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Assessing the implementation of a low-profile roof-bolter in a platinum mining section based on a systems approach

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Assessing the implementation of a Low-Profile Roof-bolter in a platinum mining section based on a systems approach

University of the Witwatersrand



by

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A report submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering

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Abstract

The drive towards mechanisation is currently in transition in many South African mines, and although it is being met with mixed reviews due to the high risks it involves and the rate of failure in implementation, it is regarded as an eminent solution around the current state of the industry. From the Original Equipment Manufacturers (OEM) to the mines, the establishment of requirements and specifications for underground trackless mechanised mining equipment is far from being an efficient process, leading to a solution prone to errors and a potentially unsuccessful implementation a piece of equipment.

The discipline of systems engineering has proven to provide integrated solutions to multidisciplinary industries in the past, and in many instances, has worked in different settings from manufacturing to aerospace and automotive to name but a few. Applying systems thinking to a set of requirements, can lead to the delivery of a holistic model that would allow the generation of specifications which would provide an adaptable solution to meet the initial requirements.

The introduction and implementation of trackless mechanised mining equipment within an existing traditional drill and blast underground mining operation would be more prone to success if implemented with a systems engineering mind-set.

A fleet of low profile equipment which generally includes face drill rigs, roof-bolters, LHDs and dozers, need to be implemented in-stope as part of a whole mechanised system. Each piece of equipment can be regarded as its own independent subsystem whose implementation can individually be optimised. Stabilizing the rock mass within the vicinity of the excavation after blasting the rock is critical in order to reduce potential hazards associated with rockfalls and rockbursts and increase safety. Falls of ground (FOG) remain the main contributor of fatalities in narrow reef stopes and an adequate implementation strategy for mechanised support needs to be addressed.

The research presented investigates a systems approach to develop a framework for implementing a low profile roof-bolter in a section of a narrow reef platinum mining operation for in-stope support. A number of specifications are generated based on initial requirements and the proposed framework is measured as a case study at a platinum mining operation. This framework is developed by means of systems engineering tools and is mainly based on assumptions.

Declaration

I declare that this research is my own, unaided work. It is submitted for the Degree of Master of Science in Mining Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University. I have read the University policy on plagiarism and hereby confirm that no plagiarism exists in this thesis. I also confirm that there is no copying nor is there any copyright infringement. I willingly submit to any investigation in this regard by the School of Mining Engineering and I undertake to abide by the decision of any such investigation.

_____

Lwabanji Tony Lumbwe
Candidate

_____ day of _____ 20_____ at _____

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Dedication

To my dear mother
Lwabandji Kindja Esther
You are appreciated.

To my nieces and my nephew
Maiah Diana, Kaylie Kindja, Kehlani and Kylian
Wobble heads!

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Chapter 1

Introduction

1.1 Overview

The poor state of the South African platinum mining industry has raised concerns not only because of the low and volatile commodity price, but also additional factors such as rising mining costs (mines are getting deeper and unsafe), industrial unrest, orebody complexity and unreliable electricity to name but a few. These factors have forced mining companies to either operate on very strict cost cutting measures or to alter the way they have been mining in order to remain profitable (Lisle 2017).

The 21st century has seen mechanisation being introduced in an effort to improve safety, reduce cost and revive the industry. Each step of the traditional mining cycle can be completed by means of a piece of equipment with unique properties and which can be manufactured to fit particular underground conditions. Hanging wall support at the face represents a crucial step of the mining cycle since, as reported by the Chamber of Mines of South Africa (2016), falls of ground (FOG) at the face represent the greatest single contributor to fatalities.A systems engineering approach can be used to introduce new equipment such as a roof-bolter. This approach has been successfully used in other industries and should insure higher rate of successful implementation.

This introductory chapter will briefly cover background topics around the mining cycle and the current state of the platinum mining industry in South Africa. It will also give a detailed look at the objectives of the research here presented, as well as its contribution. An outline of the document will also be provided.

1.2 Background

South Africa is renowned for its abundance of precious metals in particular gold and Platinum Group Metals (PGMs). The mining industry has been a major contributor

to the development of the South African economy and continues to play a vital role in shaping the country's socio-political and cultural development (Minnitt 2014).

South Africa hosts tabular and narrow gold and platinum reef deposits that are located at depths up to and exceeding 3 km, lying at various dip angles. Due to this nature of the reefs, the in-stope excavation and extraction of the ore-bearing rocks progresses with the face advancing by as little as 1 to 2 meters per day. The traditional and currently preferred mining method in most South African gold and PGM mines is known as "drill and blast" or conventional mining, where holes are drilled into the rock using handheld drills and explosives are charged in order to break the rock and expose the ore. The ore is then mucked or cleaned away from the face and support is installed. The mining cycle is shown in Figure 1.1.

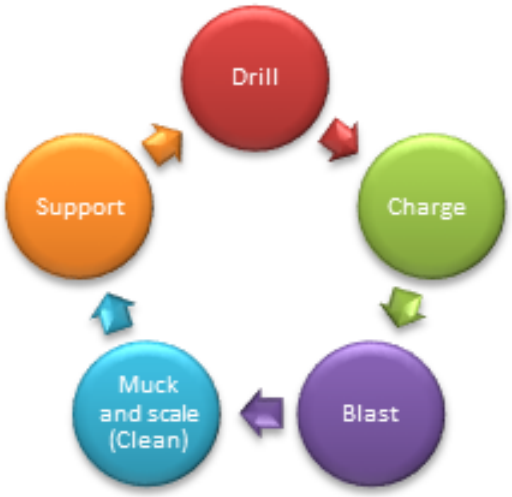

Figure 1.1: The underground conventional drill-and-blast mining cycle (Adapted from Al-Chalabi et al. (2016)

Over time, the rise in labour costs associated with demands for above-inflation increases, strikes, market volatility and other socio-economic problems that took place over the past few years, have caused major problems to the mining industry. Bohlmann et al. (2015) affirm that the five months strike that took place in the platinum industry in 2014 following the wage increase demands by the miners, had not only affected production throughout the country for the following years but had also forced mining companies to start taking drastic measures. Major restructuring and cost cutting programs have taken place in order to maintain economic viability (Baxter 2015). Further to this, the economic implications in terms of investor confidence are predicted to have a harmful effect in the future (Bohlmann et al. 2015).

A look into the future of the industry predicts that the mineable gold and PGMs in South Africa will become uneconomic by 2035 and 2045, respectively, if no action is

taken and if conventional mining is maintained as the preferred mining method. This statement was confirmed during "Mining Phakisa" which took place in November 2015 and where discussions were raised with regards to the current state of the industry, implying that action needs to be taken thereof to positively impact the industry (Singh 2017).

Considering the global advancement in technology, there is a clear call for change in the South African gold and PGM mining sectors. In order to survive, it is clear that the mining method has to radically change. The concept of change is quite broad and the introduction of a technological and futuristic mind-set remains a challenge. According to Hattingh et al. (2010), modernising the industry would require two elements:

1. Introducing machines and automation into mining operations (mechanisation) and;

2. Changing the culture of the people from every level, who are involved from planning to everyday operations (human factors).

For the research presented here, both elements will be covered, although more emphasis will be put on mechanisation.

1.3 Research objectives

A number of South African PGMs mining companies have attempted to introduce underground mechanisation within some of their operations with different levels of success. Optimising the implementation of mechanised mining equipment in the South African underground mining context will be of great benefit since it is possible to streamline the process, thus contributing to bringing solutions to the threats faced by the industry (Hattingh et al. 2010).

The discipline of systems engineering has been successfully used in many industries. A systems approach provides a synthesis of thinking with an integrated perspective about a complex system or process. It focuses on the analysis and deconstruction of a system or process in order to reveal the functions of each component in isolation and study the interactions between them with the goal of understanding how the system as a whole can function more efficiently (Dettmer 2005).

The introduction and implementation of trackless mechanised mining equipment within an existing traditional drill and blast mining operation would likely be more prone to success if implemented with a systems approach because it has shown its capabilities in fields such as aerospace and defence and is now the standard approach used in those industries (Wertz & Larson 2008) .

A fleet of low profile equipment which generally includes face drill rigs, roof-bolters, load haul and dump (LHD) trucks and dozers, would need to each be implemented in-stope as part of a whole mechanised system. Each sub-system can in turn, be regarded as its own independent system and its implementation can be optimised individually, since the requirements and specifications for each type of equipment differ.

Stabilizing the rock mass within the vicinity of the excavation after blasting the rock is critical in order to reduce potential hazards associated with rockfalls and rockbursts, and increase safety. According to Ferreira (2012), falls of ground (FOG) remain the main contributor of fatalities in narrow reef stopes and an adequate implementation strategy for mechanised support needs to be investigated. Additionally, the general poor performance of roof-bolters in narrow reef mines, particularly when first introduced, is symptomatic of a suboptimal process in terms of specifying and implementing the bolters (Kekana 2018).

The aim of the research presented here is to develop a systems engineering framework for the implementation of a roof-bolter in an underground platinum mine. The framework will then be used to identify the points of failure in a typical implementation process of a roof-bolter. Having identified these points of failure, the development, deployment and ongoing operations of the equipment can ultimately be optimised.

In line with this aim, the following research questions can be asked:

1. What processes or methods will be used for the development of the framework?
2. What criteria will be used to validate the reliability of the framework?

The objective of the research will be to evaluate whether a systems engineering approach could enhance the level of success of implementation of the roof-bolter in an underground platinum mine. Following the development of the framework, a case study will be undertaken in order to identify whether or not the framework is efficient at identifying gaps in the original implementation.

The research is focused on a single piece of equipment, which is the roof-bolter, because it is often described as the bottle-neck in underground mining operations since an improper understanding of this process could end up being costly to the mine (Spearing & Heyett 2014).

The scope of this project does not extend to investigate the system comprised of the whole fleet of mining equipment within the mechanised mining cycle although the resulting framework could be adapted to a higher systems implementation.

The study is confined to PGMs rather than gold mines because their lower dip makes them more amenable to trackless mobile mining equipment.

1.4 Significance and contribution

Mehanisation has been attempted in a number of South African PGM mines with different results, successful as much as unsuccessful (Conradie 2018). For many decades, systems engineering has been applied to other industries including aerospace and automotive to name but two, with room for flexibility in creating working frameworks based on different systems engineering tools (Reid et al. 2005).

The research presented here will define a framework for assessing the implementation of one single piece of mechanised equipment which, if applied successfully and accurately, could be altered to fit with all other mechanised equipment of an underground platinum mine fleet.The framework will serve as an identifier of gaps from the implementation and allow to improve and optimise the ongoing operations at the mine.

1.5 Research delineation

The framework will strictly be based on a systems engineering approach and systems engineering tools previously used in various industries and which will be adapted to a roof-bolter implementation in an underground South African platinum mine.

1.6 Thesis Outline

The document is structured as follows:

- Chapter 2 will cover a brief literature review around mechanisation and its challenges in a South African context as well as a brief overview of systems engineering;
- Chapter 3 will cover the systems engineering tools and the proposed methodology for the realisation of the framework.
- Chapter 4 will deconstruct the process involved in implementing the roof-bolter rig by using each one of the tools covered in the previous chapter.
- Chapter 5 is a case study conducted at a South African mechanised platinum mine and see how the framework compares with what has been accomplished at the mine.
- Chapter 6 will conclude and summarise the research and provide recommendations for future work.

1.7 Summary

A background leading to the importance of the research was provided and the objectives of the research were clearly identified. The major impact of the research was given through its significance and contribution, and the contents upcoming chapters were also briefly outlined.

The chapter to follow will cover a brief overview of mechanisation and its implementation challenges viewed in a South African platinum mining context. An brief overview of systems engineering and what it entails will also be covered.

Chapter 2

Background to roof-bolter mechanisation

2.1 Introduction

The mining cost in South African platinum mines has gradually risen over time as mining progressed. This is mainly attributed to the dipping nature of the tabular geology of the platinum deposits in the Bushvelt Complex region, particularly the Merensky and the UG2 platinum reefs (Van Schoor et al. 2006).

The further the face gets from the shaft, the more difficult it becomes for men to mine, in addition to which the conditions related to heat, men and ore movement as well as other factors, are inadequate. Mechanising the traditional drill and blast process in a mine could improve many aspects of mining if the implementation is done accurately with a high level of detail, and by following an approach that is appropriate for such a transition (Conradie 2018).

This chapter describes underground mining mechanisation by presenting its objectives. It further highlights the potential challenges faced when introducing a roof-bolter as part of the drive towards mechanisation in a platinum mine and briefly presents an overview of systems engineering and the different stages involved in a systems approach process.

2.2 Objectives and background of underground mining mechanisation

According to Robbins (2000), the objectives of mechanisation can be summarised by accomplishing the goals presented in Figure 2.1, which in turn can be summarised as follows:

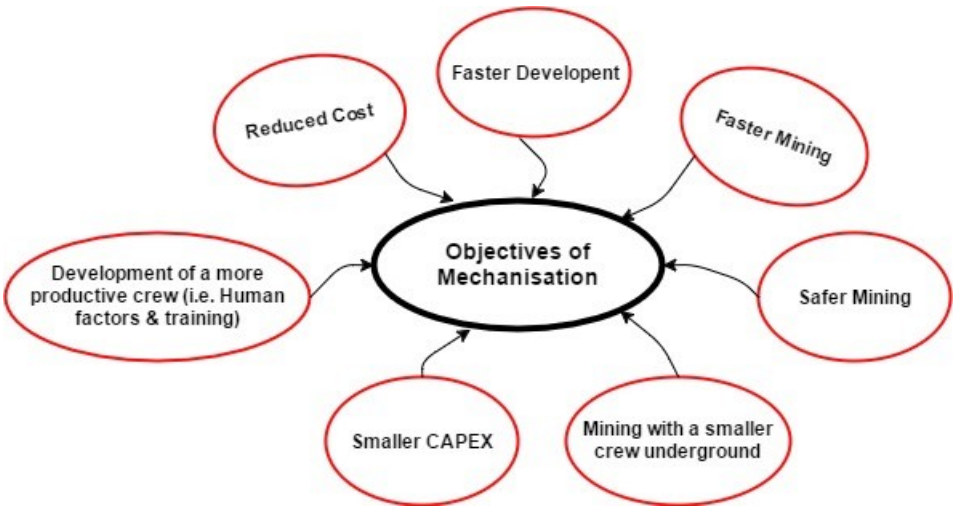

Figure 2.1: Objectives of mechanisation according to Robbins (2000)

1. Improve safety underground by introducing underground trackless equipment, which ultimately would remove the operators and mining staff from the face. Mechanisation not only promotes a much safer environment for the workforce, but also reduces the cost associated with production breaks due to stoppages caused by fatal accidents (Hattingh et al. 2010).

2. Improve the Net Present Value (NPV) of the mining operation by fast-tracking the development of the mine which is crucial as it is associated with the cost incurred until the first ore is produced (payback period). Additionally, investing in mechanised equipment will initially be regarded as a high expenditure but will ultimately lead to a sustainable cost over a given time.

2.3 The mechanised mining cycle

South African narrow reef platinum mines that have implemented a fleet of trackless mechanised equipment in sections of their operations, have done it according to the mining method that was initially used. According to Willis et al. (2004), the two variations around the mining method commonly used in South African platinum mines can be summarised as follows:

1. Bord and pillar: This method uses a simple layout and delivers high tonnage. It is also considered to be safer since the pillars are used as primary support although it is also known to limit the equipment utilisation due to the complexity involved when manoeuvring between bords;

2. Breast mining: It is generally implemented in low profile mining with low stoping widths and is known to have a good extraction ratio. However, movement of equipment between panels is also rendered complex by strike belts between them.

The fleet of equipment that needs to be included in the mining operation will follow a similar cycle as the conventional drill and blast shown earlier and each piece of equipment will be utilised for a single process of the cycle. An example of fleet of equipment used at one of Anglo American Platinum operations is shown in Figure 2.2 , where the following equipment can be identified (Fourie et al. 2014):

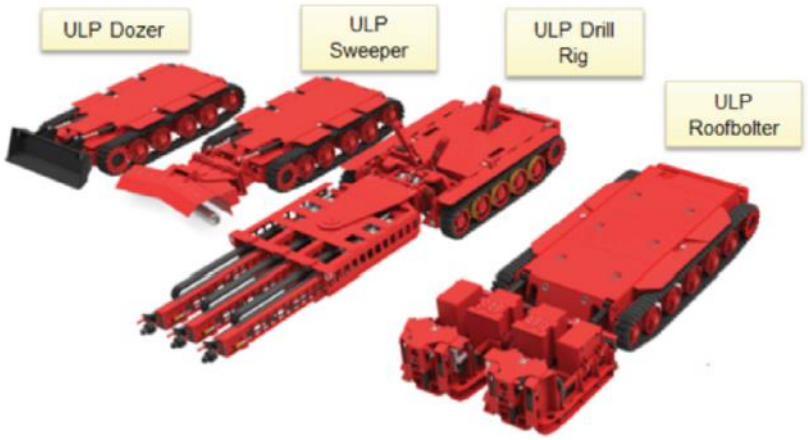

Figure 2.2: Ultra Low Profile trackless equipment fleet at Anglo American Platinum (Fourie et al. 2014)

1. A dozer to clean the broken rock following the blast;
2. A sweeper to also clean the broken rock but only in areas where the dozer cannot reach;
3. A three-boomed drill rig which drills the face to load explosives; and
4. A double-boomed roof-bolter which drills holes and installs roofbolts on the hanging wall for support.

