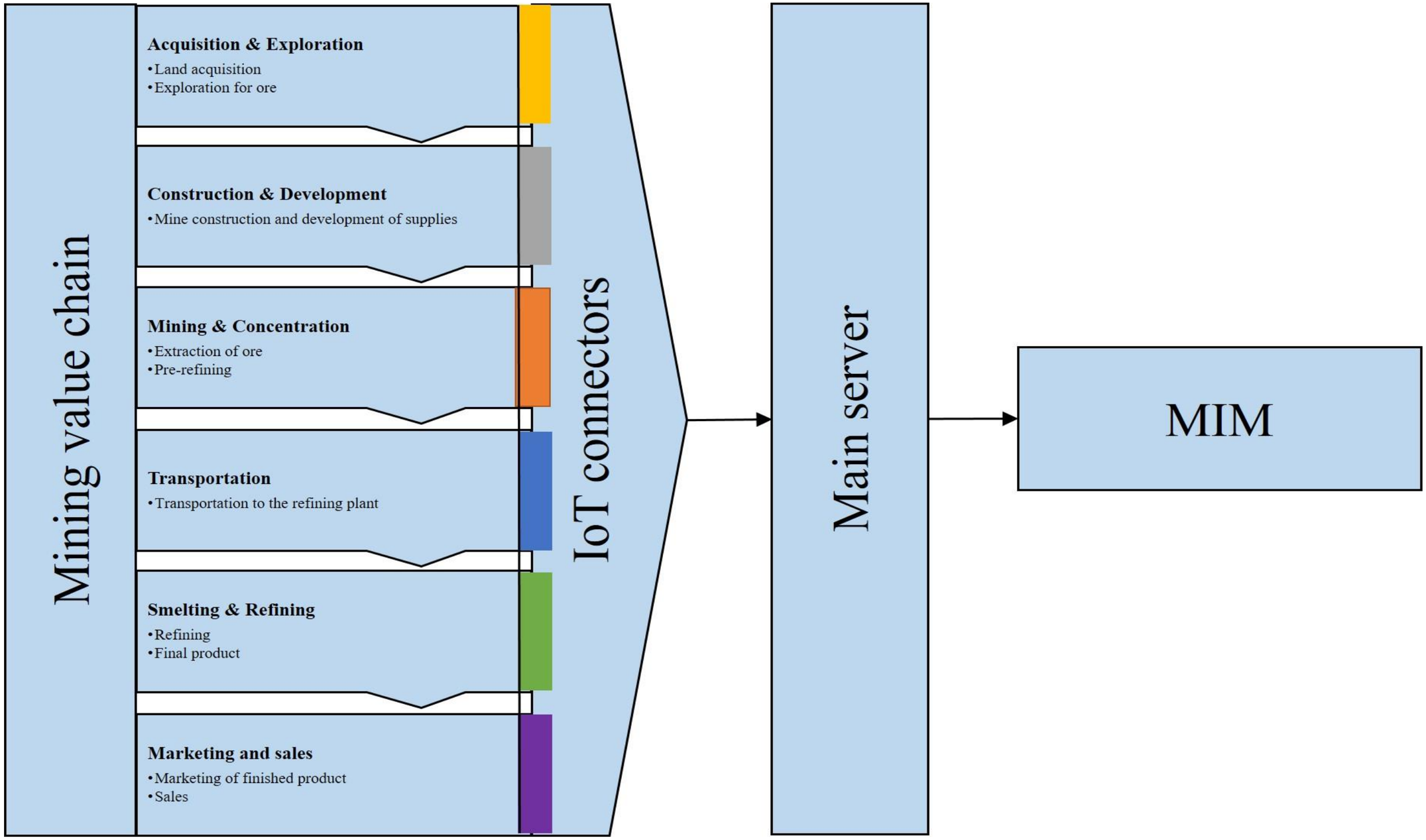


Figure 4.7 Basic architecture of MIM (Source: Author)

4.1.1 Architecture of IDM through MIM

The conceptual architecture for "IDM through MIM" consists of two primary components as shown in Figure 4.8. The figure's upper green box depicts the current decision-making process, where decisions are usually made during periodic boardroom meetings (weekly, monthly or quarterly). Before making decisions, the boardroom may ask the MRM manager to provide relevant information. The MRM manager may then contact respective MRM departments for the information. It should be noted that since such information is sourced from external parties who may not understand its purpose, it may also fail to fully answer questions. Furthermore, depending on the nature of the information, the time taken to gather it and to deliver it back to the boardroom may take days or weeks. This delay may be compounded if the boardroom meeting only takes place quarterly. Thus it may take three months or more to reach a specific decision. A number of parameters may change in such periods, thereby reducing the chances of reaching a 100%-correct decision. This prompts quotation of an interesting saying from (Zhu, 2017): "It is often said that wrong decision taken at the right time is better than a right decision taken at the wrong time". Thus the ideal is that decisions be made in time, and be precise. It is for this very purpose that IDM through MIM is suggested.

Figure 4.8's lower red box depicts the proposed "IDM through MIM" process (the box's dotted lines indicate that the system does not yet exist). In this proposed process, the mining value chain is connected to MIM through IoT connectors to enable real-time flow of information. The boardroom will have access to the IDM process which is connected to MIM. The information about the decision to be made will be fed into the decision-making process. The system will then process the information and analyse it. Following this, it will obtain further relevant information through MIM. This relevant information will be analysed again for the final response. After analysis, the result will be displayed on the dashboard. This decision will either be a "yes" or a "no" as explained in section 4.4 of this chapter. Since the information is already available in the system, the entire "IDM through MIM" process will

take minutes, not hours. The only time required will be for processing the relevant information. Thus information obtained via “IDM through MIM” will be direct, quick, more precise and reliable.

The “IDM through MIM” process is not restricted to economic decision-making, but can be also used for other decisions. Indeed, since data from the mining value chain will be fed into MIM through IoT connectors, such decision-making will be easier owing to real-time availability of information.

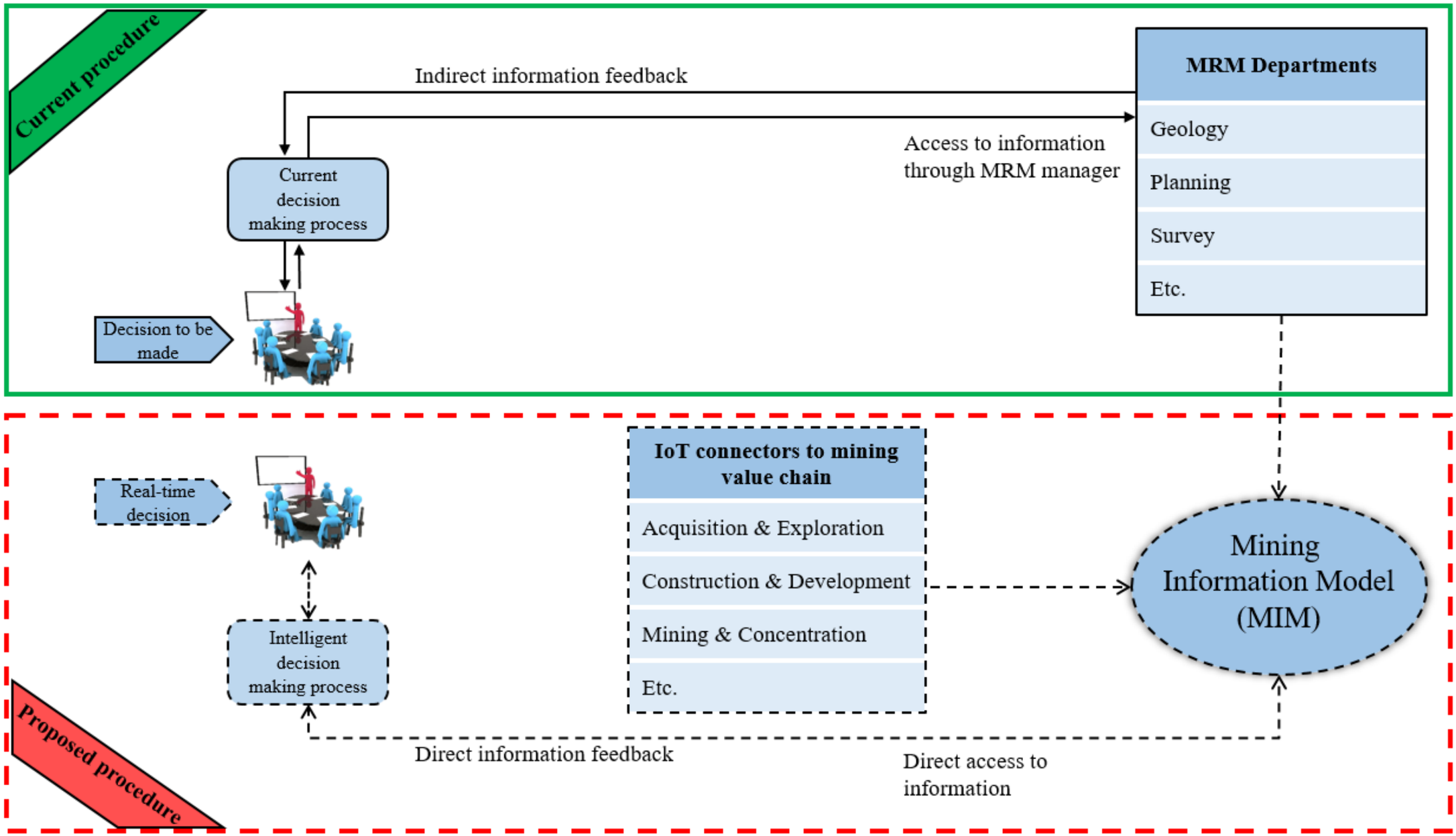


Figure 4.8 IDM through MIM architecture (Source: Author)