Ferreira (2012) asserts that the majority of Section 54 mine stopages issued by the Department of Mineral Resources (DMR) inspectorate are due to accidents caused by FOG which account for about 35% of all fatalities in South African underground mines. It is therefore necessary to reduce FOG by not only using the appropriate support technology in context with the working environment, but also to implement it efficiently. The need of in-stope bolting is evident since the dangers associated with the weak and unstable rock around the excavation following the blasting could have fatal consequences.

This research is only going to consider the roof-bolter as the system of interest, although being part of a bigger system which includes every other stage of the mechanised mining process.

2.4 Challenges and requirement in implementing stope face roof-bolting

The tabular nature of the orebody in South African PGM mines is regarded as a challenge to the introduction of fleet of trackless equipment. A typical mining width of 1.2 meters with uneven dips up to 22 degrees are requirements for a machine to fit and operate in stope. This alone represents a major constraint since it is the environment where the roof-bolting rig will operate (Pickering & Leon 2008). A typical roof-bolt rig is shown in Figure 2.3 with dimensions in mm, indicating the minimum stoping width in which the equipment can operate (SANDVIK 2006).

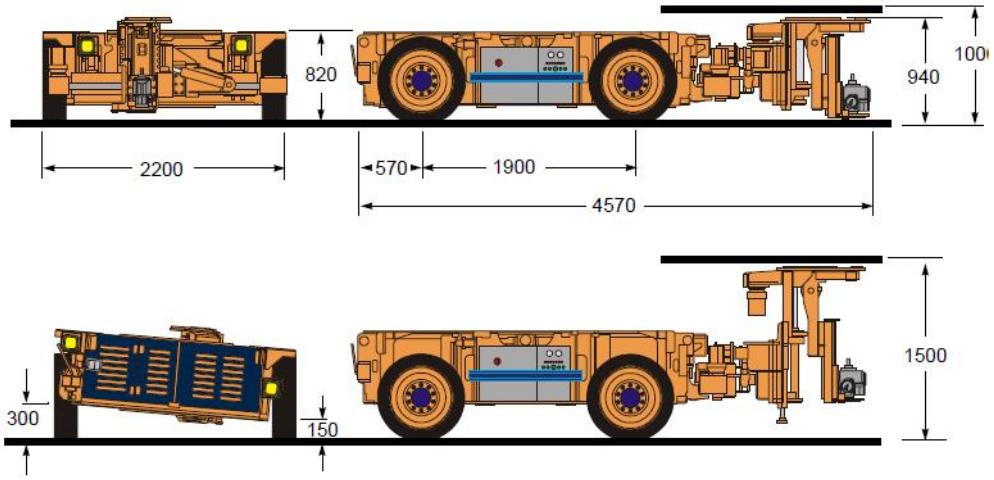

Figure 2.3: Sandvik's ROBOLT XLP roof-bolting machine (SANDVIK 2006)

Harisson (2008) further points out that, apart from being specific to the operating environment, the roof-bolting machine needs to be adapted according to the quality of the rock around the excavation, joint angle spacing as well as the filling (grouting) conditions and the hanging wall stratigraphy.

It is also important to not only note the cyclical nature of the mining process, but to also emphasize the dependency of events, which in this case represents a major constraint. For a given section at the mine with a given number of panels, the equipment needs to be on rotation and a single process is carried out every single shift per panel. With reference to Figure 1.1, this implies that it would take a total of between three and four shifts to complete a full cycle (drill, blast, clean, support) on one panel and this sequential operation can easily be compromised, should one item of equipment fail or should one process be stopped (Franklin 2008).

With regards to mine design, mining method and production scheduling in narrow reef mines, it is said that "the orebody dictates" (Rowland 2014) . The requirements from the mining company will essentially revolve around the stoping method and

characteristics of the orebody. In South African narrow reef mines, three mechanised stoping methods are generally found: Low profile (LP), extra-low profile (XLP) and ultra-low profile (ULP). Each of these methods are characterised by the height of machinery in the class. Regardless of the mining layout or the cycle time which is related to the equipment utilisation (time taken by the equipment to switch between panels) the major requirements provided by the mines in relation to these stoping methods are illustrated in Figure 2.4 (Fourie et al. 2014).

	LP	**XLP**	**ULP**
Depth+	0 – 400 m	350 – 1800 m	350 – 1800 m
Stoping width	1.8 – 2 m	1.3 – 1.7 m	0.9 – 1.2 m
Mining method	Bord and pillar	Breast mining	Breast mining
Dip	±10°	0° - 22°	0° - 22°
Production	2 100– 3 000 m²	2 100– 3 000m²	2 000– 000m²
Orebody	Consistent ore deposits without major faults	Consistent orebody, high extraction ratio	Fairly consistent orebody, high extraction ratio
Advantages	Low level operating complexity	Less dilution when compared to LP Low wastage introduced into plant	High-grade ore Able to deal with orebody complexities
Disadvantages	High volume tonnages Low grade High operating cost Complex infrastructure	Robust equipment Labour-intensive Highly skilled workforce Complex infrastructure	Advanced technology Highly skilled workforce Technology in POC phase

Figure 2.4: Summary of stoping methods and requirements for trackless mechanised mining equipment (Fourie et al. 2014)

2.5 Systems engineering overview

The discipline of systems engineering has been successfully applied to several industries including aerospace and defense as a problem solving methodology (Wertz & Larson 2008). It is a discipline that has evolved and has been governed by a set of standards which have been developed by renowned organisations such as the Institute of Electrical and Electronic Engineers (IEEE) and the International Council on Systems Engineering (INCOSE), providing a more precise description. In order to understand what systems engineering entails, it is important to firstly introduce some important concepts.

The Institute of Electrical and Electronic Engineers (IEEE) has developed a standard with the purpose of managing systems from initial concept through development, operations and disposal. This standard defines the systems engineering discipline as follows:

"An interdisciplinary collaborative approach to derive, evolve and verify a life-cycle balanced system solution that satisfies customer expectations and meets public acceptability" (Software Engineering Standard Committee of the IEEE Computer Society, 1994).

From this definition, one can infer that the goal of systems engineering is to deliver a solution based on specific requirements and specifications, while at the same time involving multiple collaborative disciplines.

The systems engineering process essentially involves the generation of information (specifications) based on the requirements provided, and the creation and development of products or solutions by following a sequential, iterative and recursive process. The higher the level of detail in the requirements, the better are the chances for the system to perform as per requirements and specifications. Following the analysis of the requirements, an iterative process occurs, where the functions and definitions of the delivered solution are continuously assessed until the verification is approved and the implementation can be declared to be a success. The systems engineering process is illustrated in Figure 2.5 (Defense Acquisition University Press 2001).

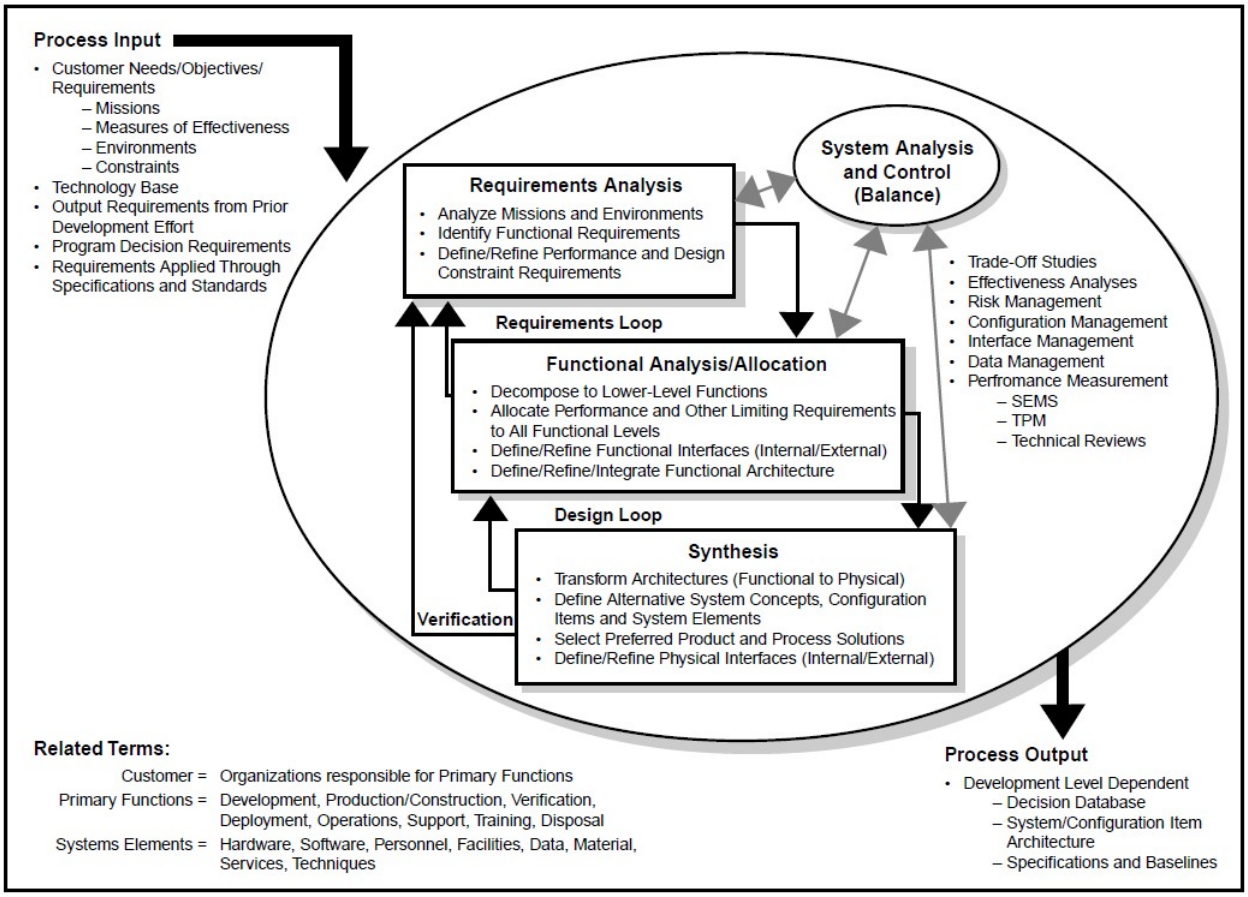

Figure 2.5: The systems engineering process according to Defense Acquisition University Press (2001)

As shown earlier in Figure 1.1, the traditional drill and blast underground mining method is cyclic and has not changed in the past hundred years (Pickering & Ebner 2001). Applying a systems approach to develop a solution to the imminent problem of implementation of mechanisation will involve a deconstruction of a particular process of the mining cycle. Once a mining method is defined and capital is spent towards the development of the mining operation, it will be difficult to change the established system. However, the subsystems which form part of the whole system can have their own processes optimised and can each be considered as a system by

themselves. In the case of this research, roof support by means of a roof-bolting machine was selected as the system of interest.

According to Jenkins (1967), a systems approach can be divided into four stages which are directly related to the systems engineering process pictured in Figure 2.5:

1. **System Analysis** (process input and requirements analysis): This stage involves an analysis of whether the current process can be improved or might be done better. The objectives of the system need to be well defined and key performance indicators (KPI) need to be known.

2. **System Design** (functional analysis and synthesis): This stage involves a granular analysis of the system including every influencing factor and constraint. Specifications are drawn according to the initial requirements and an identification of the ideal model needs to be made based on all the different options of operating the system. This also means reconsidering some of the options that have proved to work in the past and including an analogical comparison to what has worked in other industries.

3. **System implementation**: As part of the implementation process, the system of interest must have been identified within the mining cycle (here: in-stope support). A suitable optimisation process to the system of interest will be proposed and approved and adequate planning must be ensured for a successful implementation.

4. **System Deployment and Assessment** (requirement loop, design loop and verification): The newly modelled system can at this point be deployed and constraints that were identified earlier can now be assessed for performance and to confirm that the objectives that were set in the earlier system analysis phase are reached. The re-evaluation of the specifications against the initial requirements is an iterative process and until the final deployment is measured positively against the initial requirements, the design and verification loops will be ongoing.

2.6 Summary

The objectives and background of underground mining mechanisation were covered by highlighting improved safety and profitability. Potential challenges that could be faced when implementing a roof-bolter in an underground mining operation for face support were given and a generic overview of systems engineering was also covered.

The upcoming chapter expands on the literature by looking at systems engineering tools that have been applied in other industries and that can be relevant to the

research. It further presents the proposed methodology on how these tools will be applied to each stage of the systems approach in the roof-bolter implementation context.

Chapter 3

Proposed Methodology and Systems Engineering Tools

3.1 Introduction

This chapter presents the description of the research process which was followed in order to evaluate whether the developed framework based on a systems engineering approach, could enhance the level of success of implementation of the roof-bolter in an underground platinum mine. Justification regarding the methodology that was used for implementing the framework and the criteria for success are also provided.

It further elaborates on the selection of systems engineering tools to be used to develop the framework and takes a detailed look at each tool by aligning them to a particular stage of the system engineering process.

3.2 Research methodology

As stated in the introductory chapter, the aim of this research is to develop a systems engineering framework whose primary function will be to improve the implementation process of a low profile roof-bolter in a platinum mine section and identify points of failure if they occur. Referring to the research questions, a clear methodology which would lead to the development of the framework needs to be defined, as well as criteria that will be used to validate the reliability of the framework.

3.2.1 Followed process

An illustrated overview of the methodology to be followed is shown in Figure 3.1.

Following the presentation and definition of systems engineering in Chapter 2, an investigation of systems engineering tools that are applicable to each stage of the

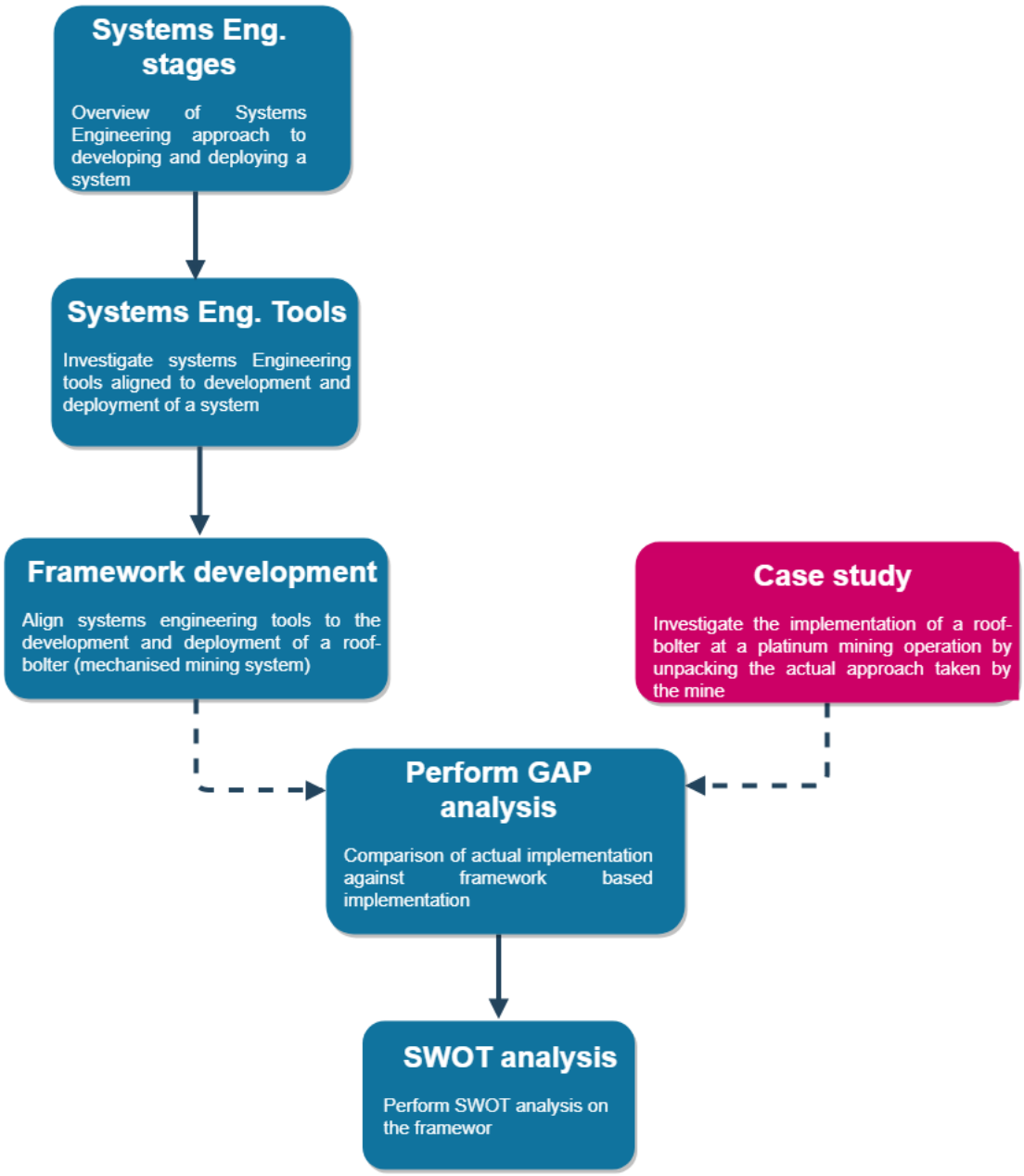

Figure 3.1: Overview of methodology

systems approach must be conducted. As a result of this investigation, the appropriate toolbox necessary to adopt and to develop the framework for implementation of the low-profile roof-bolter will be defined.

The framework will then be developed by aligning the toolbox to the development and deployment of the roof-bolter as a system of the mechanised mining cycle, and by taking into account limitations and requirements provided at each stage.

As a method of measurement and evaluation of the framework whose main purpose is to increase the level of success in the implementation process of a roof-bolter, a gap analysis will be performed. This gap analysis will be based on a comparison of a real-life implementation of a roof-bolter at a platinum mining operation against

the developed implementation framework. The case study will essentially unpack elements of the implementation at the mining operation and isolate all the relevant stages in order to align them to the framework and perform the gap analysis in order to measure and evaluate the efficacy of the systems approach.

Finally, a SWOT analysis will be performed on the framework with the aim of analysing aspects of the framework which stood out as effective in the gap analysis as well as those that could be improved. Similarly, aspects of the framework which would appear to be threatening or out of context of will be highlighted.

3.2.2 Justification for using a case study methodology

In order to identify whether the level of success of implementation of a low-profile roof-bolter in a platinum mine could be enhanced by means of the designed framework, an evaluation by means of a case study has been undertaken.

The choice of a case study to evaluate the framework was motivated by the fact that it generally allows improve understanding of an item (a system in this case) by extending the experience and adding more strength to what is already being done. According to Yin (1984), a case study can be defined as *"a qualitative method which examine a real-life situation in order to provide an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident, and in which multiple sources of evidence are used"*.

Hartley (1994) further emphasizes that case studies are known to be the best methods for exploring new processes and mostly, the ones that have potential for improvement.

For a certain type of research, it could be difficult or close to impossible to approach them by a method other than a qualitative one such as the case study, which has the advantage of providing a holistic view of a given process (Skyes 1990).

3.3 Selecting Systems Engineering Tools

The complex nature of an underground mining operation brings about a large number of processes whose interactions and interdependence can introduce individual differences. These differences can create significant variability over time if not monitored accurately.

An appropriate toolbox of systems tools is required in order to provide an understanding of requirements, drawing specifications, navigating through various design

options and implementing the system before deployment and assessment. A number of systems engineering tools have been developed and successfully applied in the past, each with a particular purpose related to the four four stages aforementioned (system analysis, system design, system implementation, and system deployment and assessment).

These tools aim at generating and managing the information which links them together from the system's initiation and concept to its delivery. Depending on the system of interest, a particular combination of the right tools will be able to produce the optimal framework for implementation of the system.

Burge Hughes Walsh Limited (2009) has populated a list of verified and available systems engineering tools and has classified them according to their appropriate application to each stage of the systems engineering process. This conceptual tool map is illustrated in Figure 3.2 and shows some pathways which can be followed, depending on the system of interest.

The remainder of this chapter will expand on three particular tools which have been identified as ideal for deconstructing the system of interest, the roof-bolter, in the current context. These tools have been applied in various industries with high levels of success.

3.3.1 Quality Function Deployment(QFD)-House of Quality

The initial stage in a systems approach is system analysis, which essentially involves a detailed definition of requirements upon which the given system will be built and verified. In an underground mining operation, the need to introduce a piece of mechanised equipment will also be guided by a set of requirements (identified as customer needs) which will ultimately define specifications for the equipment to be manufactured. In addition to these specifications are constraints imposed by the underground environment, and which should also be considered.

In order to develop a product's requirements from customer needs, Quality Function Deployment (QFD) is a common systems engineering tool that has been widely used in the aerospace industry. QFD involves a series of matrices organized to define attributes and characteristics of a system and can be applied over many areas of decomposition (Wertz & Larson 2008).

Wertz & Larson (2008) further identify this tool as a structured means for a design team to address customer needs and to develop the consequent design characteristics to satisfy them.The House of Quality matrix is the most recognized and widely used form of this tool. It translates customer requirements based on marketing research and benchmarking data, into an appropriate number of engineering targets to be met by a new product design (Tapke et al. n.d.). It is configured in its simplest form as shown in Figure 3.3 and contains the following elements:

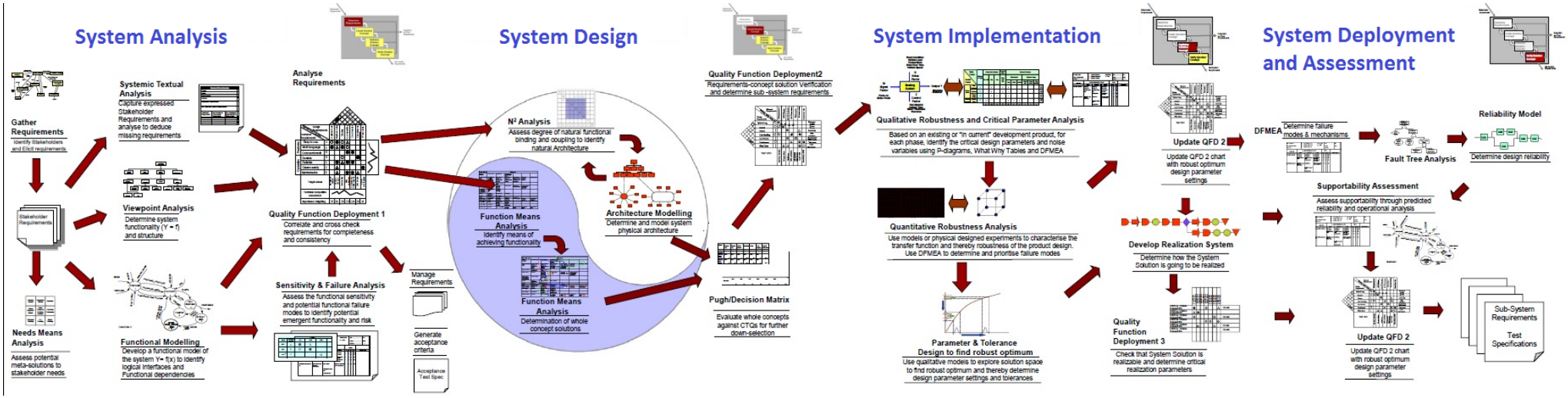

Figure 3.2: Systems Engineering tool map (Burge Hughes Walsh Limited 2009)

1. **What**: Also known as *"the voice of the customer"*. These represent the actual needs of the customer. In the underground mechanised mining context and in relation to the study being conducted, these elements would represent the requirements necessary to manufacture a roof-bolter capable of operating under certain conditions and withing a number of constraints set by the equipment performance. These conditions and constraints will be elaborated in more details in a later chapter.

2. **How**: These represent the technical attributes which define the means for fulfilling the needs and related technical attributes.

3. **Weighing**: These are numbers that are applied to the *"what"* side of the matrix and they translate in in levels which represent the priority of a particular need. Depending on the manufacturer's practice, they can be converted into a percentage which indicates the level of importance from a customer's perspective.

4. **Relationships**: This section identifies and classifies the relationship, if any, between the *"whats"* and the *"Hows"* and indicates the level of importance or priority according to the chosen weighing index. This area is also known as the *"interrelationship matrix"* as it simply establishes the relationship between the customer's needs and the technical attributes. This is done by questioning the customer (in the mining context, the OEM questions the mining team) and strengths and weaknesses of the company are weighted against the customer priorities in order to evaluate what aspects will need to be altered and adjusted in order to improve on possibly existing equipment. The level of importance is assigned to a number between 0, 3, 6 or 9 which represent a neutral, weak, moderate or strong relationship respectively.

5. **Correlations or conflicts**: Also known as *"the roof of house of quality"*. It is used to assist in the development of relationships between the technical attributes (hows) and it identifies where these elements have to work together (correlation), otherwise they will create a conflict in the design. The following symbols are normally used to represent the level of impact each attribute possesses on another:

   - (++): Strong positive;
   - (+): Positive;
   - (– –): Strong negative and
   - (–): Negative.

   The symbols are entered into the cell of the roof where a correlation between two technical attributes was identified. This process helps the design team

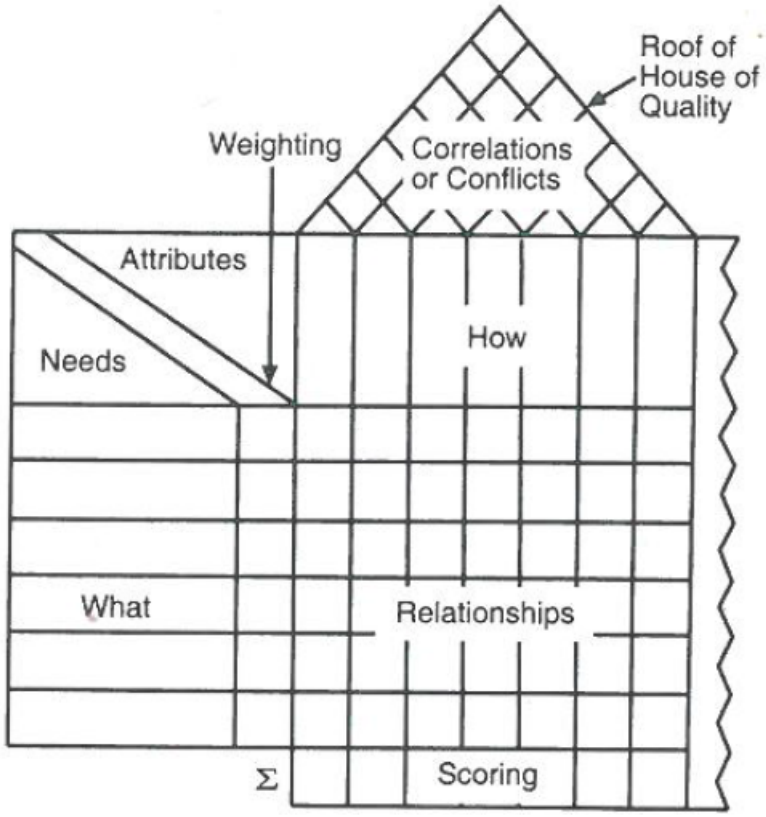

Figure 3.3: Elements of a House of Quality (Wertz & Larson 2008)

to communicate efficiently when changes are to be made and avoid negative impact on one requirement to the detriment of the other.

6. **Scoring**: The total of every rating on the technical attribute columns is added and noted in this section. This figure indicates the overall importance of the technical attribute and is usually calculated as a percentage against the relative weight of the customer requirement.

As stated earlier, the aerospace industry has used the QFD's house of quality technique as a tool to not only generate space mission requirements but also to identify the interrelationship between each requirements in terms of correlation and conflicts as well as priority (Wertz & Larson 2008). The mining industry faces a number of issues when it comes to establishing requirements with OEMs, be it from an equipment manufacturing or maintenance stand point (Callow 2006). It is therefore important to link technical attributes responsive to needs, to functions of the system before engaging in designing it.

3.3.2 Business Process Model and Notation-BPMN

The implementation of a newly built piece of equipment in an underground mine can be regarded as one of the most complex tasks following it being manufactured according to previously defined requirements and specifications. Personnel and departments at every level of the mining operation need to understand their role and be able to carry out what is expected from them at any given time in order to guarantee a successful implementation and technology transfer (Willis et al. 2004).

Rosing et al. (2015) define the business process model and notation (BPMN) as a standard systems engineering tool for business process modeling which provides a graphical notation that specifies business processes based on traditional flowchart techniques. This tool has been widely used in the information technology industry to develop blueprints for software solutions and has branched out into other industries. The main objective of BPMN is to support business process modeling for both technical and business users by providing notation that is intuitive to business users, yet able to represent complex process semantics. Ultimately, BPMN can serve as a common systems engineering tool which helps in efficiently bridging the communication gap that may exist between the implementation of a new technology and the process involved in running and maintaining this technology.

In a mining context, this would involve the efficient implementation of mechanised underground equipment in terms of reporting as well as mitigating issues that could potentially contribute to poor performance of equipment. These issues can be classified in terms of equipment availability, equipment utilization and equipment productivity and will be expanded in a later chapter (Fourie 2015).

The BPMN tool is based on different elements or objects that interconnect to show the flow of of events from the start of a process to the end. This approach makes the notation understandable by every member or every department in the organisation running the process. The elements used are usually grouped in four basic categories and each element is assigned a particular symbol.

The four categories of elements shown in Figure 3.4 are:

- **Events**: These are two-part symbols made up of an outer circle with an icon inside the circle that represents an event type, such as a message, a timer, an error, a signal, or multiple related actions.
- **Activities**: An activity shows which of four standard types of work a process performs: tasks, task groups (sub-processes), transactions, or call activities.
- **Gateways**: A gateway separates or combines flow objects. The standard gateway types include event-based, exclusive, exclusive event-based, inclusive, parallel, and parallel event-based
- **Connections**: These symbols are the lines that connect flow objects.

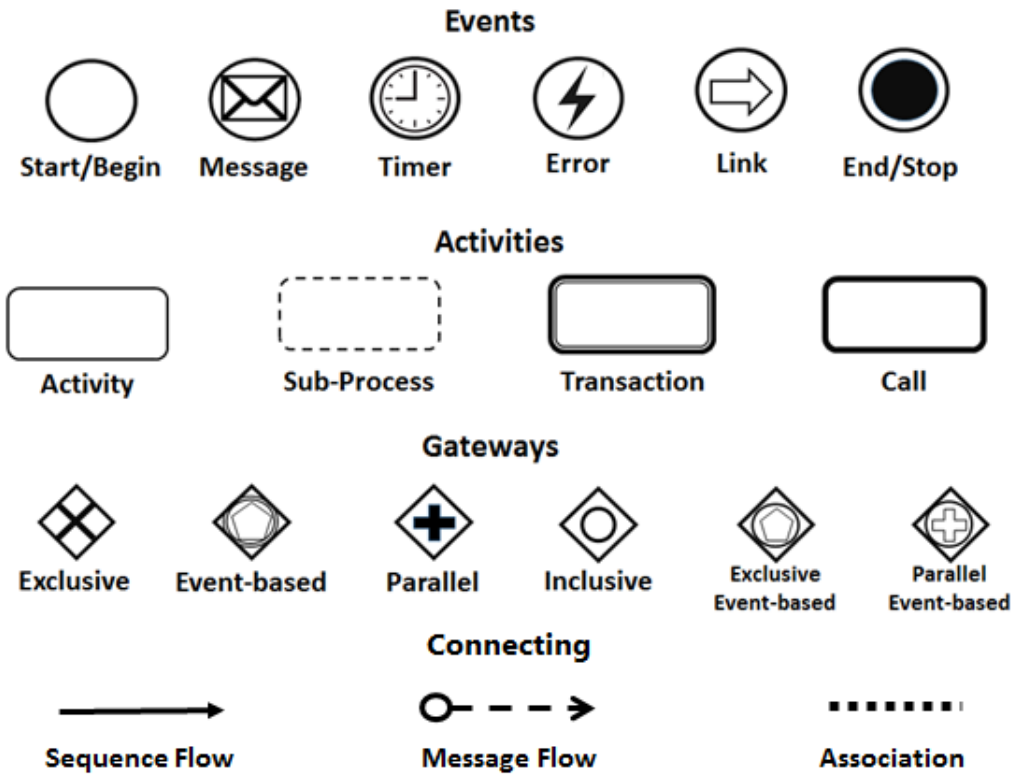

Figure 3.4: A sample of the categories of BPMN symbols (study.com 2006)

A typical BPMN workflow diagram is shown in Figure 3.5, for a process of applying for a job. The process starts with a candidate submitting an application which

is received by recruiter who reviews it and either accepts or rejects it. In case of rejection, the candidate will get notified and this will trigger an activity which will terminate the process. Otherwise, should the application be considered, a scheduling activity will be triggered and an invitation will be issued to the candidate to attend an interview. This particular diagram represents a process in which there are two levels of interaction between two participants and where the flow of events varies naturally (study.com 2006).

When deconstructing the implementation of a piece of equipment in an underground mechanised mining environment, the BPMN tool can can provide a high level of detail regarding the interaction needed in order to get the best performance. Breakages, delays and other unforeseen circumstance are a reality and processes need to be enforced firmly to guarantee a successful system implementation.