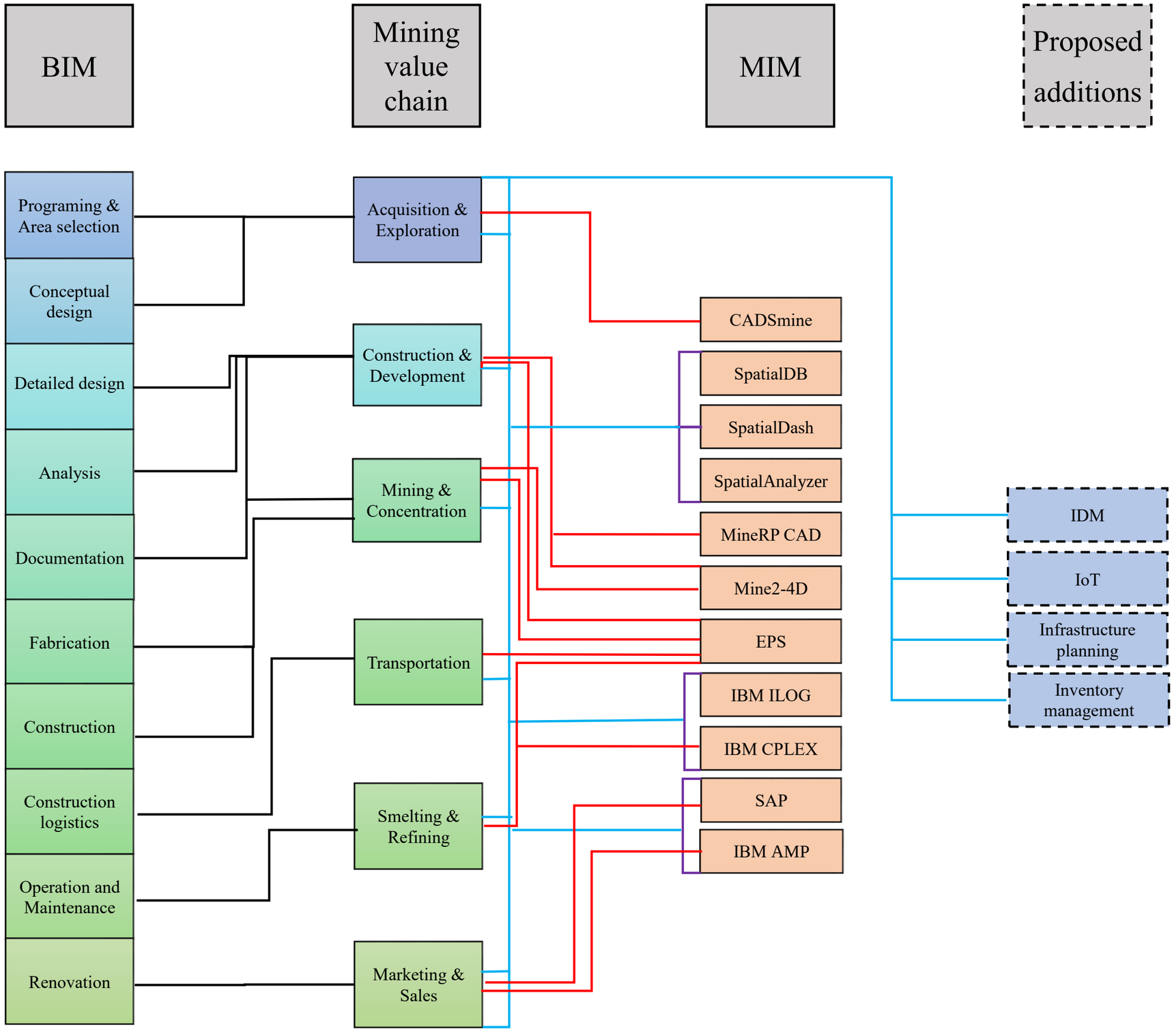


Figure 4.9 MIM architecture across the mining value chain (Source: Author)

4.5.2 MIM architecture across the mining value chain

A complete MIM architecture across the mining value chain is shown in Figure 4.9. This architecture explains how BIM relates to MIM, and how MIM links to the various stages of mining value chain. The figure explains this in four columns, namely:

- BIM (lifecycle of a building under BIM);
- Mining value chain;
- MIM; and
- Proposed additions.

Explanation of these columns is given in the following paragraphs.

- **BIM**

  The stages of a building lifecycle under BIM are listed in this column. These stages are discussed in detail in section 1.3 of chapter 1. Figure 4.9 provides a relationship comparison between BIM stages and mining value chain for MIM.

- **Mining value chain**

  The mining value chain, as discussed in section 1.2 of chapter 1, is shown in Figure 4.9's second column. Each mining value chain phase-item is linked to its closest BIM lifecycle-item. Each mining value chain phase-item is also linked to proposed MIM software components in the following way:

  - The first phase in the mining value chain is related to exploration, thus CADSmine would be required for this phase.
  - Construction and development phase need planning, designing and scheduling. Hence it needs Mine2-4D, MineRP CAD, and EPS.
  - Mining and concentration phase needs Mine2-4D for planning and EPS for scheduling.
  - Transportation phase requires Mine2-4D data for planning and EPS for scheduling.

- Smelting and refining phase needs EPS for scheduling and IBM CPLEX for optimisation.
- IBM ILOG and IBM CPLEX can be used for optimisation and improvement purposes in the entire value chain.
- SAP and IBM AMP are components of MineRP's GeoFinance and may be used for Marketing and Sales. They may also be used for financial modelling in the mining operation.

- **MIM**
  - As discussed in section 3.2.1 of chapter 3, CADSmine is a software package offered by MineRP which is not included in MineRP's Optimization package. MIM will require it for geological and resource modelling in the "Acquisition and exploration" phase.
  - SpatialDB, SpatialDash and SpatialAnalyzer are for database and visualisation purposes, hence may be used in the complete mining value chain.

- **Proposed additions**

  IDM, IoT, Infrastructure Planning and Inventory Management (highlighted in blue in Figure 4.9) are required throughout the mining value chain, thus are connected to the whole chain.

4.5.3 Infrastructure and resource requirements for MIM, IoT and IDM through MIM

Internet of Things, MIM and IDM are connected and directly related to each other. This fact is explained in the following paragraphs:

- **IoT**

  IoT is essential for both MIM and IDM. For MIM to have complete, real-time information about the mine, the mining value chain must be connected to IoT. Connections should include vehicles operating in the mine, underground

personnel, sensors, conveyers and other equipment such as generators etc. Figure 4.10 shows how a shovel can be connected to a mine control room through IoT. IoT-connected devices shown in Figure 4.10 not only enable real-time data-transfer in the complete mine, but full-control of key equipment (even vehicles) from one location. It therefore bears repeating that IoT would be a critical component of proper MIM and IDM operation.

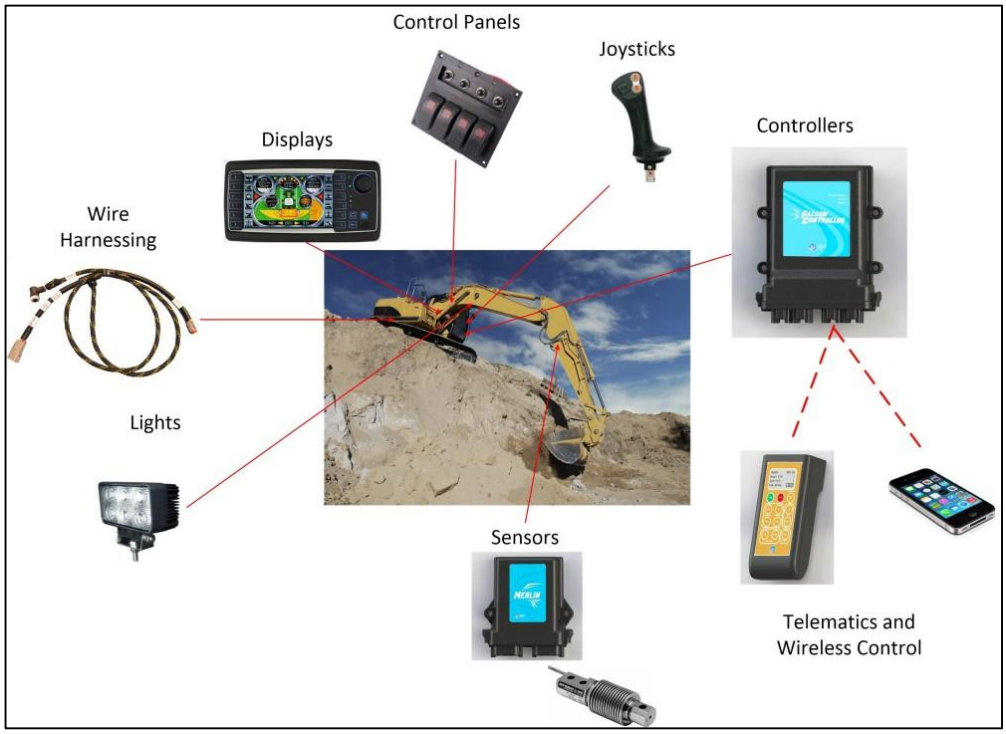


Figure 4.10 How a shovel can be connected to IoT *(Gomori, 2016)*

- **MIM**

  Once the mine and its value-chain are fully connected to IoT, MIM will be able to communicate, gather and transfer information from a central server or cloud. The server must have the capacity to store data from the entire operation. Considering the extent of current mining-software processing and data-size requirements, a super-computer may be needed - unless data sizes and processing power requirements are able to be reduced for MIM.

- **IDM**

  An IDM process may utilize a sophisticated tool or software such as Microsoft Excel. Youngblood (a WMI supplying-company partner discussed in section 4.5.4 of this chapter) utilises Microsoft Excel for dashboard reporting. The latter can also be used as a visualisation tool to inform the boardroom about the decision (as discussed in section 4.3 of this chapter). The fact that data for IDM will come from MIM and IoT, implies that IDM cannot work without MIM and IoT.