The advantages of using BPMN over a simple flowchart is that it allows to visualize processes in much more detail than a flowchart would; for instance it is possible to know who triggers a process or makes a decision at what point, what would happen in case a task or subtask is not done or even to visualize a multi-level approval chain.

3.3.3 Integrated DEFinition for Process Description Capture Method (IDEF3)

Once the newly manufactured equipment has been deployed underground and has begun to operate under the newly defined process flow between each one of the departments involved in the operation, it is important to look in depth at logistical issues related to human factors as well as the value chain in maintenance with the goal to optimize utilisation and availability of the fleet.

Horberry et al. (2011) defines human factors as: "The scientific discipline concerned with the understanding of the interaction among people and the other elements of a working system, and as the profession that applies theory, principles, data, and methods to design in order to optimise human well-being, safety and overall system performance".

From this definition and looking into a mining context, it is important to put a lot of emphasis on the training process of the personnel as well as the process around maintenance and repair of the equipment when different scenarios occur.

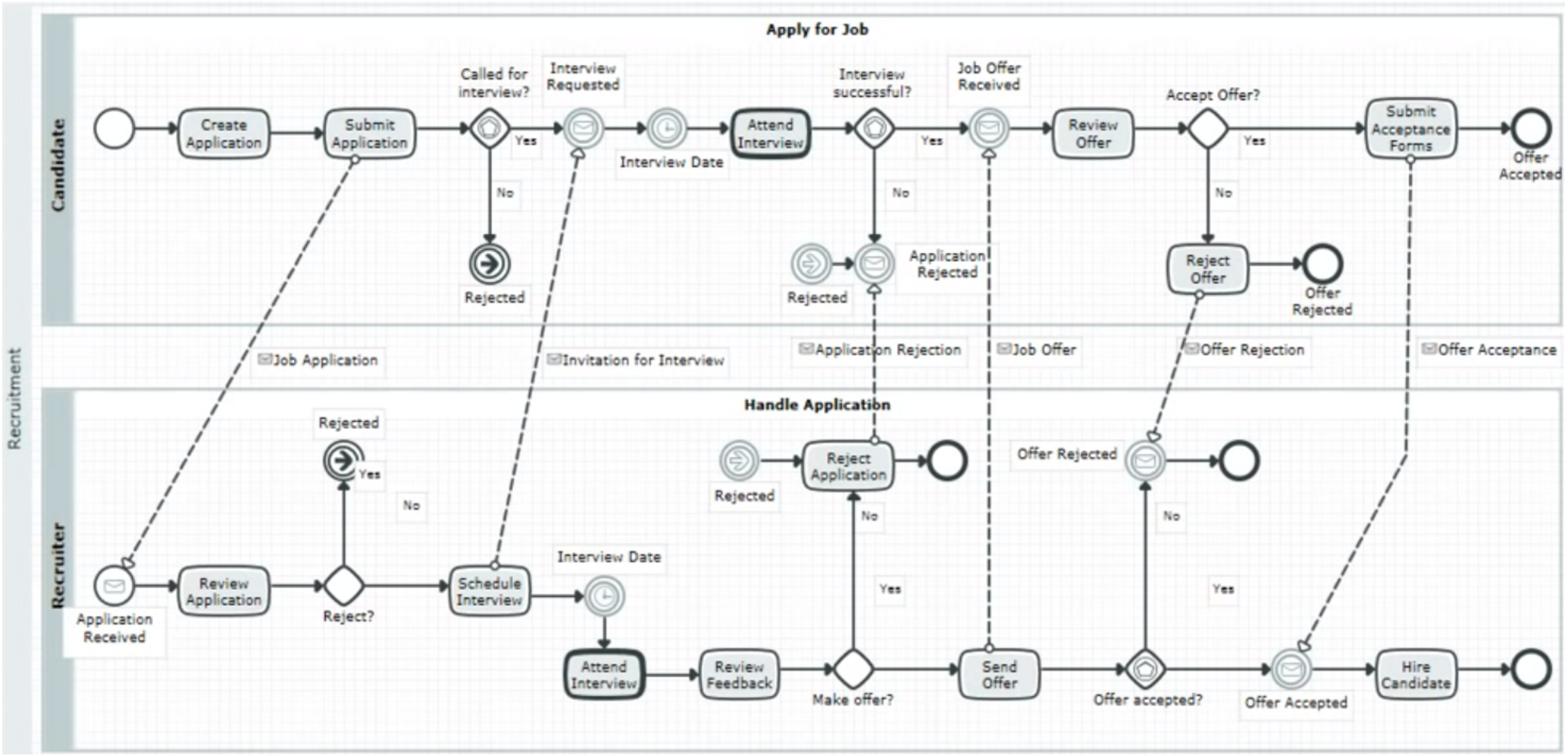

Figure 3.5: Employment application template of a BPMN (Burge Hughes Walsh Limited 2009)

A common systems engineering tool used in the automotive industry is known as the Integrated DEFinition for Process Description Capture Method, or IDEF3. It is a scenario-driven process flow modeling method which describes a process as as an ordered sequence of events or activities. IDEF3's goal is to provide a structured method for expressing how a particular system works by enabling a mechanism for collecting and documenting decision procedures affecting the life-cycle of critical shared engineering and maintenance data (Mayer et al. 1992).

There are two IDEF3 description modes:

1. **Process flow**: Captures knowledge of how things work in an organisation i.e: what happens to a part as it flows through a sequence of manufacturing process. This mode is more relevant to the context of this study.

2. **Object state transition network**: summarizes the allowable transitions an object may undergo throughout a particular process.

An IDEF3 Process Flow Description captures a description of a process and the network of relations that exists between processes within the context of the overall scenario in which they occur. The intent of this description is to show how things work in an organisation when viewed as being part of a particular problem solving or recurring situation. This is done by using a IDEF3 Process Description diagram which uses elements presented in Figure 3.6 (Mayer et al. 1995).

The elements which are represented by boxes are known as *"Units of Behavior"* or UOBs. Links tie the boxes (UOBs) and also define the flow of logic whilst junctions describe the flow of logic (points where a process flow path branches into multiple paths or multiple process flow paths merge into one).

The example shown in Figure 3.7 depicts a IDEF3 process diagram of the scenario titled "Order Material". Newly employed workers can be trained about the standards used by the organisation when making a purchase by using this IDEF process diagram. Purchase requests are routed to the purchasing department which either identifies current suppliers or, in case where there are no suppliers for the material, sends the request to potential suppliers, and then evaluates bids. At this decision point, the supplier is selected and the material can be ordered. However, a purchase request needs to be prepared prior requesting the material. This is routed to the account manager for approval where an account number of the project needs to be included. In some cases, an authorisation signature can be required, depending on whether the purchase request involves direct projects or indirect projects. The requester then submits the purchase request to the purchasing department which orders the material. The purchase request is then converted to a purchase order (Mayer et al. 1995).

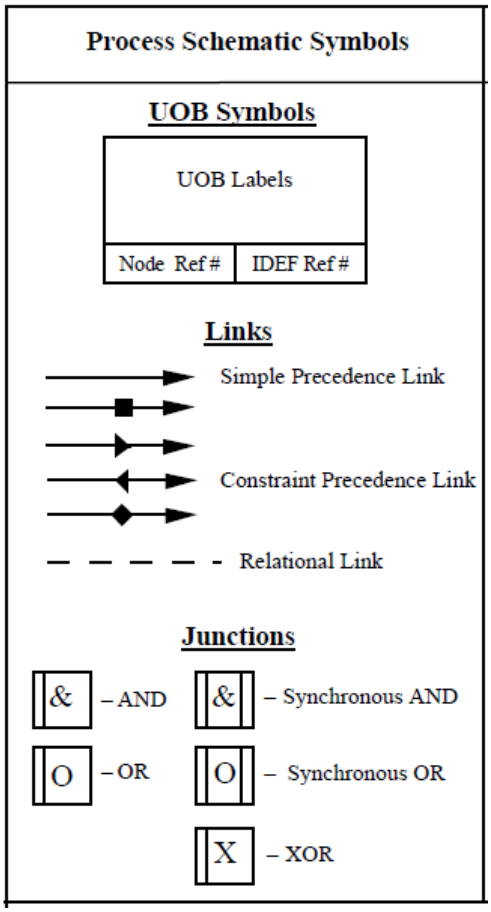

Figure 3.6: Symbols used for IDEF3 diagrams (Mayer et al. 1995)

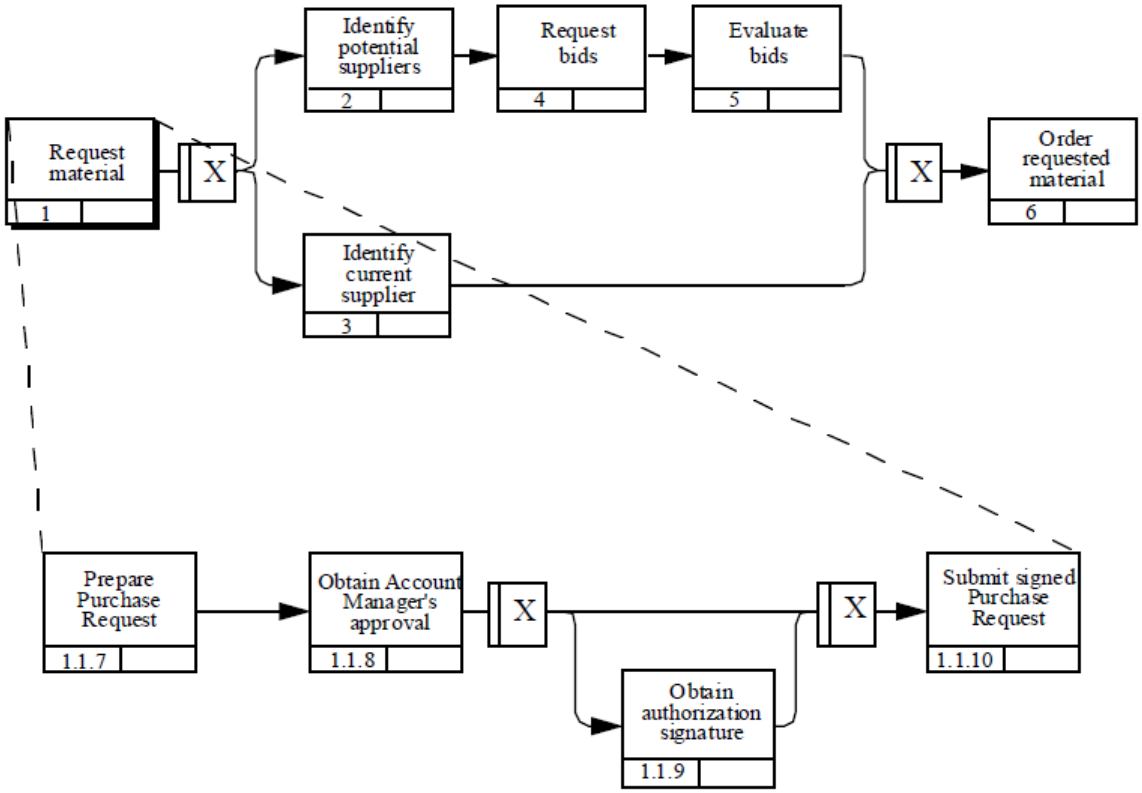

Figure 3.7: IDEF3 process diagram example for ordering material for repair (Mayer et al. 1995)

As a systems engineering tool, IDEF3 can be used in the deployment and assessment stage related to field operations including logistics in an underground mechanised mining operation. The interaction among people and the working system is of crucial importance and needs to be standardised and iterated to adapt it to all possible scenarios.

3.4 Summary

In this chapter, the research process to be used in the development of the framework was presented. A justification of using the case study methodology as a mean to assess the framework was given, emphasizing it as being the most suitable method to explore new processes. The systems engineering tools to be used in the development of the framework to be implemented were also presented, each directly relating to stages of a systems approach.

The roof-bolter's requirements and specifications will be derived and optimised by populating a House of Quality (QFD) which will take into account the requirements from the mine. These requirements are mainly dependant on the underground geology and will need to be fulfilled by the OEM contracted to manufacture the roof-bolter. The House of Quality will also be used to perform a functional analysis of the system by looking at all influencing factors and how the initial requirements compare to what has been accomplished by other OEMs.

The implementation of the roof-bolter will be specified by means of BPMN diagrams, which will allow for optimisation the equipment's performance by reporting availability and utilisation.

The iterative process of continuously assessing the deployment of the roof-bolter will be validated by using the IDEF3 tool. This will involve logistics as well as handling of the equipment when breakdowns occur.

The upcoming chapter will cover the development of the framework by making use of the systems engineering tools that were introduced.

Chapter 4

Framework Development

4.1 Introduction

A number of South African mines implementing mechanisation in their operations face the challenging task of selecting the right equipment and often get constrained to use commercial-off-the-shelf (COTS) mechanised equipment. This decision is often linked to the fact that it is significantly cheaper to purchase equipment from an existing catalogue than to commission a unique development. Such an approach constitutes a risk since the mine planners would have to retrofit their designs to suit the equipment whilst it should be the other way around.

There are a multitude of factors to consider which can influence the success of implementing a roof-bolter in an underground platinum mine section, going from the geology of the mining operation to the definition of requirements and specifications of the equipment to be developed as well as the deployment and continuous assessment of the equipment. This entire life-cycle of the mining equipment can be regarded as a system which can be deconstructed into the phases discussed in the previous chapter.

In this chapter, the geology of South African PGM deposits is covered in order to establish a general overview of the investigated area. A general presentation of a low-profile roof-bolter and various hanging wall roof-support techniques are given. Finally, the systems engineering tools presented in the previous chapter are utilised to model the system implementation framework across each stage of the process and the implementation framework is presented.

4.2 Geology of South African platinum mines

4.2.1 The Bushveld complex

South African is well known for its abundance of metalliferous minerals of which PGMs are a part. This is a family of six metals, namely platinum, ruthenium,

rhodium, palladium, osmium and iridium. PGMs originate from a series of mafic and ultramafic igneous rock formations which occur in the same deposit in form of layer intrusions (Schouwstra & Kinloch 2000).

The Bushveld complex is found in the northern part of South Africa and is the world's largest known layered intrusion. It hosts over half of the world's known PGM resources as well as chromium and vanadium. This intrusion consists of three sections, also known as limbs (northern, eastern and western) which can be identified in Figure 4.1 (Cawthorn 2010).

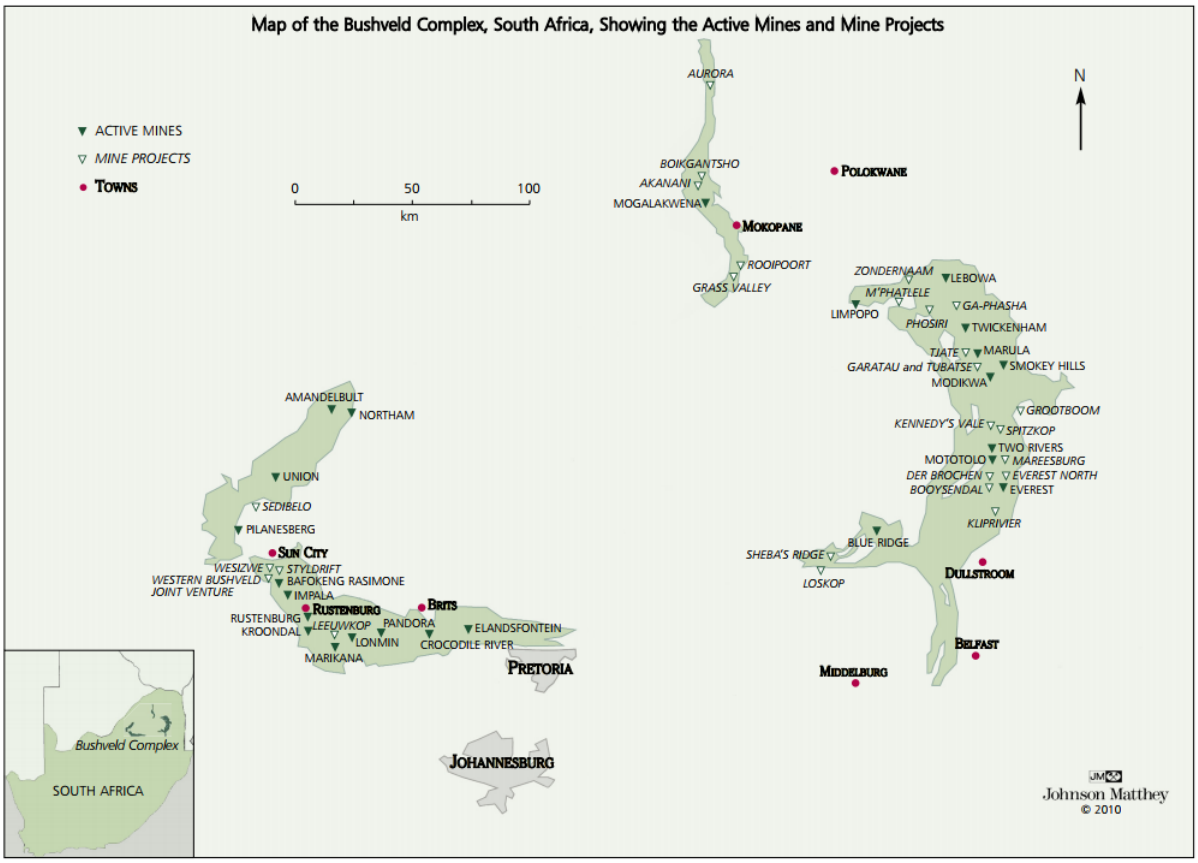

Figure 4.1: The Bushveld Complex showing the northern, eastern and western limbs as well as active mines, mine projects and towns in the area(Cawthorn 2010).

The economically important minerals of the Bushveld complex are found in three different reefs or layers (Schouwstra & Kinloch 2000):

1. **The Merensky**: Generally regarded as a uniform reef type although large variations occur in thickness, composition and position of the mineralisation. The total thickness of this reef does not exceed 30 cm . It is composed of proxenite which is rich in sulfide minerals. Byproducts include copper, nickel, cobalt and gold. It is mined on both eastern and western limbs.

2. **The Upper Group 2 (UG2)**: Consisting mostly of chromite (up to 90 % by volume), it lies below the Mersenky reef and is known to have a higher grade and tonnage of PGMs. It is mined on the eastern and western limb of the Bushveld complex with chromite seams generally less than 20cm in thickness.

3. **The Platreef**: Only mined in the northern limb, it consists of three mineralised horizons. All mining on this reef is currently done using open pit mining methods since the mineralisation can, at some places, reach a thickness of up to 40 meters.

In the underground reefs, the UG2 and Merensky orebodies are typically less than 1 m thick, at dip of between about 8 and 20 degrees. The narrow reef makes for a difficult mining environment due to the limited space, while the shallow dip means that gravity cannot assist in cleaning blasted ore as in steep dip, narrow vein mining techniques such as long hole open stoping.

4.2.2 Platinum mining environment in South Africa

The current volatility of the global platinum mining industry is quite alarming considering the global competitiveness and particularly, the issues related to labour unrest in South African narrow reef platinum mines. Directly linked to the aforementioned are factors related to health, safety and the environmental conditions where mining is being conducted.

Despite the constant effort leading to a decrease in fatalities in the mining industry, the target of zero harm is yet to be reached and according to the Mine Health and Safety Council (2014), a culture of transformation has to be adopted to reach this milestone. The unstable environmental conditions underground have seen a drive to prioritize safety over production although performance bonuses are still driven by production,which constitutes a challenge when enforcing safety procedures (Vogt & Hattingh 2016).

With regards to rock mechanics in the Bushveld Complex, the hanging wall of the UG2 and Merensky reefs are generally divided into fragmented blocks which can have bad structural properties once tensile stress is applied to them. The hanging wall of the UG2 reef hosts three or more chromite planes known as "*the triplets*", which render the hanging wall potentially unstable. In addition to the triplets joints, curved joints and other irregular structures are also present as shown in Figure 4.2 (Sellers et al. 2016).

The reef is said to be stratified and blocky, making the hanging wall prone to separation leading to falls of ground (FOG), hence the need for support for rocks taking

into account the tensile zone which indicates the type of support to be used (Hochreiter et al. 1985). The mineral reserves are accessed via excavations that are mined out and have to remain stable throughout the entire life of the mine. The hanging wall of these excavations is permanently subjected to tensile stresses which in shallow conditions, makes the hanging wall susceptible to collapses or FOG as pictured in Figure 4.3 (Stacey & Wesseloo 2004).

It is therefore critical to implement a robust and adequate support system, predominantly at the face of a platinum mining section in order to avoid fatal accidents.

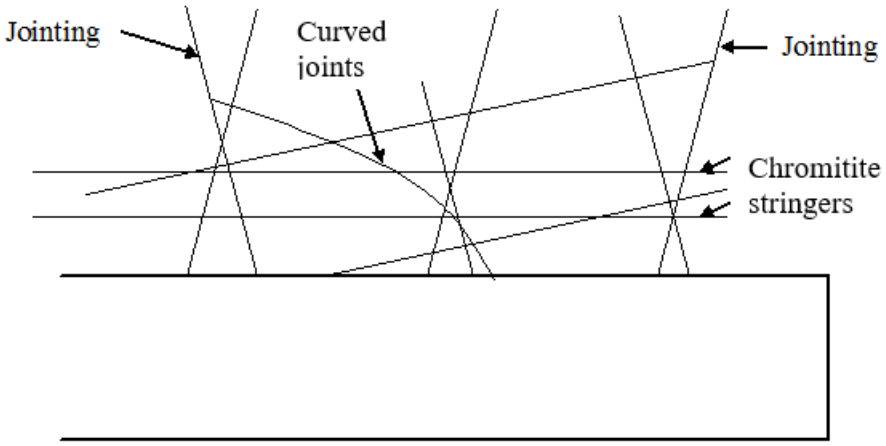

Figure 4.2: Stratified and blocky nature of UG2 reef type. Also shown are jointing, curved joints and chromite stringers. (Sellers et al. 2016)



Figure 4.3: Hangning wall collapse in a platinum mine caused by tensile stress (Stacey & Wesseloo 2004)

4.3 Background on hanging wall roof-support techniques

As stated earlier, FOG is currently the major contributor to accidents in deep level platinum mines in South Africa and accounts for about 35 % of fatalities. The implementation of an appropriate technology for hanging wall support is necessary in order to increase safety in the working areas.

According to Henning & Ferreira (2010), conventional narrow reef support systems are found in many platinum mines and essentially consist of permanent support about 3 meters from the face, and jacks or mechanical props which are removed before a blast (temporary support) as shown in Figure 4.4. The space between the face and the permanent support is left unprotected and makes for an unsafe zone where multiple cases of injury (fatal at times) have been recorded. In a conventional support system, permanent support consists of timber packs, cementitious packs or pre-stressed elongates. This approach to support has multiple drawbacks among which the unsafe hanging wall conditions and the fact that support has a low stiffness with the risk of being blasted out.



Figure 4.4: Temporary support made of mechanical props installed close to the face in a conventional mine (Ferreira 2012).

The advancement in technology has driven the implementation of semi-mechanised roof-bolting for both temporary and permanent supports in narrow reef stopes in order to reinforce the support provided by conventional practices (timber packs and props). Roof-bolt installation by means of suitable drilling equipment has been tremendously successful in deep level South African mines and has proven to drastically reduce the occurrence of FOG at the face, hence also reducing the number of accidents (Ferreira 2012).

A variety of roof-bolts are available to chose from depending on the nature of the excavation as well as the severity and depth of the sheared area in the hanging wall. Three types of roof-bolts are commonly found to be used in South African platinum mines:

1. **Hydrabolts**: This type of roof-bolts is made of steel tubes rolled into a C shape and is welded closed at the end which is inserted into the drilled hole. Water flows into the assembly through a nozzle equipped with a non-return valve and builds pressure, expanding the hydrobolt which takes the shape of the drilled hole and provides hanging wall support. A variation of hydrabolts known as RS bolt is a longer and flexible version of a hydrabolt (New Concept Mining 2017).

2. **Resin bolts**: This type of roof-bolt consists of a steel rod which has an anchor at the one end and a face plate with a nut at the other end. The anchor can be of mechanical or chemical nature. Following their installation, the bolts are tensioned and depending on the application, the space between the rock and the bolt can be filled with resin grout in case there is presence of corrosive ground water in the rock; alternatively, the roof-bolt can be left ungrouted. A cone with an internal thread is screwed in the threaded end of the bolt while the roof bolt unit is placed into the drilled hole. Provision for the hole to be a about 1 cm longer that the bolt must be taken to avoid dislodging of the bail when reaching the end of the hole. Once the bolt is tightened, this forces the cone to move further into the wedge and increases the anchor force. A typical resin bolt which is shown in Figure 4.5 (Hoek 2007) .

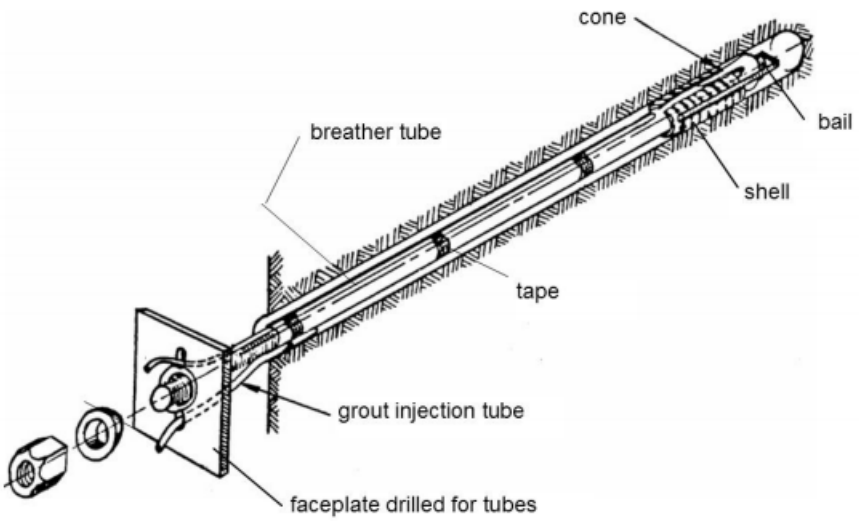

Figure 4.5: Mechanically anchored roof-bolt showing the different components (Cawthorn 2010).

3. **Cable anchored bolts**: These are a flexible type of roofbolt which are made of steel wires, making them resistant to abrasion and the impact caused by blasting (Hoek 2007). Cable anchored bolts are classified as passive type of support since they necessitate a displacement to occur within the vicinity of the rock to start developing resistive support (Kolokoto & Yimaz 2013).

Roof-bolt installation starts with drilling of the hanging. In narrow reef platinum mines, the diameter of the drill hole is of critical importance. Should the hole's diameter be too small or too big, failure during installation is prone to occur. In the case of resin bolts, common drill hole diameters vary between 28 mm and 36 mm when using steel bolts between 16 mm and 20 mm diameter (Ferreira 2012). In addition to the characteristics of the drill hole, the rock type is also of high importance since the geology is a major external component of the support process. According to Canbulat (2008)'s investigations, the rock type constitutes a primary factor influencing the performance of a support system.

Roof bolts are usually installed using hand held devices equipped with either hydraulic or pneumatic power packs or more recently, by means of trackbound or trackless roof-bolter rigs. Roof-bolter rigs are more advantageous to use when compared to hand held roof-bolters since they provide much safer working conditions for the operator who is no longer exposed to the unsafe hanging wall and who can safely operate the roof-bolter rig remotely from a distance (Marek et al. 2012).

Figure 4.6 illustrates different parts of a single boom roof-bolter rig. Depending on the application, there are two different types of roof-bolter rigs available:

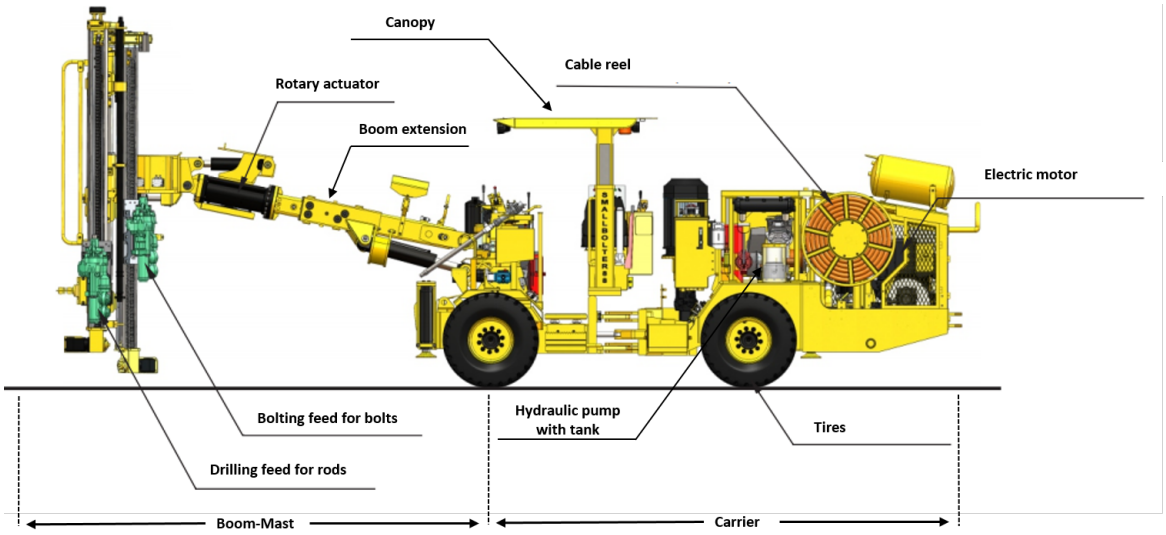

Figure 4.6: Single boom roof-bolter rig for mechanised roof support (Resemin 2015).

1. **Single boom**: Roof bolts are installed one at the time from one setting. The roof-bolter rig must be repositioned prior drilling and installing a new roof bolt.

2. **Dual or twin boom**: The boom extensions can either be independent or branch out into two masts which operate concurrently. This setup reduces the time spent to install roofbolts in a given section since two roofbolts can be installed simultaneously.

General characteristics of a make of roof-bolter rig are usually provided by OEMs in form of a datasheet which contains all the specifications. As an example, the datasheet of Resemin's Small Bolter 88 can be found in Appendix A. The specifications shown on this datasheet are the parameters used in the first stage of designing the roof-bolter rig system. By varying these specifications according to the mine's requirements, the desired design can be achieved.

4.4 Implementation framework development

Developing a framework for the implementation of a roof-bolter involves the development of a generic approach which can be used across multiple organisations (mining operations in this case) with the aim of ensuring that there is little to no area prone to error. The implementation process will therefore be deconstructed to its smallest detail in order to identify and isolate problem areas beforehand. The proposed approach will consist of four distinct stages which will each bring an end result to be evaluated and possibly altered until the system as a whole fits in the originally specified requirements. Each stage leading to the framework will be deconstructed in the upcoming sub-sections.

4.4.1 System requirements and design

The aim when defining requirements, is to translate them into relevant and accurate technical descriptors which can be implemented into a given design.

Akao (2004) has identified six steps to follow in order to implement Quality Function Deployment (QFD) by means of the house of quality:

1. Identifying **"what the customer wants"**: It is critical to define what exactly does the customer desires. This is the first step which needs to be verified in the end, and affirmed by the customer. The **"whats"** will be expanded into much more details and willbe captured with high precision first-hand in the steps to follow.

2. Identifying **"how will the customer be satisfied with the final product"**: Looking at the "wants" form the customer, the OEM has to identify characteristics or attributes which will be specific to the end product as requested initially. These are attributes are identified as the **"hows"**.

3. Identifying **"the relationships between the Hows"**: In this step, the relationship between these characteristics and attributes will need to be defined. This particular step can turn up to be complex since all the attributes will have to be evaluated against each other to see how they tie together.

4. Developing **"importance ratings"**: Following the establishment of relationships between the "hows", the OEM must go back to the customer and get input of how important each attribute is when referring to the final product. The result is the generation of importance ratings from the previous relationship matrix.

5. Evaluating other **"products which can pose a threat as potential competition"**: Based on research, the OEM will identify products on the market with similar attributes and will measure how they compare to what is being offered.

6. Determining **"technical attributes which will be implemented"**: Performance from the potential competitor and that of the product to be designed and developed are compared and advantages of the later over the former are highlighted.

In the context of the roof-bolter rig, these steps will also apply and will follow this format. For the upcoming section, the requirements, parameters and other variables will be generated based on a number of assumptions which will be verified against real conditions throughout the case study in the later chapter. Note that these assumptions are not a reflection of true customer requirements.

1. Identifying **"what the customer wants"**: In this case, the customer is represented by the mining operation and the end product is a roof-bolter rig. Assuming that the customer wants a roof-bolter which should be capable of achieving the following:

    - Operate within a low-profile platinum mine environment (stoping width between 1.8m and 2m);
    - Be able to easily manoeuvre from one panel to another without difficulty;
    - Operate on diesel;
    - Minimise fumes;
    - Be easily serviceable;
    - Allow for remote operation.

    It is necessary however to consider a maximum throughput (bolts per cycle) as being the most important parameter since the customer's satisfaction will

highly depend on whether the roof-bolter is capable of installing the necessary number of roof-bolts per day or per shift. Failing to reach the required number of roof-bolts installed in a given section after a shift will result in the roof-bolter becoming the bottleneck of the entire mining cycle and will slow down production.

It is also important to mention that there is a major trade-off between the use of diesel in mechanised mining equipment and the need to minimise fumes. Mechanising implies the need for equipment to move freely from one panel to another which is more practical for diesel equipment as compared to electrical equipment, which produces no fumes and has a significantly reduced heat emission in order of 3:1 (kW of heat per rated kW). Therefore, considerations around ventilation and cooling will also need to be taken into account and a compromise will need to be reached.