To assist understanding of mining-operation infrastructure that is needed for IoT, MIM and IDM, following sections will consider the Wits Mockup-mine. Following Wits Mockup-mine discussions are also intended to highlight the importance of IoT in the implementation of MIM and IDM.

4.5.4 Infrastructure and architecture of Wits Mockup-mine

The Wits Mockup-mine includes an underground mine-tunnel constructed beneath University of the Witwatersrand's Chamber of Mines building. The Mockup-mine contains various state-of-the-art systems that are linked to WMI's Digital Mine laboratory control room for research purposes. The Mockup-mine is shown in Figures 4.11 and 4.12. Details of systems installed in the mine by various supplying-companies are discussed in following paragraphs.



Figure 4.11 Wits Mockup-mine (Source: Author)

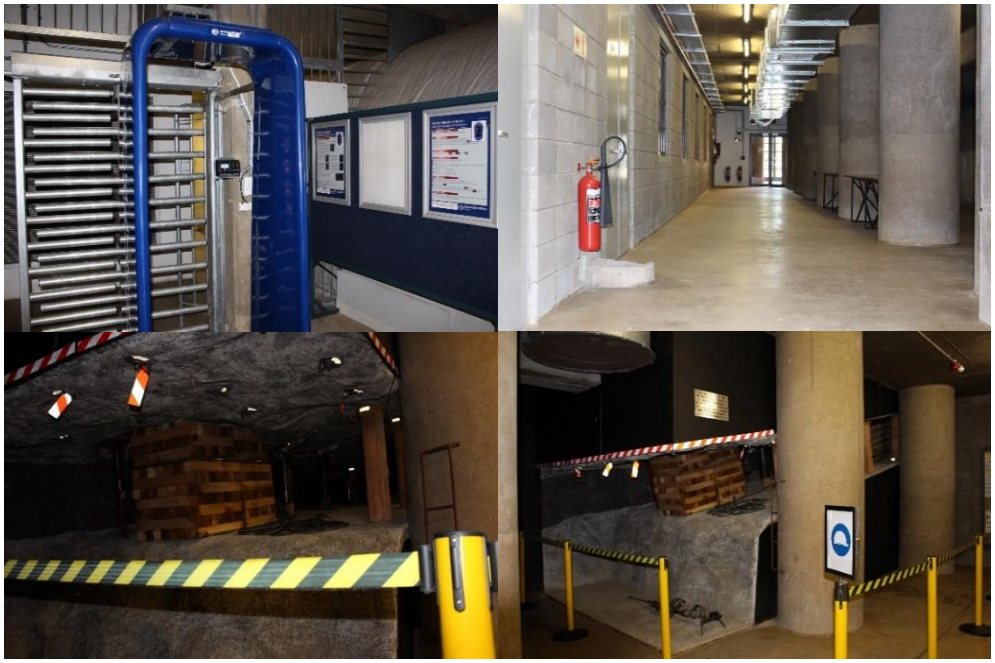


Figure 4.12 Wits Mockup-mine lamp room, tunnel and stope
(Source: Author)

- **Vibra-Tech**

  Technology supplier Vibra-Tech has installed sensor-based detection and communication systems in the following areas:

  - Stope of the Mockup-mine for detection of rock movement;
  - Weather station and seismometer on the roof top;
  - Seismometer in the Mockup-mine.
  - Extensometers and crack meters in the Mockup-mine.

  Figure 4.13 shows sensors installed at various locations, which communicate with the WMI laboratory control room in real-time. Figure 4.14 shows sensor-data displayed in the control room. An "alert" is generated whenever an unusual event occurs.



Figure 4.13 Vibra-Tech sensors
Seismometer, extensometers and weather station (Source: Author)

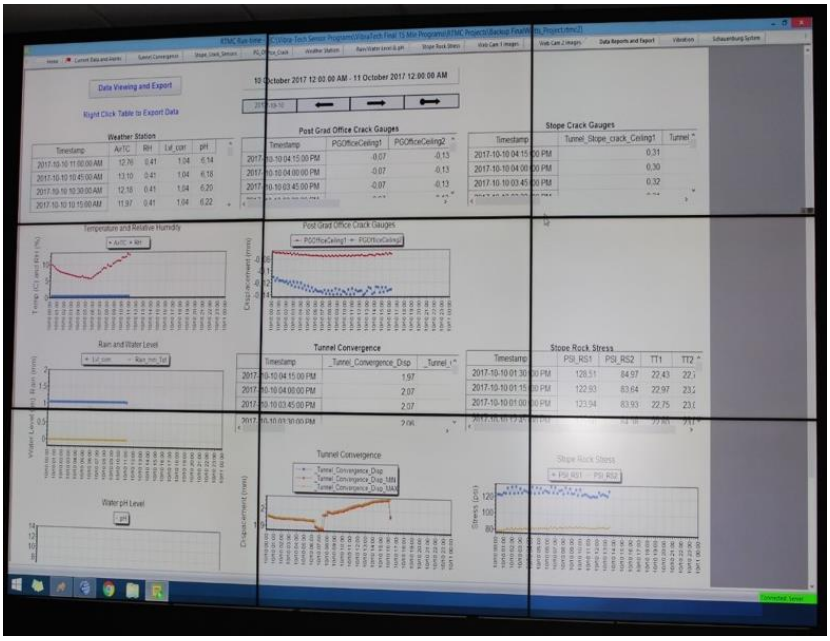


Figure 4.14 Vibra-Tech live feed in WMI control room from different sensors (Source: Author)

- **Schauenburg's Mine Wide Integrated Monitoring and Control System (MIMACS)**

  MIMACS is a mine access control, asset management and environment monitoring system. It enables the lamp room in-charge to manage personal protective equipment (PPE) and personnel access to the mine. The system will create an alert whenever an unauthorized person tries to access the mine or a person tries to access without proper PPE. It also has Gas Detection Instruments (GDI) carried by miners. These GDIs detect and inform the miner of any gas-level irregularities. Figure 4.15 shows instruments installed by Schauenburg in the Mockup-mine.

  Schauenburg's paging system enables control rooms to keep track of miner locations. It also provides two-way communication in case of emergencies. Figure 4.16 shows MIMACS console (software) and tracking agent.



Figure 4.15 Schauenburg's system in the Mockup-mine.
Access control, PPE, Gas detection instruments, environmental sensors and S-link for location monitoring (Source: Author)

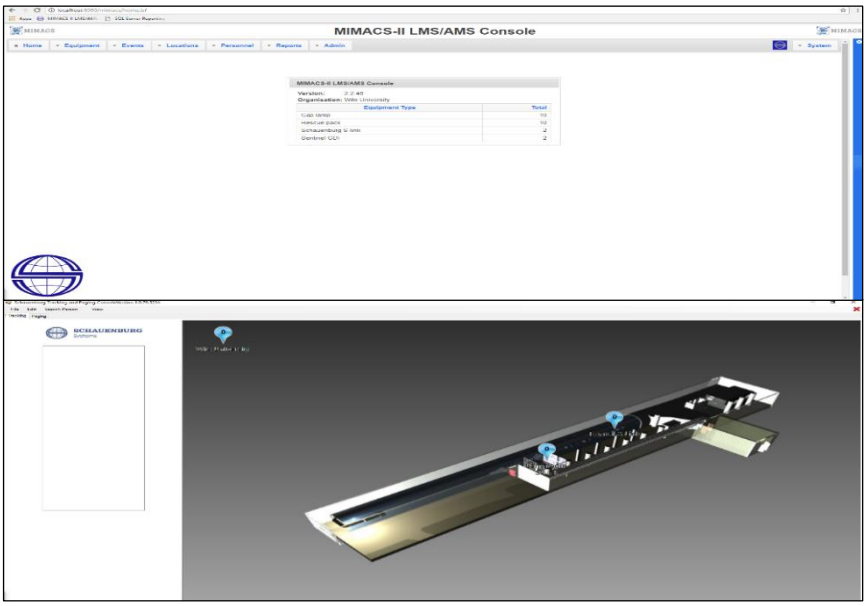


Figure 4.16 Schauenburg's MIMACS software in control room.
MIMACS asset management console and tracking agent.
(Source: Author)

- **Camera system**

  A camera system procured from EOH is used for surveillance in the Mockup-mine. Research cameras donated by IBM are used for face-recognition, personnel-counting and anomaly-detection. The anomaly-detection system is designed to identify unusual incidents such as a falling mine worker. An alert is generated if such an incident occurs.

- **Tracking and positioning from Minetec**

  The Minetec system is used for real-time tracking and positioning of personnel in the Mockup-mine. The positioning-accuracy of this system is approximately 1 meter. The system is also capable of data communication in real-time, task management and two-way communication. Figure 4.17 shows equipment installed in the Mockup-mine by Minetec.



Figure 4.17 Minetec tracking and positioning system
Referencing node, control cabinet, data collector/transmitter and real time tracking display (Source: Author)

- **Dashboard production reporting from YoungBlood**

  YoungBlood has installed a production reporting system in the Mockup-mine. The system operates through YoungBlood's IoT platform named "ThatThing". Figure 4.18's production graphs are generated by the system.



Figure 4.18 YoungBlood's production reporting system
(Source: Author)

- **Sterkfontein caves system**

  Sterkfontien caves is an archaeological site which has been selected for installation of a safety system. The reason for the selection is that the caves experience many surface and sub-surface movement-triggering factors that affect mines, including seismic, geotechnical, hydrological and environmental. Thus the safety system will be tested at Sterkfontein caves to understand its functionality and robustness in a real mining environment. The control centre for the system will be in Wits Mining Institute (WMI) which will monitor and control the system via remote access.