The enumerated "whats" are populated into the house of quality as shown in Figure 4.7.

Customer requirements or "Wants"	Rating Weight out of 5	% out of total rating
Operate in low-profile environment	5	20%
Easily manoeuverable	4	16%
Increase throughput	3	12%
Operate on diesel	2	8%
Minimise fumes	4	16%
Easily serviceable	3	12%
Allow for remote operation	4	16%

Figure 4.7: Whats-Customer requests regarding quality of the roof-bolter

These requirements primarily focus around performance as well as safety. The mining operation determines what is best suited to the orebody geometry and deduce these requirements. In addition to the listing of requirements by the customer, the OEM captures the ratings in terms of importance and expresses them as a percentage. The customer is also involved in this process. These ratings vary between 1 and 5 in terms of importance (5 being the highest and 1 the lowest) and will be used at a later stage after populating the relationship matrix. They are also expressed in terms of percentage.

2. Identifying **"how will the customer be satisfied with the final product"**: Following the listing of requirements, parameters which relate to the requirements need to be listed. These physical and measurable parameters are ones that the OEM design team needs to decide to focus on and which relate directly to the requirements. In this context, the following parameters were identified and added to the house of quality as shown in Figure 4.8:

- Size (height, length, width);
- Type of tyre;
- Number of booms;
- Bolt length;
- Engine size;
- Engine transmission;
- Tramming speed;
- Fuel tank size;
- Boom length;
- Cost.

The list can be exhaustive and further include parameters such as the drilling speed and the cycle time (from drilling to placing the roof-bolt) among many others. An additional constraint would include the various types or length of roof-bolts to be installed. As stated in section 4.3 of this report where the three commonly used types of roofbolts are listed, they each have different installation procedures which have a direct impact on the measurable parameters to be implemented by the OEM.

The direction of improvement which is found directly above each parameter indicates whether a parameter can be improved by increasing or decreasing its measure.

3. Identifying **"the relationships between the Hows"**:Some of the OEM's parameters are related to one another and the correlations matrix on the roof of the house of quality establishes them. These correlations can either be strong, medium or weak. For instance, the size of the roof-bolter and the length of the boom would have a strong relationship, whilst the size of the roof-bolter will have a weak relationship with the type of tyres to be used. Similarly, the engine size and the tramming speed would have a strong relationship whilst having a medium one with the number of booms. On the other hand, some correlations are simply non existent, such as the size of the fuel tank and the boom length. Figure 4.9 shows how the previously listed parameters correlate on the roof of the house of quality.

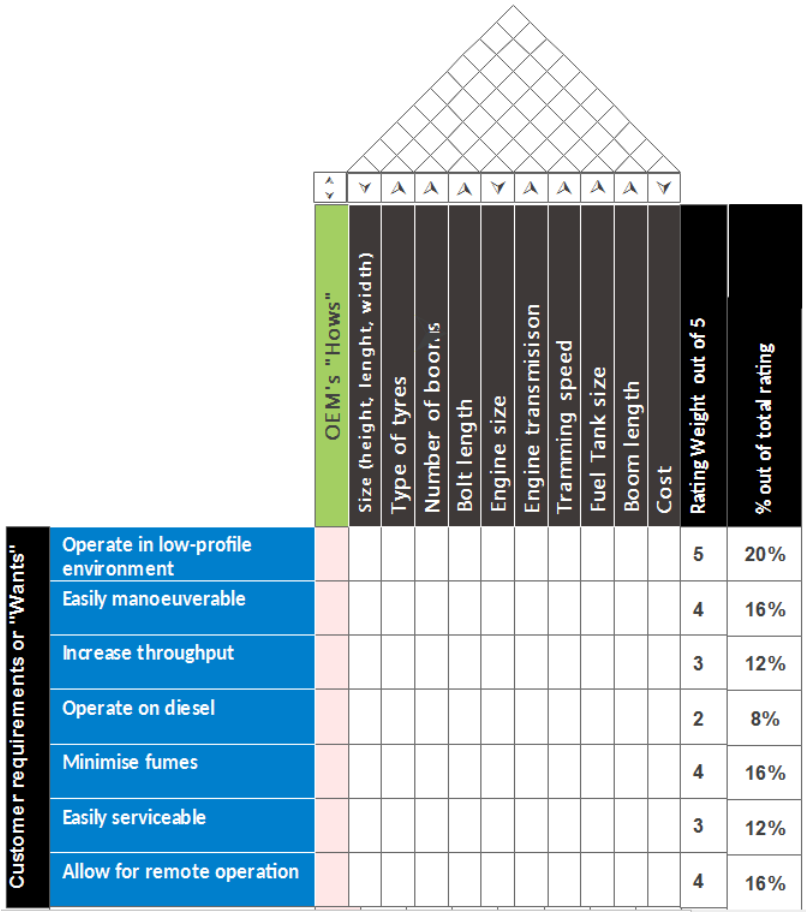

Figure 4.8: Hows-OEM measurable parameters

This step must once again be performed by the OEM's design team and would normally take time to accomplish through multiple brainstorming sessions.

4. Developing **"importance ratings"**:This step is the longest to complete since it establishes the relationship between the "whats" and the "hows". Once completed, the matrix will indicate how each one of the design parameters affects customer requirements. The relationships are based on a numerical weight scale from 0 to 9 which indicate no relationship when assigned a 0, a weak relationship when assigned a 1, a medium relationship when assigned a 3 and a strong relationship when assigned a 9. The populated relationship matrix is shown in Figure 4.10 where the same symbols are used from the roof of the house of quality.

The importance rating is calculated for each parameter by multiplying the percentage ratings of each requirement by the numerical scale corresponding to the symbol used for the relationship between the same requirement and that parameter, leaving out the elements with no relationship. These are then summed for each parameter and the weight percentage of he importance rating is deduced. The normalized weight percentage of the importance rating will help determine the design choices and indicate to the OEM, which parame-

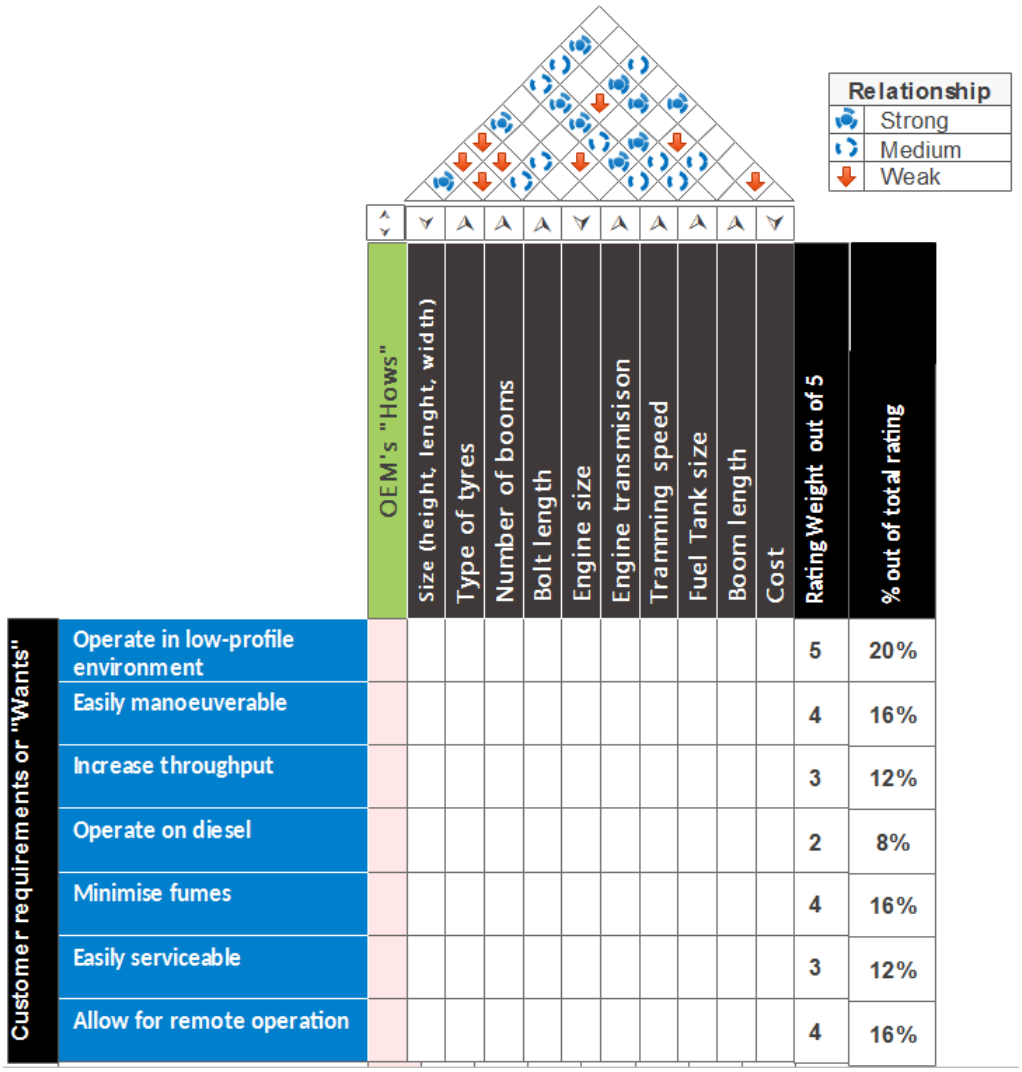

Figure 4.9: Correlations matrix between technical parameters

ter to focus on the most or the least. In this case and according to the way the relationship matrix was populated, the tramming speed will be of higher importance (18%) followed by the size and the type of tyres (12%) when designing the roof-bolter. The cost (6%) and the bolt length (4%) should be the least parameters to focus on. It is of high importance that the design team agrees on these figures before engaging into the engineering design of the product in order to avoid conflicts on product delivery.

5. Evaluating other **"products which can pose a threat as potential competition"**: This step can be viewed as an add on to the house of quality. It is based on internal market research which would allows the OEM to compare the product to be developed with what is already available on the market. As a result, the OEM will figure out discrepancies that exist and how they weight compared to the competition. Adjustments can hence be made on the different matrix elements before finalising the design parameters. In Figure 4.11, three makes of roof-bolters from other OEMs were identified as

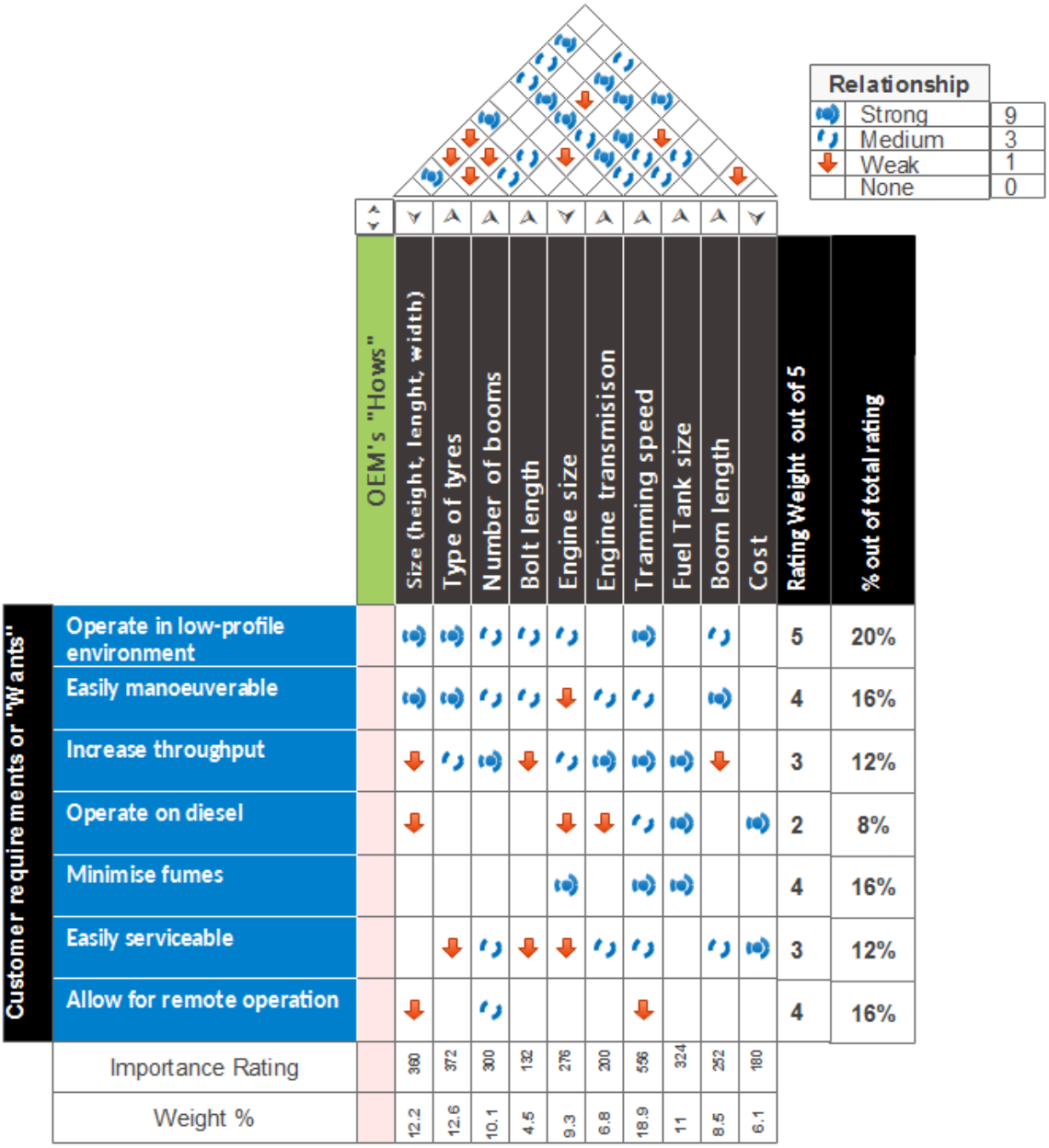

Figure 4.10: Whats and Hows relationship matrix and importance ratings

Bolter A, Bolter B and Bolter C.

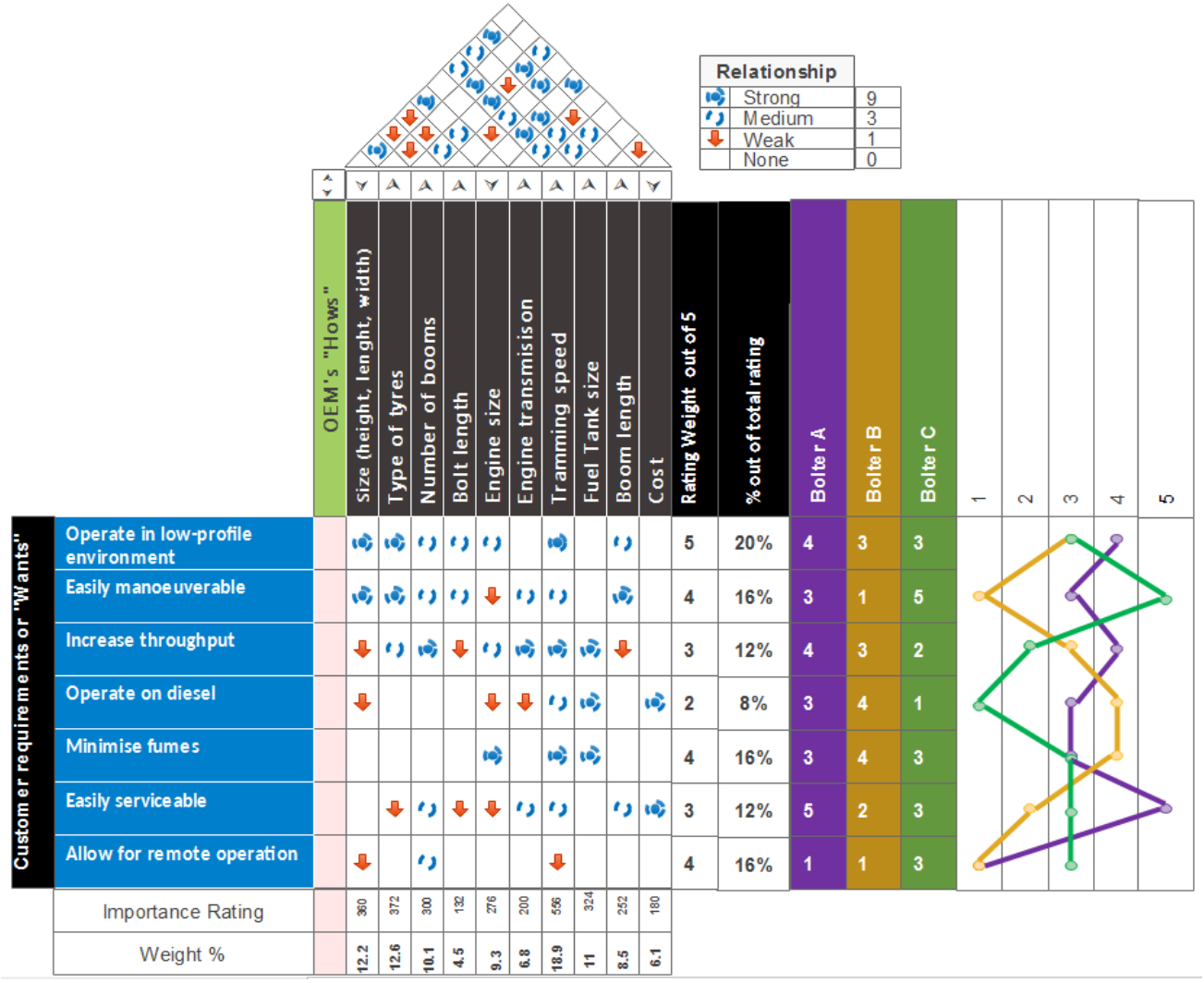

Figure 4.11: Completed house of quality inclusive of potential competition weighing

Each roof-bolter's ratings were populated accordingto the previously listed customer requirements. These ratings are once again based on assumptions resulting from the OEM's market research. At this point, the OEM will meet again with the customer and discuss possible alterations with regards to the requirements and populate a new matrix (step 3) to fit in with the new alterations with the aim to deliver a roof-bolter that stands out better than what the competition has to offer.

6. Determining **"technical attributes which will be implemented"**: Following the benchmarking exercise with the potential competitors in step 5 and the re-adjustment of requirements ratings, the final design attributes for the roof-bolter to be developed can be populated. Documentation highlighting engineering design parameters showing a mutual agreement between the mine representatives and the OEM should be signed as it is the case in step 4 to avoid potential conflicts.

The generation of design specifications is a crucial phase since it directly involves the OEM which is required to deliver a product according to the customer' requirements. The OEM is expected to not only meet the customer's requirements, but exceed them by maintaining and improving the final product's performance.

4.4.2 System implementation

Following the design of the product based on the mining operation's requirements, the roof-bolter has to be implemented into the mine as an operating and functioning system. This step of the process will involve multiple departments at the mine and will focus on three attributes namely reporting, equipment availability and equipment utilisation. These attributes are discussed in more details in the subsections to follow.

It is important to consider tuning and optimising these attributes as a means to improve on-time delivery which relates to the time taken to complete the installation of roof-bolts in one section. The unpredictability of the mining geology as well as operational constraints renders underground operations prone to a high level of variability. A balanced choice between adding resources to the process or improving the actual process in order to meet delivery must be made; although addressing the causes of these variations and improving the utilisation of existing resources in the process is recommended (McIntyre 2009).

1. **Reporting**

   From the start of a shift, a daily reporting practice is necessary as it is crucial to the longevity and performance assessment of the mining equipment as well

as the mining crew operating the equipment. When enforced and implemented adequately, reporting can effectively uphold quality and isolate potential bottlenecks in the system and optimise the problematic areas.

In the context of a roof-bolter in a platinum mining section, the mining department and the engineering department of the mining operation would directly interact while reporting activities from both sides. These activities or processes need to be captured and monitored by a control management system which acts as an interface between the two departments. As stated in Chapter 3, BPMN as a tool, can allow to visualize processes in much more details as opposed to a flowchart since it is possible to know details about a transaction such as what happens when a task is not done or who in the process, initializes a task. With the lowest level of details, a reporting sequence of events would flow according to the BPMN diagram illustrated in Figure 4.12 where the following elements and sequence of events can be identified:

- 3 pools of events representing 3 departments, are involved in the roof-bolter implementation stage: Mining, Engineering and capturing;
- The mining department initiates the chain of events as a shift begins. Following the drilling and blasting of the face, a re-entry exam is performed by the rock engineering team of the mining division to affirm that the conditions of the hanging wall are safe for the cleaning crew to proceed. Otherwise, install temporary support before cleaning;
- The mining department then sends a request for roofbolt support which is received by the capturing department;
- The capturing department generates a work order which is transferred to the engineering department;
- At the start of the shift, the engineering crew is mobilised and dispersed according to the work orders received from the capturing department. In case no work order received involves the roof-bolter, the available crew will be assigned to a different panel requiring a different task to be complete;
- Daily readings are captured on a checklist before mobilising the roof-bolter to the designated section and panel;
- Once on site, the roof-bolter can start drilling and installing the required roofbolts according to the drilling pattern. Should the pattern not be present, a request for drawing it can be placed, which in this case will mean that drilling will only occur on the following shift and a delay will be incurred; and

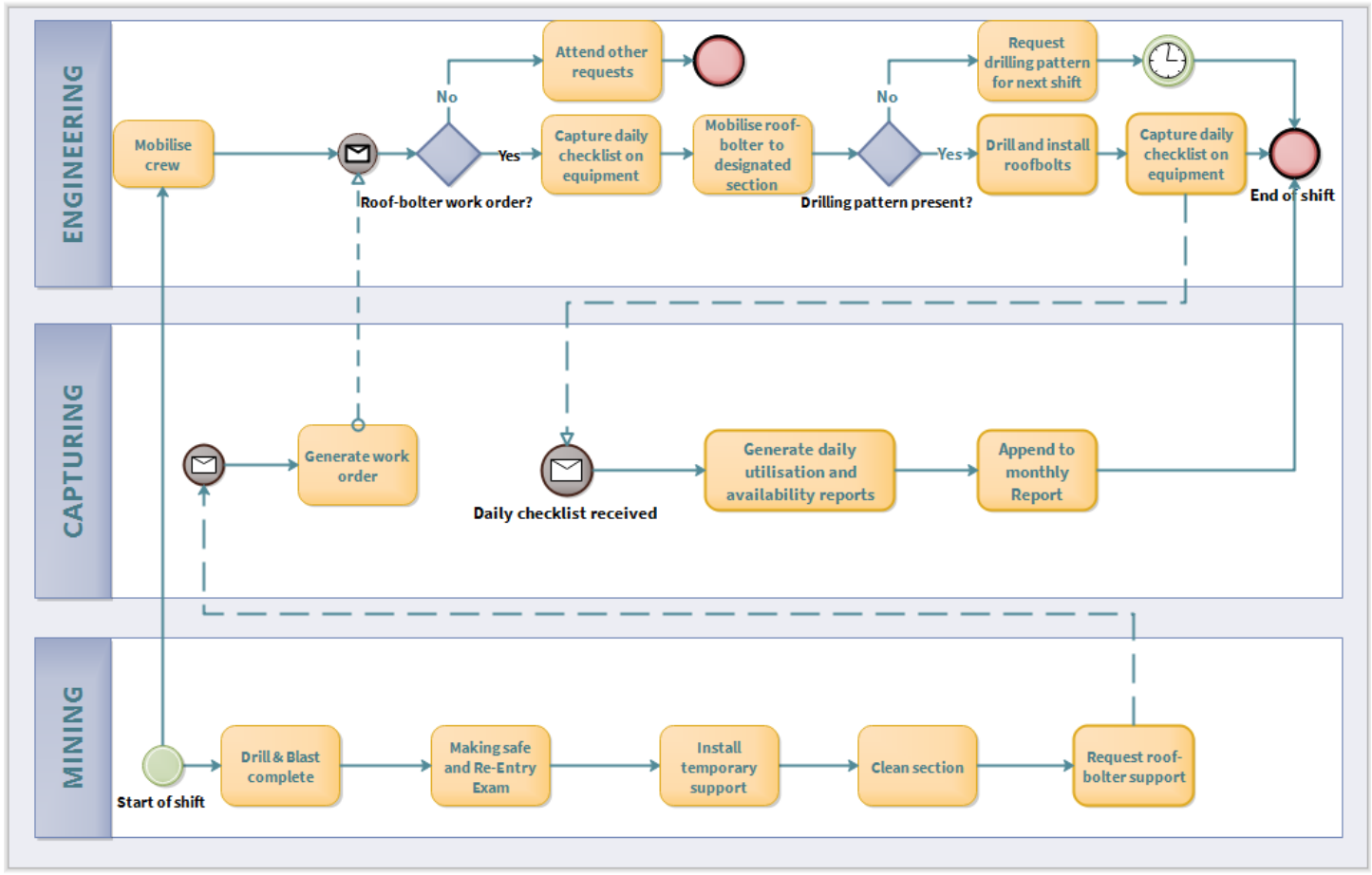

Figure 4.12: BPMN diagram representing different tasks within a single shift

- By the end of the shift closing readings are captured by the roof-bolter operator on the daily checklist which is transferred to the capturing department.

This BPMN process can be expanded and additional tasks can be added for a more granular and detailed sequential representation. The daily reports drawn as a result, can be analysed to provide measurements of the daily and monthly utilisation and availability and to facilitate improvements in terms of the process itself.

2. **Equipment availability**

According to Walden et al. (2015), availability can be defined as the probability that a system that is repairable is operating at a given point in time under a given set of environmental conditions. It is the ability of the machine to accomplish its required task at a certain point in time which is expressed as a percentage of the time the equipment is in an operating state.

The optimal figure for availability for mining equipment should be better than 90% (Balt 2007). Availability can be calculated using the following formula:

$$Availability = \frac{\text{Possible operating hours - Total downtime}}{\text{Possible operating hours}} \times 100$$

Downtime can be defined as the period of time during which a piece of equipment is not performing its required production function (Balt 2007). Two measures influence downtime (Birolini 1994) :

- Mean Time Between Failures (MTBF): This is the total time that the equipment would spend between each maintenance routine. The higher the MTBF, the higher will the availability be.
- Mean Time To Repair (MTTR): This is the average time taken to perform maintenance on equipment. This value is preferred to be low since it would increase the availability of the equipment.

From these definitions, availability can also be expressed as:

$$Availability = \frac{MTBF}{(MTBF + MTTR)}$$

3. **The equipment utilisation**

   Walden et al. (2015) also defines utilisation as a common performance measure of using the available time during which production time happens. Utilisation can be calculated using the following formula:

$$Utilisation = \frac{\text{Total run hours}}{\text{Possible operating hours}} \times 100$$

   where

   - "Total run hours" is the sum of hours that the piece of equipment has been running or working. This is calculated by subtracting opening hour meter reading from closing hour meter reading from the same piece of equipment; and
   - "Possible" operating hours is the total time available for the piece of equipment to do work.

   With regards to improving availability and utilisation figures for mining equipment, Fourie (2015) cited the elements listed in Table 4.1 as the major contributors to poor performance. Isolating and mitigating each one of these elements in order to improve utilisation and availability of the roof-bolter will ultimately improve the overall process and hence increase productivity and throughput.

   The nature of the ground engaging tools (in this case, the drill steel and the type of roof-bolt) is a critical factor for improving availability and utilisation since selecting the wrong tool for given underground conditions would lead to constant maintenance stoppages and decrease equipment performance.

4.4.3 System deployment and assessment

Following a successful implementation of the roof-bolter, the deployment and assessment of the entire system has to follow. This stage involves the measurement of outputs provided by the system in terms of its key performance indicators (KPIs) which should be tied back to the initial requirements from the first stage. Verification and validation have to be performed and the functions of the system have to be mapped to the designed roof-bolter rig.

Table 4.1: Contributors to poor equipment performance (Fourie 2015)

Availability	Utilisation
-Accident damage	-Blasting delays
-Power/Cables	-Housekeeping
-Machine reliability	-Safety stoppages
-Tyres	-Equipment moves
-Ground engaging tools	-Meetings and travel to workplace
-Supply chain	-Shift change
-Maintenance by OEM/Contractor	-Attendance/absenteeism
-Sources and facilities	-Dewatering
-Maintenance scheduling	-Equipment performing wrong job
	-Road conditions

The use of IDEF3 process flow diagrams allows to expand and tune a particular process during the deployment and assessment of the roof-bolter. It will also allow for a better way to generate documentation regarding the chain of decisions to be taken at a particular point and by a particular department.

The units of behaviour (UOBs) form part of a given scenario in the deployment and assessment stage where a particular activity is decomposed and different views are allowed to describe the event. Two major events in the deployment and assessment of the roof-bolter are driven by different scenarios: the installation of roofbolts and breakdown (repair).

1. **Installation of roofbolts**:The series of events leading to this KPI delivery through different scenarios is illustrated in Figure 4.13 and which is represented by the following steps:

    - Once a work order is assigned to a roof-bolter, operators check whether it is available. The outcome would either be that the roof-bolter had a breakdown and a follow up is needed in which case the state of repairs will be reported at the begining of the next shift; or the roof-bolter is available and a re-entry exam needs to be completed.
    - As a result of the re-entry exam, temporary support by mean of timber packs, could be required. Ideally, the roof-bolter can be mobilised to the panel.
    - Depending on whether a drilling pattern has been painted on the hanging wall or sidewalls, the roof-bolter can begin with the drilling of holes and installing the roofbolt at different marked locations.
    - The process will repeat until all the designated holes for the shift are drilled and roofbolts are installed and tensioned.

    These events only include the minimum possible scenarios. UOBs can be added to create additional scenarios which would vary from one mining operation to

another. Procedures for each scenario must be documented and let be known to operators, artisans and other staff involved in the deployment of the roof-bolter.

2. **Breakdown**: Repair of equipment constitutes a major operating cost for a mining operation and efficient measures must be put in place to not only mitigate the risks of a breakdown, but also to ensure that the MTTR is kept at a minimum. The series of events leading to this KPI delivery through different scenarios is illustrated in Figure 4.14 and which is represented by the following steps:

    - Once a fault has been identified on the roof-bolter, it is moved to the workshop where diagnostic is run;
    - The fault can either be fixed directly (faulty connection, or disconnected pipe) and the roof-bolter can be made available, or it could involve a part replacement;
    - The part to be replaced can either be readily available from the inventory spares or will have to be ordered in which case, the MTTR will be longer and hence, the availability will decrease.
    - Once the part is available and replaced, the roof-bolter can be made available.

    Due to the inconsistency in any underground mining operation with regards to environmental conditions, breakdowns are unplanned occurences and imply that the fault needs to be investigated and isolated before being attended to. Regular maintenance of equipment has to be implemented and preventative maintenance is recommended since it is based on an average rate of failure of a piece of equipment equipment or a component and has the advantage of minimising the risk of equipment failure, hence increasing production throughput over time.

Additional consideration must be given with regards to the installation of the roof-bolts, which involves operator training. A roof-bolter is considered as "heavy equipment" and requires qualified and skilled operators. Training should be an integral part of the process and an active participation in the implementation should be required from the operators.