Systems discussed in above bullet points are sourced from multiple supply-companies situated in various parts of the world. As has been seen, the systems are installed in the Mockup-mine and are controlled from the WMI control room. In addition, supply-companies have remote access to their respective systems, which they can access whenever required. WMI's Mockup-mine control room is shown in Figure 4.19.



Figure 4.19 WMI control room
(Source: Author)

As has also been seen, the systems transmit data in real-time to the control room. The infrastructure and architecture supporting these systems' functionality mimic real mines in order to assist research and understanding of real-mine requirements. The Mockup-mine systems architecture is shown in Figure 4.20.

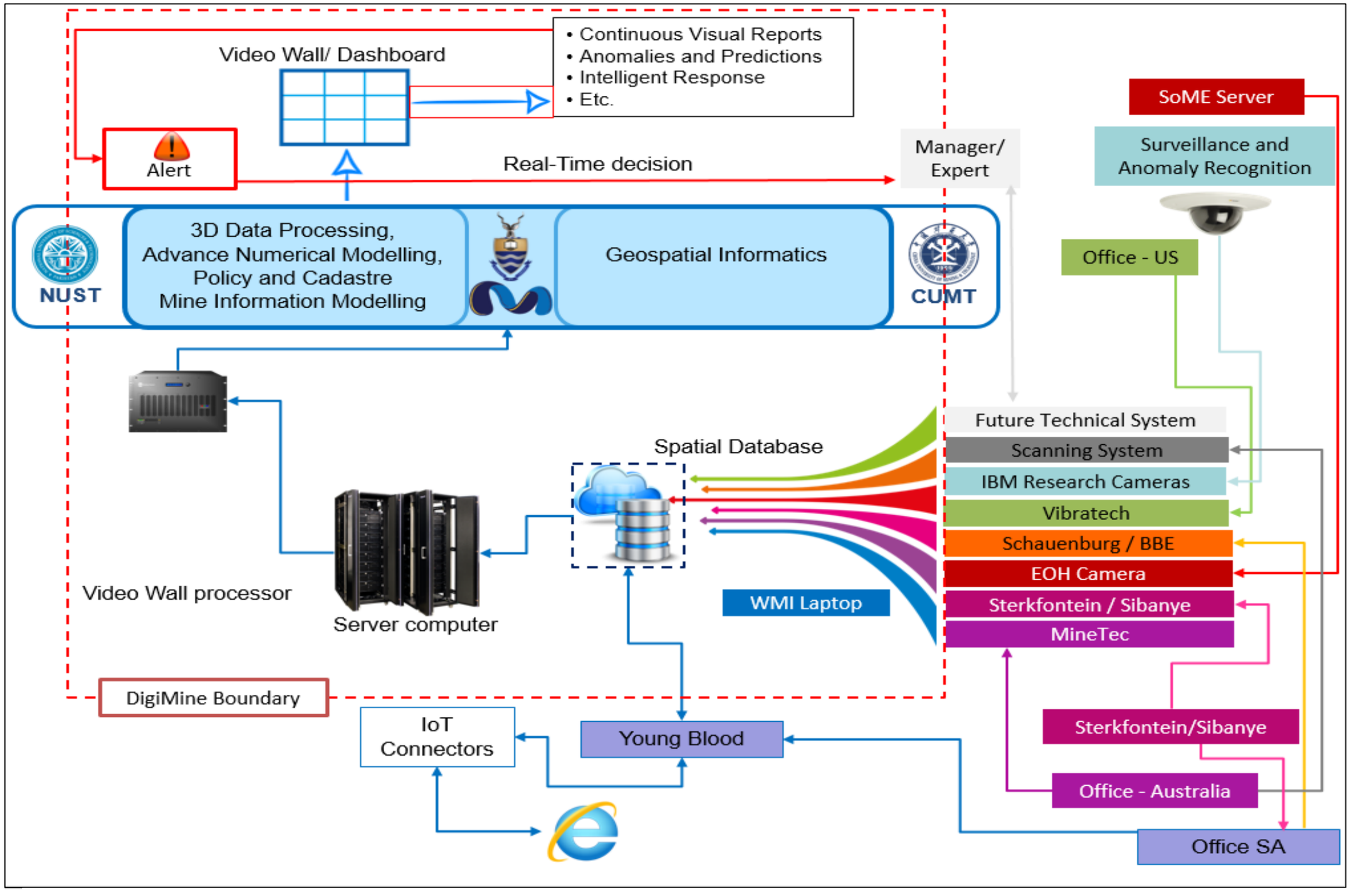


Figure 4.20 Architecture of systems installed in the Mockup-mine
(Source: WMI)

Systems installed in the Mockup-mine are connected to the control room in the following way:

- The WMI control room contains a number of supplier-company-installed computers. Each supplier-company's computer is connected to the supplier-company's systems installed in the Mock-up-mine;
- Each of the above systems is also connected to a spatial database and a central server-computer for data storage; and
- This central server is connected to the video wall through video wall processor.

Whereas supplier-companies can access their computers and systems for maintenance or installation purposes, only WMI-approved parties can access the WMI central server (approved parties include project-partners such as National University of Science and Technology Pakistan and China University of Management and Technology).

The video wall processor, with the help of server computer, displays information from Mockup-mine systems on the video wall. Whenever there is a situation, an alert is generated and displayed on the video wall. This allows the responsible person to assess the situation and take appropriate action at the right time.

4.5.5 Action scenario

Scenario: Rock movement in the stope of the Mockup-mine. In the latter scenario, Mockup-mine systems would operate in the following way:

- Vibra-Tech sensors installed in the stope will inform the control room of the rock movement. An alarm will also go off inside the stope.
- The person sitting in the control room will instantly inform miners about this emergency. This communication will be executed through Schauenburg's paging system. Upon receipt of this evacuation message, miners will evacuate and proceed to the refuge bay or a place of safety.
- Using the database from central server computer, Minetec's positioning and tracking system will provide information on the current location of miners. In

this way, it can be made sure that the stope is evacuated and the miners safely reach the refuge bay.

- If a miner falls during evacuation, the IBM camera system will detect the anomaly and inform the control room.

4.6 Wits Mockup-mine case studies – a step towards MIM

As discussed in section 1.11 of chapter 1, WMI research projects are focused on a common goal. Two of these projects will also assist MIM as follows:

- **Integration of systems** (Opiti, 2017)

  In this project, sections of WMI's building were converted to simulate a mine, with the roof as surface and floors of the building as different levels of a mine. The aim of the project was integration of sensors and software installed in the Mockup-mine together with spatial relationship between data and sensors. For this purpose, data from Vibra-Tech sensors was used and simulated. A dashboard was placed in the control room to display key parameters from the sensors. Figure 4.21 shows the dashboard together with details on how sections of the building were converted into a mine.

  For testing, time-stamped data was used and the dashboard was configured to display parameters and locations of where data was sent from in the building. The project requires further development and will be continued as a PhD research-topic.

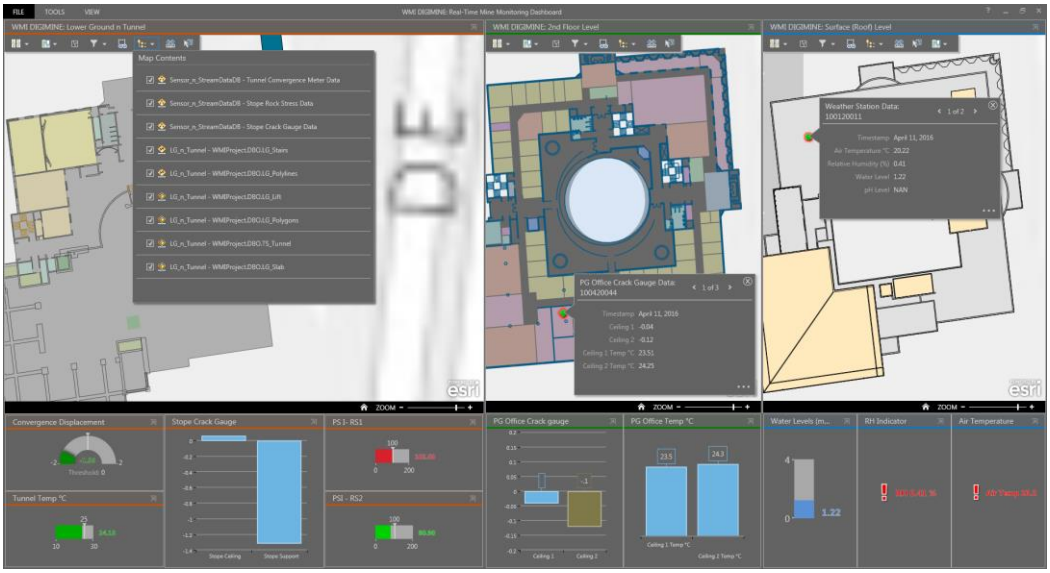


Figure 4.21 Dashboard-display of data sent from sensors housed in displayed sections of WMI's building which were converted to simulate different levels of a mine *(Opiti, 2017)*

- **IBM Intelligent Operations Center**

  Another ongoing project in WMI is the Intelligent Operations Center. This project is a collaboration between WMI and IBM. The aim of the project is further integration of systems and decision-making through Intelligent Operations Center. The data coming from systems will be analysed and Key Performance Indicators (KPIs) will be displayed on the video wall of the control room. Visualisation on the video wall will aid in decision-making whenever there is a need. Figure 4.22 shows the architecture of WMI-IBM Intelligent Operations Center.

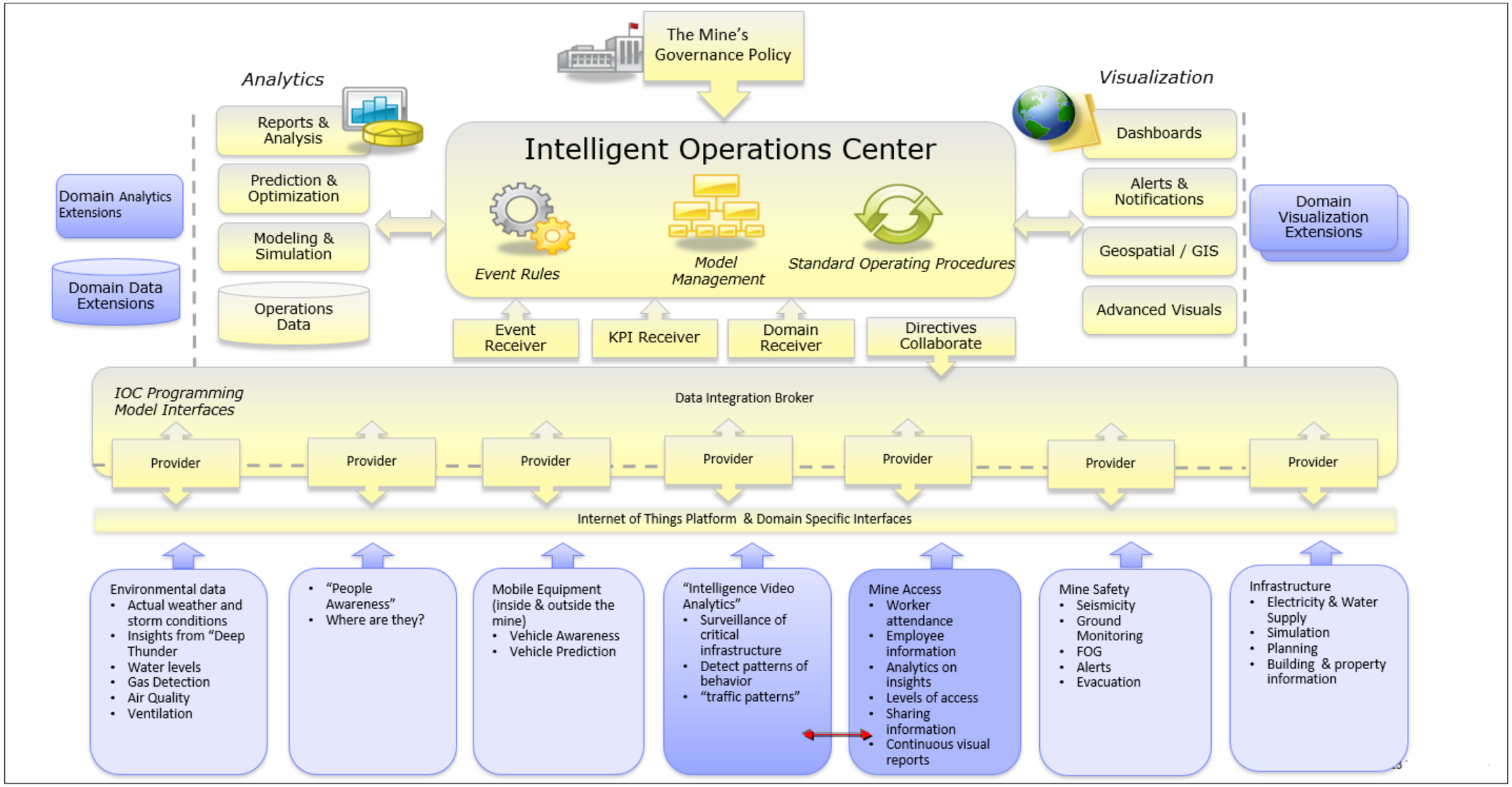


Figure 4.22 WMI-IBM Intelligent Operations Center architecture
(Source: WMI)

4.7 Conclusion

This chapter starts with conceptualising an intelligent information system for making smart, real-time decision in mining. Although, the concept covers the economics of mining, it could easily be expanded to include decisions for mine and health and safety. The chapter also explained the following: Process of IDM; basic architecture of MIM; architecture of IDM; architecture of MIM across the mining value chain; process of Intelligent Decision-Making through MIM (termed "IDM through MIM"); infrastructure requirements for MIM; WMI Mockup-mine to highlight importance of IoT in the implementation of MIM and IDM.

The following chapter will present conclusions and recommendations from this study. It will also provide suggestions on the next phase following implementation of MIM and IDM in a mine, and will present future prospects of this study.

5 CONCLUSION AND RECOMMENDATION

This chapter draws conclusions and recommendations from the study, and presents prospects on how 21st-century devices and technologies can assist improvement of mine planning and optimisation processes.

5.1 Overview

This study's research was aimed at developing a conceptual model for MIM and IDM. To achieve this, BIM was analysed in conjunction with currently-available mining-industry software. A comparison was made between "what is available and what is required by the mining industry". On the basis of this comparison, a conceptual model of MIM was developed. Using MIM, the concept of IDM was developed and its architecture was presented.

5.2 Key findings of the research

- MIM can be achieved via the combination of software from a number of providers, together with some additions. Ideally, the combination should cover the entire mining value chain;
- To use MIM effectively, IoT infrastructure in the mine is a prerequisite;
- By the means of MIM and IoT, IDM can be used for decision-making; and
- IDM can be used for economic as well as operational decision-making.

5.3 Conclusions of the study

- MIM will improve the process of mine-optimisation by considering all processes that affect mining operation and decisions;
- The current economic decision-making process is time-consuming and involves multiple risks due to uncertainties. IDM through MIM can overcome this problem;
- The benefits of MIM and IDM through MIM are not confined to mine planning and optimization or economic decision-making. MIM may also

be used for the complete mining value chain, and IDM through MIM may also be used for non-economic decisions;

- With the help of IoT, mines can improve their day-to-day operations; and
- This study is only a first-step towards MIM. Further study will be required to remove gaps, shortcomings and to materialise the concept.

Although some aspects of MIM are not fully quantifiable at this initial stage (e.g. some parts of MIM information are still conceptual), the future of the model is optimistic. It may take time to develop proposed MIM facets, but this should not discourage associated research. Many inventions, such as air travel, television and cellular-phones, appeared to be mere aspirations during their conceptual stages. Yet time proved these technologies to be not only real, but also beneficial to humankind. Similarly, conceptualising MIM from BIM will face challenges and require perseverance. Yet by exposing existing gaps, this study's research provides insight into what is needed. In doing so, quantifiable encouragement has been given to the fact that even though much work is required, MIM is achievable.

It furthermore needs to be understood that working in silos will be increasingly difficult in the 21st century. Most industries are taking advantage of technologies invented and used by other industries. Even the mining industry is taking advantage of other engineering disciplines such as telecommunication engineering, electrical and electronics engineering, mechanical and mechatronics engineering, etc. Clearly, the allegorical portrait of mining as a shovel is being eclipsed through extraordinary technology.

The same allegory applies to the construction industry. The fact is that prior to the development of BIM, the construction industry was plagued with multiple wastage and cost issues. BIM was conceived, but until research-analysis was able to quantify expected benefits, the concept could have been viewed as unreachable. Obviously, BIM development costs needed evaluation in relation to expected benefits. Obviously also, evaluation likely indicated that BIM development-costs vs. benefits were impractical in a one-company silo scenario. Thus today, BIM benefits many industries world-wide.

From a mining-industry perspective, some South African mines are between sixty and a hundred years old. Their lifecycle is reaching completion and it is time for

reclamation and rehabilitation. Yet a disturbing fact is that lack of adequate information on older areas of mines has inhibited reclamation and rehabilitation. If MIM had been available 60 years ago, then closure would have been substantially easier. Thus it stands to reason that MIM will enormously ease future mine closures through the volumes of on-line information that will be available. Furthermore, it also stands to reason that such information could extend the life of mines and enable implementation of future technologies.

5.4 Research limitations

- This research has primarily focused on conceptualisation of the idea. Materialisation of the concept will need to be followed by further research;
- Only software used in the South African mining industry was considered for this study; and
- Software capabilities stated in this study were based on supplier-company affirmations and were not tested during the study.

5.5 Recommendations and suggested future research

- Different mining companies in South Africa use different software for mine planning and optimization. There is, however, a need to develop a software platform (MIM) that incorporates all requirements that can also be used for intelligent decision-making;
- The South African Mining industry should consider developing IDM through MIM instead of using software that was not designed to make economic and other critical decisions;
- Modern-day technologies such as MIM can be one of the enablers for profitable growth in the mining industry;
- Further study on the topic is required to materialise the concept of MIM and IDM; and

- As part of prospective application of IDM through MIM, Virtual Reality and Augmented Reality should be evaluated to aid visualization in the IDM process.

5.6 Wits Mockup-mine architecture with MIM

Figure 5.1 shows the proposed architecture of the WMI Mockup-mine once MIM and IDM-through-MIM have been included. It is advised that the new systems (MIM and IDM through MIM) be installed on WMI's server computer (which is currently connected to other systems and the WMI spatial database). This will assist MIM and IDM-through-MIM in the collection of data from other systems, and enable display of results on the WMI video wall for decision-making.

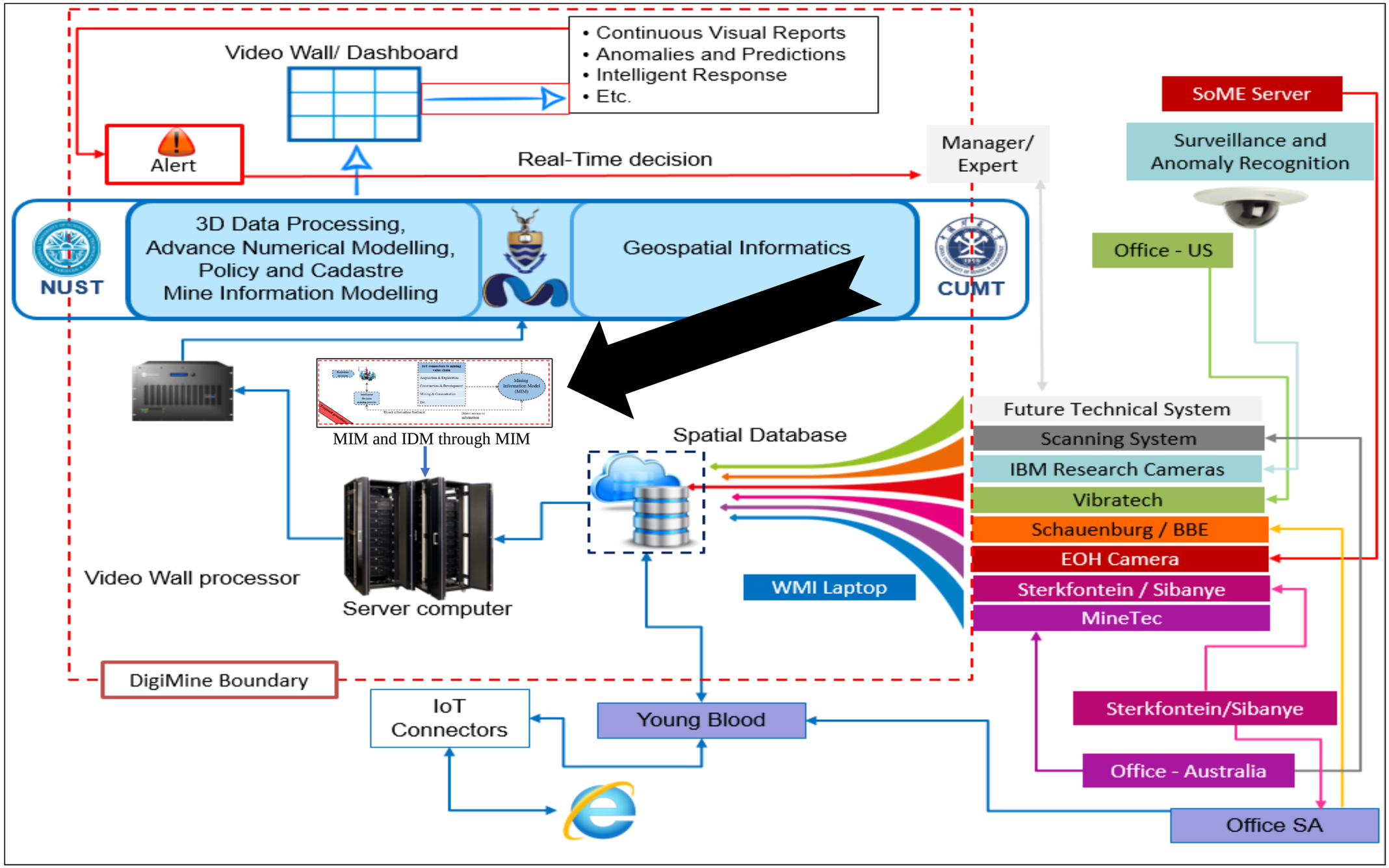


Figure 5.1 Architecture of Wits Mockup-mine with the addition of MIM and IDM through MIM
(Source: WMI)

5.7 Conclusion

In summary: This chapter presented study-conclusions and recommendations. The research strongly suggested that the mining industry consider using MIM and IDM-through-MIM processes to maximize profitability and sustainability. The chapter also motivated research to be continued to enable MIM to move from conceptual phase into development and testing phases. This will enable industry to assess MIM and IDM benefits for 21st-century mining benefits which could turn out to be comparable to computers which originally weighed approximately 45 metric tons and covered multiple floors of a single building, yet today weigh a few grams and cover minuscule portions of every cell phone.

REFERENCES

Ahmed, A., Bwisa, H., Otieno, R. & Karanja, K., 2014. Strategic Decision Making: Process, Models, and Theories. *Business Management and Strategy,* 5(1), pp. 78-104.

Anglo American Platinum, 2015. *Mine Profile: Mogalakwena.* [Online]
Available at: http://www.angloamerican.com/media/our-stories/mine-profile-mogalakwena
[Accessed 29 June 2017].

Anthony, R. N., 1965. *Planning and Control Systems: A Framework for Analysis.* s.l.:Division of Research, Graduate School of Business Administration, Harvard University, 1965.

Arumugam, A., 2012. *Costing Introduction.* [Online]
Available at: https://www.slideshare.net/seettarun/costing-introduction
[Accessed 21 May 2018].

ASHRAE, 2009. *An Introduction to Building Information Modeling (BIM): A Guide for ASHRAE Members,* Atlanta, United States of America: American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc..

Autodesk, 2009. *Revit Case Studies.* [Online]
Available at:
https://damassets.autodesk.net/content/dam/autodesk/www/industries/civil-infrastructure/water-wastewater-infrastructure/Docs/sundt_construction_customer_story.pdf
[Accessed 29 March 2017].

Autodesk, 2014. *Revit Case Studies.* [Online]
Available at:
https://damassets.autodesk.net/content/dam/autodesk/www/products/autodesk-

revit-family/docs/pdf/shanghai_tower_story_usletter_template_FY14.pdf
[Accessed 2 April 2017].

Azhar, S., Nadeem, A., Mok, J. Y. N. & Leung, B. H. Y., 2008. *Building Information Modeling (BIM): A New Paradigm for Visual Interactive Modeling and Simulation for Construction Projects.* Karachi, s.n., pp. 435-446.

Barrett, J., 2012. *Youtube: The Internet of Things: Dr. John Barrett at TEDxCIT*. [Online]
Available at: https://www.youtube.com/watch?v=QaTIt1C5R-M&t=257s
[Accessed 03 10 2017].

Bhorat, H., Naidoo, K. & Yu, D., 2014. *Trade Unions in an Emerging Economy: The case of South Africa.* Cape Town: Development Policy Research Unit, Univesrity of Cape Town.

Braham, S., 2017. Plan early for profitable mines. *Mining Prospectus,* Issue 32, pp. 24-26.

Chadwick, J., 2007. China Shenhua Coal. *International Mining,* pp. 12-16.

Chamber of Mines of South Africa, 2013/2014. *Facts & Figures 2013/2014*, Johannesburg: Chamber of Mines of South Africa.

Chamber of Mines of South Africa, 2017. *Facts and Figures 2016*, Johannesburg: Chamber of Mines of South Africa.

Chamber of Mines of South Africa, 2017. *Mine SA 2017: Facts and Figures Pocketbook*, Johannesburg: Chamber of Mines of South Africa.

Consult Australia and Australian Institute of Architects, C. A., 2012. *O5 Quantity surveyors & cost planners – How can BIM improve my business?.* [Online]
Available at: https://revitall.wordpress.com/2014/06/07/a-bimpicture-is-worth-a-thousand-unread-words/
[Accessed 2 April 2017].

Cox, J. & Schleier, J., 2010. In: *Theory of Constraints Handbook.* s.l.:McGraw-Hill, p. 149.

CRC Construction Innovation, 2007. *Adopting BIM for facilities management: Solutions for managing the Sydney Opera House,* Brisbane, Australia: Cooperative Research Centre for Construction Innovation.

CSIRO, 2016. *FastGrade: on-site elemental drillhole analysis.* [Online] Available at: https://www.csiro.au/en/Research/MRF/Areas/Ore-management/Intelligent-mining/Downhole-neutron-logging-tool [Accessed 19 June 2017].

CSIRO, 2016. *Optimising mining supply and transport.* [Online] Available at: https://www.csiro.au/en/Research/MRF/Areas/Ore-management/Intelligent-mining/Rio-Tinto-modelling [Accessed 19 June 2017].

CSIRO, 2016. *Rapid ore sorting.* [Online] Available at: https://www.csiro.au/en/Research/MRF/Areas/Ore-management/Intelligent-mining/Ore-sorter [Accessed 19 June 2017].

Davenport, J., 2013. *The 1987 mine strike.* [Online] Available at: http://www.miningweekly.com/article/the-1987-mineworkers-strike-2013-09-27 [Accessed 19 May 2017].

Department of Mineral Resources South Africa, 1996. *Mine Health and Safety Act, 1996.* Pretoria: Department of Mineral Resources South Africa.

Department of Mineral Resources, 2016. *Reviewed Broad Based Black-Economic Empowerment Charter for the South African Mining and Minerals Industry,* Prertoria: Green Gazette South Africa.

Dispenza, K., 2010. *The Daily Life of Building Information Modeling (BIM).* [Online]

Available at: http://buildipedia.com/aec-pros/design-news/the-daily-life-of-building-information-modeling-bim
[Accessed 30 March 2017].

Drury, C., 2012. Information for decision-making. In: *Management and Cost Accounting.* Hampshire: Cengage Learning EMEA, pp. 257-259.

Elsafadi, H., 2016. *BIM 3D to 7D Implementation.* [Online]
Available at: https://www.linkedin.com/pulse/bim-3d-7d-implementation-hani-elsafadi
[Accessed 03 April 2017].

Folger, P., 2009. *Geospatial Information and Geographic Information Systems (GIS): Current Issues and Future Challenges ,* s.l.: Congressional Research Service.

Genc, B. & Musingwini, C., 2016. *Estimating Mine Planning Software Utilisation for Decision-Making Strategies in the South African Diamonds Mining Sector.* Turkey, s.n.

Genc, B., Musingwini, C. & Celik, T., 2016. Estimating mine planning software utilization for decision-making strategies in the South African coal mining sector. *The Journal of The South African Institute Mining and Metallurgy,* 116(3), pp. 221-227.

Goerlich, K., 2016. *How Quickly Are Industries Adopting the Internet of Things?.* [Online]
Available at: http://www.digitalistmag.com/iot/2016/03/02/how-quickly-are-industries-adopting-the-internet-of-things-2-04044088
[Accessed 13 7 2017].

Goldratt, E. & Cox, J., 2004. In: *The Goal: A Process of Ongoing Improvement.* Great Barrington: North River Press, p. 313.

Gomori, P., 2016. *IoT Makes Construction Machinery More Productive and Intelligent.* [Online]

Available at: https://www.engineering.com/IOT/ArticleID/11408/IoT-Makes-Construction-Machinery-More-Productive-and-Intelligent.aspx
[Accessed 25 September 2017].

Guj, P. et al., 2017. *Transfer Pricing in Mining with a Focus on Africa: A Reference Guide for Practitioners.* Washington, D.C.: World Bank Group.

High, R., 2012. *The Era of Cognitive Systems: An Inside Look at IBM Watson and How it Works*, New York: IBM Corp.

Hungu, C. F., 2013. *Utilization of BIM from Early Design Stage to facilitate efficient FM Operations,* Goteborg, Sweden: Department of Civil and Environmental Engineering, Division of Construction Management, Chalmers University of Technology.

Jianguo, H., 2015. *Shenhua's Development of Digital Mines.* [Online]
Available at: http://www.studentnewsrox.com/?p=143
[Accessed 9 17 2017].

Kettering University, 2016. *5 Steps to Understanding and Applying the Theory of Constraints.* [Online]
Available at: https://online.kettering.edu/news/2016/07/25/5-steps-understanding-and-applying-theory-constraints
[Accessed 23 May 2018].

Lind, G. H., 2001. Activity Based Costing: Challenging the way we cost underground coal mining systems. *The Journal of The South African Institute of Mining and Metallurgy*, Issue 2, pp. 77-82.

Meola, A., 2016. *Why IoT, big data & smart farming are the future of agriculture.* [Online]
Available at: http://www.businessinsider.com/internet-of-things-smart-agriculture-2016-10
[Accessed 13 7 2017].

Merry, H., 2017. *5 benefits IoT is having on the mining industry.* [Online]
Available at: https://www.ibm.com/blogs/internet-of-things/mining-industry-benefits/
[Accessed 25 May 2017].

Mihindu, S. & Arayici, Y., 2008. *Digital Construction through BIM Systems will drive the Re-engineering of Construction Business Practices.* London, IEEE Computer Society.

MineRP, n.d. *MineRP Solutions.* [Online]
Available at: http://www.minerp.com/solutions
[Accessed 15 11 2017].

Minxcon Group, 2017. *Gold Cost Curves,* Roodepoort: Minxcon Group.

Müller, J. & Frimmel, H., 2010. Numerical Analysis of Historic Gold Production Cycles and Implications for Future Sub-Cycles. *The Open Geology Journal,* Volume Vol. 4, pp. 29-34.

NBS, 2016. *National BIM Report 2016,* Newcastle upon Tyne: Riba Enterprises Limited.

Nederveen, G. v. & Tolman, F. P., 1992. Modelling multiple views on buildings. *Automation in Construction,* 1(3), pp. 215-224.

Opiti, C., 2017. *A Spatio-Temporal Modelling and Analysis of Digital Sensor Data for Underground Mine Health and Safety,* Johannesburg: University of the Witwatersrand.

Pristine, E., 2017. *Costing Methods & Important Cost Terms.* [Online]
Available at: https://www.edupristine.com/blog/costing-methods
[Accessed 21 May 2018].

Prowse, K., 2014. *The Internet of Things in Mining: A Billion-Dollar Toy Store.* [Online]
Available at: https://techvibes.com/2014/12/09/mining-things-internet-2014-12-

09
[Accessed 27 March 2017].

Reed, S., 2014. *Despite Slowdown in China, Rio Tinto Stays Committed to Mining Plans.* [Online]
Available at: https://www.nytimes.com/2014/04/03/business/international/despite-slowdown-in-china-rio-tinto-stays-committed-to-mining-plans.html
[Accessed 19 7 2017].

Rio Tinto, n.d. *Mine of the Future™.* [Online]
Available at: http://www.riotinto.com/australia/pilbara/mine-of-the-future-9603.aspx
[Accessed 03 October 2017].

Singh, N. & Macfarlane, A., 2018. *Presentation to Mining Engineering Education South Africa (MEESA) Forum.* Johannesburg: Mining Precinct at Carlow Road.

South African Reserve Bank, 2017. *Selected historical rates: Rand per U S Dollar.* [Online]
Available at: https://www.resbank.co.za/Research/Rates/Pages/SelectedHistoricalExchangeAndInterestRates.aspx
[Accessed 20 March 2017].

Srivastava, S. C. & Teo, T. S. H., 2004. *IT Training as a Strategy for Business Productivity: A Framework for Small and Medium-Sized Enterprises in Asia.* s.l., AIS Electronic Library (AISeL).

Statistics South Africa, 2012. *National Accounts: Mineral Accounts for South Africa: 1980–2009,* Pretoria: Statistics South Africa.

Vella, H., 2013. *Rio Tinto's autonomous mining trucks.* [Online]
Available at: https://www.mining-technology.com/features/featurerio-tinto-autonomous-trucks-haulage-milestone/
[Accessed 23 May 2018].

Walker, G. et al., 2017. *The digital disconnect: problem or pathway?,* s.l.: EYGM Limited.

Wentzel, F., 2012. *Productivity and Cost Management.* s.l.:PricewaterhouseCoopers (PwC).

World Bank, 2017. *Commodity Markets (Pink Sheet).* [Online] Available at: http://pubdocs.worldbank.org/en/204941488488024459/CMO-Pink-Sheet-March-2017.pdf [Accessed 20 March 2017].

World Bank, 2017. *The World Bank In South Africa.* [Online] Available at: http://www.worldbank.org/en/country/southafrica/overview [Accessed 12 7 2017].

Wu, L. & Che, D., 2008. Developments of spatial information-based Digital Mine in China. *Journal of Coal Sciences & Engineering (China),* 14(3), pp. 415-419.

Yu-fang, L. & Jin-xing, S., 2011. Using the Internet of Things Technology Constructing Digital Mine. *Procedia Environmental Sciences,* Volume 10, pp. 1104-1108.

Zhu, P., 2017. *Decision Master: The Art and Science of Decision Making.* s.l.:BookBaby.

APPENDICES

Appendix A

Calculation of possible increase in revenue. Statistics used in the section 1.2.1 of chapter 1.

- **Production**
  - Production of platinum in 2014-2015 = 275.5 metric tons
  - 1 metric ton = 32 150 troy ounce (toz)

- **Production in toz**
  - Total production in toz = 275.5 (production of that time) x 32 150 = 8 857 325 toz …….. Eq. 1
  - Production multiplied by rate of platinum in 2015 = 8 857 325 x 1 384 = $ 12 258 537 800 …….. Eq. 2
  - Production multiplied by rate of platinum in 2014 = 8 857 32 x 1 053 = $ 9 326 736 225 …….. Eq. 3
  - Difference of 2015 and 2014 (Eq. 2 – Eq. 3) = $2 931 774 575 ……. Eq. 4

- **USD to ZAR exchange rates**
  - Average USD to ZAR price in 2015 = 12.76 ZAR/USD
  - Average USD to ZAR price in 2014 = 10.84 ZAR/USD
  - Average of 2014-2015 = 11.8 ZAR/USD ……. Eq. 5
  - Difference of production in USD by average exchange rate:
    2 931 774 575 (Eq. 4) x 11.8 (Eq. 5) = 34 594 939 985 ZAR ≈ 34.6 billion ZAR

- **Total sales of 2014 to 2015**

  Total sales of 2014-2015 = ZAR 94.14 billion

- **Expected / possible revenue**

  Expected sale if price would have remained the same or known: ZAR 94.14 billion + ZAR 34.6 billion = ZAR 128.8 billion ……. Eq. 6

- **Possible effect on total sale of 2015 with new figure (Eq. 6)**
  - Employee earning was 43.6 billion from 94.14 billion which is 46.31%. Applying the same percentage (46.31%) to 128.8 billion (Eq. 5) = 59.64 billion ZAR
  - Royalties paid are 0.72 billion out of total 94.14 billion which is 0.76%. Applying the same percentage (0.76%) on 128.8 billion = 0.97 billion ZAR.
  - 34.6 billion ZAR is 36.7 % of 94.14 billion ZAR

Appendix B: Table A Microsoft Excel formulas used to illustrate the example 2 (section 4.4 of chapter 4) in decision-making concept.

Scenario 1											
Sr. No.	**Required info**	**Sub category**	**Status**	**Sub category**	**Status**	**Sub category**	**Status**	**Can be arranged**	**Cannot be arranged**	**Possible**	**Not possible**
1	**Resource - processes**	Orebody	1							=IF(E3=1,1,IF(J3=1,1,0))	=IF(K3=1,1," ")
2		Drill and blast	1							=IF(E4=1,1,IF(J4=1,1,0))	=IF(K4=1,1," ")
3		LHD	1							=IF(E5=1,1,IF(J5=1,1,0))	=IF(K5=1,1," ")
4		Hoist	1							=IF(E6=1,1,IF(J6=1,1,0))	=IF(K6=1,1," ")
5		Primary processing	1							=IF(E7=1,1,IF(J7=1,1,0))	=IF(K7=1,1," ")
6		Secondary processing	1							=IF(E8=1,1,IF(J8=1,1,0))	=IF(K8=1,1," ")
7	**Resource - general**	Labour	1							=IF(E9=1,1,IF(J9=1,1,0))	=IF(K9=1,1," ")
8		Power	1							=IF(E10=1,1,IF(J10=1,1,0))	=IF(K10=1,1," ")
9		Time (Shifts)	1							=IF(E11=1,1,IF(J11=1,1,0))	=IF(K11=1,1," ")
10		Plant	1							=IF(E12=1,1,IF(J12=1,1,0))	=IF(K12=1,1," ")
11		Health and safety	1							=IF(E13=1,1,IF(J13=1,1,0))	=IF(K13=1,1," ")
12	**Product mix**	**Increase concentrate - 5%**		Change in orebody	1					=IF(G14=1,1,IF(J14=1,1,0))	=IF(K14=1,1," ")
13				Drill and blast	1					=IF(G15=1,1,IF(J15=1,1,0))	=IF(K15=1,1," ")
14				LHD and hoist	1					=IF(G16=1,1,IF(J16=1,1,0))	=IF(K16=1,1," ")
15				**Input balance in plants**		Power	1			=IF(I17=1,1,IF(J17=1,1,0))	=IF(K17=1,1," ")
16						Shift	1			=IF(I18=1,1,IF(J18=1,1,0))	=IF(K18=1,1," ")
17						Throughput	1			=IF(I19=1,1,IF(J19=1,1,0))	=IF(K19=1,1," ")
18						Labour	1			=IF(I20=1,1,IF(J20=1,1,0))	=IF(K20=1,1," ")
19						Maintenance	1			=IF(I21=1,1,IF(J21=1,1,0))	=IF(K21=1,1," ")
20						Time	1			=IF(I22=1,1,IF(J22=1,1,0))	=IF(K22=1,1," ")
21						SHEQ	1			=IF(I23=1,1,IF(J23=1,1,0))	=IF(K23=1,1," ")
22	**Prices forecast**	Currency exchange rate	1							=IF(E24=1,1,IF(J24=1,1,0))	=IF(K24=1,1," ")
23		Commodity prices	1							=IF(E25=1,1,IF(J25=1,1,0))	=IF(K25=1,1," ")
24	**Capacity bottlenecks and Constraints**	Transport to market	1							=IF(E26=1,1,IF(J26=1,1,0))	=IF(K26=1,1," ")
25		Regulatory	1							=IF(E27=1,1,IF(J27=1,1,0))	=IF(K27=1,1," ")
26		Product specification	1							=IF(E28=1,1,IF(J28=1,1,0))	=IF(K28=1,1," ")
27		Capacity bottlenecks	1							=IF(E29=1,1,IF(J29=1,1,0))	=IF(K29=1,1," ")
Decision						=IF(M31>=1,1,0)					=COUNT(M3:M28)

Appendix C: Table B Microsoft Excel formulas used to illustrate the example 2 (section 4.4 of chapter 4) in decision-making concept.

Scenario 2											
Sr. No.	**Required info**	**Sub category**	**Status**	**Sub category**	**Status**	**Sub category**	**Status**	**Can be arranged**	**Cannot be arranged**	**Possible**	**Not possible**
1	**Resource - processes**	Orebody	1							=IF(E3=1,1,IF(J3=1,1,0))	=IF(K3=1,1," ")
2		Drill and blast	1							=IF(E4=1,1,IF(J4=1,1,0))	=IF(K4=1,1," ")
3		LHD	1							=IF(E5=1,1,IF(J5=1,1,0))	=IF(K5=1,1," ")
4		Hoist	1							=IF(E6=1,1,IF(J6=1,1,0))	=IF(K6=1,1," ")
5		Primary processing	1							=IF(E7=1,1,IF(J7=1,1,0))	=IF(K7=1,1," ")
6		Secondary processing	1							=IF(E8=1,1,IF(J8=1,1,0))	=IF(K8=1,1," ")
7	**Resource - general**	Labour	1							=IF(E9=1,1,IF(J9=1,1,0))	=IF(K9=1,1," ")
8		Power	1							=IF(E10=1,1,IF(J10=1,1,0))	=IF(K10=1,1," ")
9		Time (Shifts)	1							=IF(E11=1,1,IF(J11=1,1,0))	=IF(K11=1,1," ")
10		Plant	1							=IF(E12=1,1,IF(J12=1,1,0))	=IF(K12=1,1," ")
11		Health and safety	1							=IF(E13=1,1,IF(J13=1,1,0))	=IF(K13=1,1," ")
12	**Product mix**	**Increase concentrate - 5%**		Change in orebody	1					=IF(G14=1,1,IF(J14=1,1,0))	=IF(K14=1,1," ")
13				Drill and blast	1					=IF(G15=1,1,IF(J15=1,1,0))	=IF(K15=1,1," ")
14				LHD and hoist	0			1		=IF(G16=1,1,IF(J16=1,1,0))	=IF(K16=1,1," ")
15				**Input balance in plants**		Power	1			=IF(I17=1,1,IF(J17=1,1,0))	=IF(K17=1,1," ")
16						Shift	1			=IF(I18=1,1,IF(J18=1,1,0))	=IF(K18=1,1," ")
17						Throughput	1			=IF(I19=1,1,IF(J19=1,1,0))	=IF(K19=1,1," ")
18						Labour	1			=IF(I20=1,1,IF(J20=1,1,0))	=IF(K20=1,1," ")
19						Maintenance	1			=IF(I21=1,1,IF(J21=1,1,0))	=IF(K21=1,1," ")
20						Time	1			=IF(I22=1,1,IF(J22=1,1,0))	=IF(K22=1,1," ")
21						SHEQ	1			=IF(I23=1,1,IF(J23=1,1,0))	=IF(K23=1,1," ")
22	**Prices forecast**	Currency exchange rate	1							=IF(E24=1,1,IF(J24=1,1,0))	=IF(K24=1,1," ")
23		Commodity prices	1							=IF(E25=1,1,IF(J25=1,1,0))	=IF(K25=1,1," ")
24	**Capacity bottlenecks and Constraints**	Transport to market	1							=IF(E26=1,1,IF(J26=1,1,0))	=IF(K26=1,1," ")
25		Regulatory	1							=IF(E27=1,1,IF(J27=1,1,0))	=IF(K27=1,1," ")
26		Product specification	1							=IF(E28=1,1,IF(J28=1,1,0))	=IF(K28=1,1," ")
27		Capacity bottlenecks	1							=IF(E29=1,1,IF(J29=1,1,0))	=IF(K29=1,1," ")
Decision						=IF(M31>=1,1,0)					=COUNT(M3:M29)

Appendix D: Table C Microsoft Excel formulas used to illustrate the example 3 (section 4.4 of chapter 4) in decision making concept.

Scenario 3											
Sr. No.	**Required info**	**Sub category**	**Status**	**Sub category**	**Status**	**Sub category**	**Status**	**Can be arranged**	**Cannot be arranged**	**Possible**	**Not possible**
1	**Resource - processes**	Orebody	1							=IF(E3=1,1,IF(J3=1,1,0))	=IF(K3=1,1," ")
2		Drill and blast	1							=IF(E4=1,1,IF(J4=1,1,0))	=IF(K4=1,1," ")
3		LHD	1							=IF(E5=1,1,IF(J5=1,1,0))	=IF(K5=1,1," ")
4		Hoist	1							=IF(E6=1,1,IF(J6=1,1,0))	=IF(K6=1,1," ")
5		Primary processing	1							=IF(E7=1,1,IF(J7=1,1,0))	=IF(K7=1,1," ")
6		Secondary processing	1							=IF(E8=1,1,IF(J8=1,1,0))	=IF(K8=1,1," ")
7	**Resource - general**	Labour	1							=IF(E9=1,1,IF(J9=1,1,0))	=IF(K9=1,1," ")
8		Power	1							=IF(E10=1,1,IF(J10=1,1,0))	=IF(K10=1,1," ")
9		Time (Shifts)	1							=IF(E11=1,1,IF(J11=1,1,0))	=IF(K11=1,1," ")
10		Plant	1							=IF(E12=1,1,IF(J12=1,1,0))	=IF(K12=1,1," ")
11		Health and safety	1							=IF(E13=1,1,IF(J13=1,1,0))	=IF(K13=1,1," ")
12	**Product mix**	**Increase concentrate - 5%**		Change in orebody	1					=IF(G14=1,1,IF(J14=1,1,0))	=IF(K14=1,1," ")
13				Drill and blast	1					=IF(G15=1,1,IF(J15=1,1,0))	=IF(K15=1,1," ")
14				LHD and hoist	0			1		=IF(G16=1,1,IF(J16=1,1,0))	=IF(K16=1,1," ")
15				**Input balance in plants**		Power	1			=IF(I17=1,1,IF(J17=1,1,0))	=IF(K17=1,1," ")
16						Shift	1			=IF(I18=1,1,IF(J18=1,1,0))	=IF(K18=1,1," ")
17						Throughput	1			=IF(I19=1,1,IF(J19=1,1,0))	=IF(K19=1,1," ")
18						Labour	1			=IF(I20=1,1,IF(J20=1,1,0))	=IF(K20=1,1," ")
19						Maintenance	0		1	=IF(I21=1,1,IF(J21=1,1,0))	=IF(K21=1,1," ")
20						Time	1			=IF(I22=1,1,IF(J22=1,1,0))	=IF(K22=1,1," ")
21						SHEQ	1			=IF(I23=1,1,IF(J23=1,1,0))	=IF(K23=1,1," ")
22	**Prices forecast**	Currency exchange rate	1							=IF(E24=1,1,IF(J24=1,1,0))	=IF(K24=1,1," ")
23		Commodity prices	1							=IF(E25=1,1,IF(J25=1,1,0))	=IF(K25=1,1," ")
24	**Capacity bottlenecks and Constraints**	Transport to market	1							=IF(E26=1,1,IF(J26=1,1,0))	=IF(K26=1,1," ")
25		Regulatory	1							=IF(E27=1,1,IF(J27=1,1,0))	=IF(K27=1,1," ")
26		Product specification	1							=IF(E28=1,1,IF(J28=1,1,0))	=IF(K28=1,1," ")
27		Capacity bottlenecks	1							=IF(E29=1,1,IF(J29=1,1,0))	=IF(K29=1,1," ")
Decision						=IF(M31>=1,1,0)					=COUNT(M3:M29)