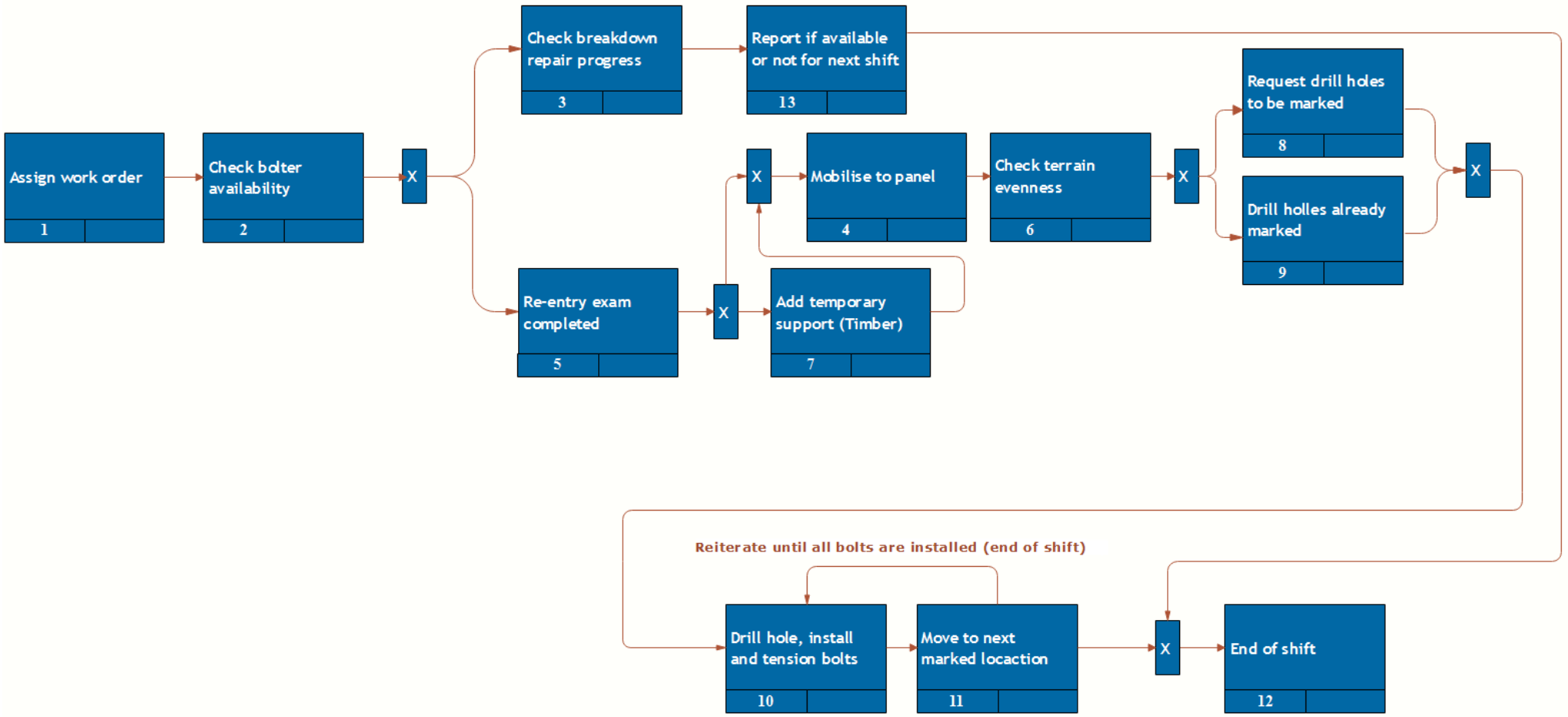

Figure 4.13: IDEF3 diagram of roofbolt installation scenario

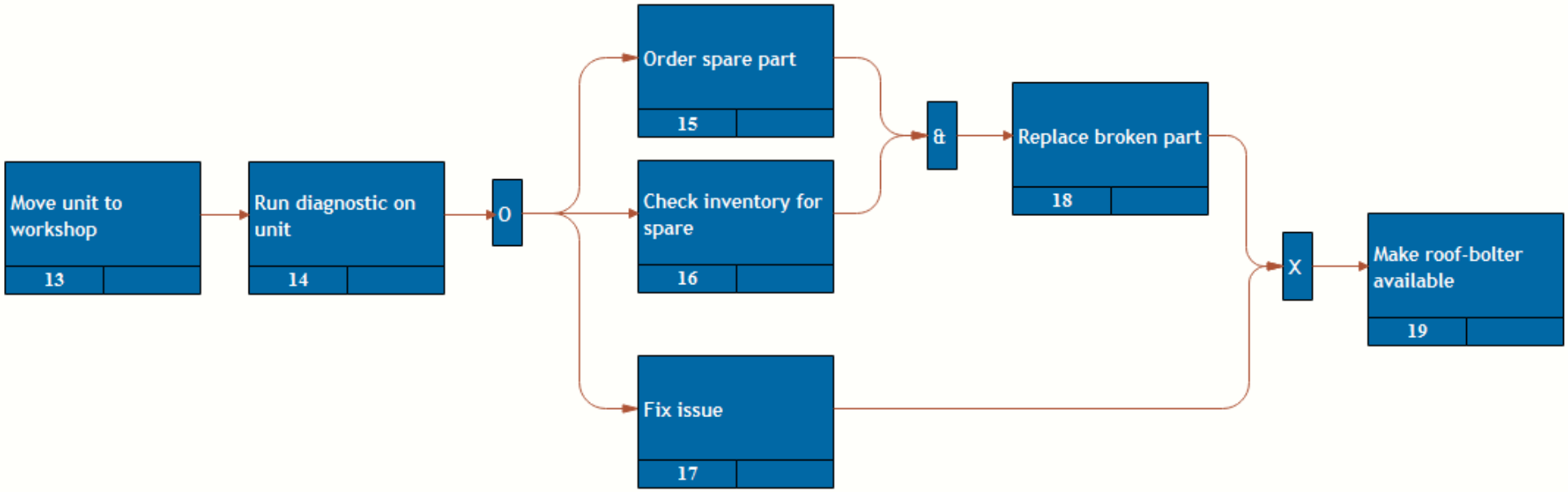

Figure 4.14: IDEF3 diagram of breakdown scenario

The supply of spare parts represents a challenge for maintenance and breakdown repairs. All services must be integrated for spare parts delivery, on-site repairs and potential delays in the supply chain. Longer downtimes (MTTR) linked to high variability can translate to low equipment utilisation and rising operational costs.

4.4.4 Summarised framework

The developed and proposed framework is presented in Figure 4.15, where each stage of the process can be identified. Steps leading to the completion of each stage are also shown. The implementation stage is indicated to constantly seeking improvement, since the reporting process as well as the equipment availability and utilisation need to be optimised regularly. The deployment and assessment stages are indicated to be iterative since the roof-bolter is constantly installing roof-bolts and is also prone to breakdowns and needs to be serviced or repaired should breakdowns occur.

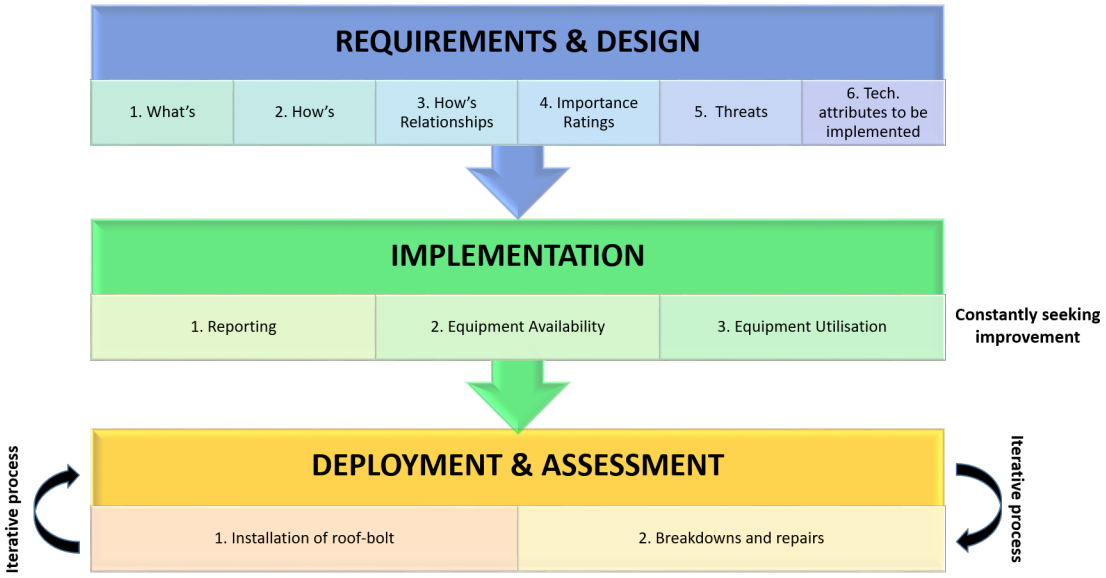

Figure 4.15: Proposed implementation framework and its elements

4.5 Summary

In this chapter, the Bushveld Complex's geology was presented and challenges that are particular to the South African platinum mining industry were highlighted. An overview of hanging wall support techniques was given and in terms of safety, reliability and productivity, preference was given to roof-bolter rigs.

Stages in the implementation of the roof-bolter were developed by means of systems engineering modeling tools. The system requirements and design were accomplished by means of QFD and involved six steps. The system implementation was accomplished by means of BPMN and contained three pools of events representing three

departments within the mine operation which should directly be involved during this stage. Utilisation and availability, which play a vital part in the system implementation, were also defined. Finally, the system deployment and assessment was accomplished by means of IDEF3 and two major events were identified as the installation of roofbolts and the breakdown scenario.

In the upcoming chapter, the developed framework will be tested against the post-implementation of a roof-bolter at a current underground mechanised platinum mine operation. Information provided at the mine will be packaged to fit within the framework and potential points of failure in this implementation will be identified as compared with the developed framework.

Chapter 5

Framework Verification

5.1 Introduction

The main goal in developing the framework was to increase the level of success in implementing a roof-bolter at a mining operation and subsequently, identifying points of failure in a typical implementation. The development of a mine plan spans throughout the entire value chain and mining equipment can either be acquired by the mine (capital expenditure) or rented out directly from contractors. In both cases, the operating cost needs to be kept at a minimum. Cost reduction is highly dependant on how efficiently the mining operation runs and by how much variability can be cut to a minimum. Using a systems approach to develop an implementation framework for the roof-bolter could reduce variability by isolating areas of weakness in the implementation process with the goal to improve throughput.

In order to verify and validate the developed framework, a platinum mine was investigated. This chapter covers the findings from the on-site investigations and observation around the roof-bolter being used at the mining operation. A gap analysis is performed, based on a comparison of the implementation at the mining operation against the developed framework. Elements of the implementation at the mining operation are unpacked and isolated into the different stages of the framework with the aim to measure the efficacy of the the systems approach. Finally, a SWOT analysis will be performed on the framework.

5.2 Presentation of the research area

The investigation for this portion of the study was conducted at a platinum mining operation that has requested to remain anonymous. The mining operation is situated on the western limb of the Bushveld Complex and is a fully underground mechanised mine, mining the Merensky reef. Bord and pillar is the mining method of choice and the stoping width varies roughly between 1.8 meters and 2 meters.

The investigation was conducted at the production level where an entire fleet of trackless mechanised mining equipment operating synchronously between the face, the washing and parking bays, and the workshops.

Observations were conducted on surface as well as underground with focus on the supporting equipment for a period of five days with the aim of understanding and reconstructing the implementation process as applied by the mining operation. An active section of the mine assigned to a shift boss was monitored and access to equipment data was also provided by the mine. As a result, a comparison between the implementation process at the mining operation and the proposed implementation framework could be made.

5.3 Framework verification

The implementation of the roof-bolter at the mining operation will be assessed against the framework developed in the previous chapter by going through the four stages of the systems approach. Each stage will be assessed individually by fitting the mining operation into the same context as the framework.

5.3.1 System requirements and design

The mining operation mines a narrow portion of the Merensky reef and in reference to Figure 2.4 of Chapter 2, its stoping width qualifies to be a low profile (LP) operation.

With regards to the fleet of equipment, the mining operation had chosen to implement mechanisation through one single OEM which is SANDVIK. The fleet of equipment which consists of drill rigs, roof-bolters, access rigs (used for secondary support) and LHDs were all purchased directly from the OEM. In this case, the fleet of equipment qualifies as commercial-off-the-shelf (COTS) since it results from a generic set of requirements and specifications and underwent an assessment relative to the mine specifications prior to their implementation and deployment phases (Simpson & Sheppard 1993).

The roof-bolter of choice in this case is SANDVIK's DS11L-V. This is a low-profile electro-hydraulic roof bolter equipped with a 45°-elevation capable single-boom, able to provide hanging wall as well as sidewall support. Some of its key features are that it can drill and install bolts from 2.2 meters up to 10 meters in length and has a bolting head capable of rotating to a maximum angle of 110° up, down and sideways (SANDVIK n.d.). A datasheet containing additional specifications about the roof-bolter can be found in Appendix B.

There is a tradeoff when selecting COTS as opposed to custom equipment (mine specific). Before making the decision on whether to design the roof-bolter according to specifications derived from initial requirements, or to purchase a readily available product in the current context, the following attributes must be considered as KPIs:

- Cost;
- Performance;
- Time to market; and
- Maintenance (lifecycle).

By purchasing COTS equipment, the investigated mining operation leverages a significant cost which if the roof-bolter was to be designed according to specifications, would have gone into research and development (R&D) as well as testing. The selected OEM has a tangible track record in mining equipment manufacturing. Through its R&D department, it has over the years developed and tuned a suite of roof-bolter rigs which can easily be implemented and deployed according to South African platinum mines specifications. However the product does not adapt completely to the specifications imposed by the geology and hence, performance is compromised to some extent. Mining throughput and levels of dilution at the plant feed can be severely impacted not only by equipment set-points but also by environmental conditions at the mine, which can in turn further impact on the entire value chain (Classen 2015).

The proposed implementation framework makes use of the house of quality as the tool to generate specifications based on initial requirements. Assumption was made that the customer, who in this case is the mining operation, would develop these requirements in collaboration with the OEM and agree on a final set of specifications according to which the roof-bolter would be designed, hence making it a custom design. This approach has the advantage of providing a tailored solution which would be specific to the mine and would deliver maximum throughput should the design requirements be met. As stated earlier, the process of conducting specific R&D based on the geology, and running trials would not only be costly, but would also take up a substantial amount of time.

A more balanced alternative however, would be to use a COTS roof-bolter and carry over all the cost and effort to customise it to the mining operation's requirements. This approach would result in a moderately shortened R&D time to market and a l ower cost than a custom design, and is known as "hybrid".

Figure 5.1 illustrates a radar chart where each one of the design concepts aforementioned are represented. This chart shows how they compare in terms of previously

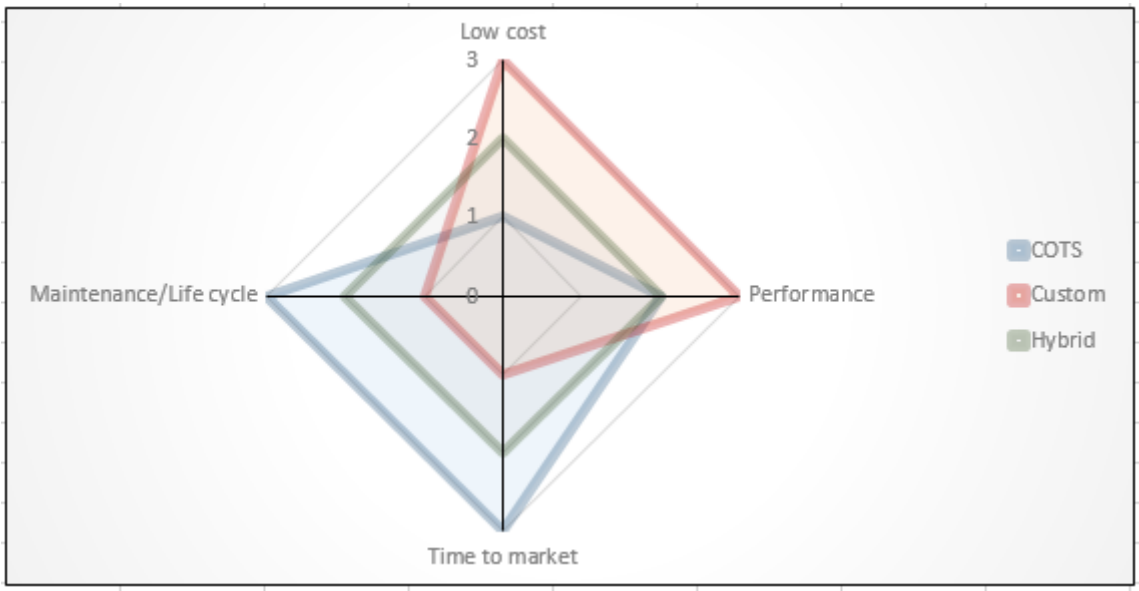

Figure 5.1: COTS vs Custom vs Hybrid KPI radar chart

cited attributes on a normalized metric scale from 1 to 3, with 1 indicating a weak influence and 3 indicating a strong influence.

With the aim to reduce cost and be able to start operating within the shortest time-span following the exploration and initial development phases, it made sense for the mining operation to select a COTS roof-bolter, which ultimately nulls the QFD process in the first two stages of the developed framework.

5.3.2 System implementation

The proposed framework approached the implementation stage by first deconstructing the process using BPMN, where 3 pools representing 3 departments were identified, then by looking at possible ways to improve productivity through increased utilisation and availability.

The mining operation was found to handle reporting in a similar way as described by the proposed framework with some alterations. The control room department manages the interactions between the mining and engineering departments with regards to daily checklists and work orders are also issued to artisans via the control room which communicates directly with the engineering workshops.

The mine follows a three shift cycle made of morning, afternoon and night shifts. Activities for each shift vary according to the section being mined. Artisans in the workshop have different tasks depending on the shift being completed. Maintenance and service routines are done during the morning and afternoon shifts whilst damage repair is done during all three shifts. At the beginning and end of a shift, the roof-bolter operator completes the checklist where he/she captures the powerpack

readings. This reading is used to deduce the availability and utilisation based on the actual working hours and the total downtime.

It was however noted that the control room happens to deal with quite a backlog of daily checklists which need to be captured before being sent back to the engineering department for filing and generating reports. This is due to the number of transactions that this department has to deal with on a daily basis.

The data capture system is based on Excel spreadsheets where readings from the daily checklists are entered and pre-edited macros are used to generate indicative figures for utilisation, availability, MTTR and MTBF. A dataset for a 4 week period is shown in Figure 5.2 and Figure 5.3 [1]. This data represents the average for all the operating roof-bolters in the section of the mine being investigated.

It can be observed that availability targets (80%) are met on a regular whilst utilisation sits way below the set target of 60% (down to 2% and never above 10%). This emerges as a red flag and can be attributed to two possible reasons:

1. This is an indication that the mining operation has a very poor performance on a KPI that directly affects the bottom line;

2. The management system is continuously collecting irrelevant data and this can be attributed to the human error factor. Checklists are completed manually by the operators and the artisans and thereafter, batches of these daily checklists are sent from underground to the control room on surface; the data is then captured on the spreadsheet system. At times, an end of shift entry for a given roof-bolter would not correspond to a start of shift reading, making the figures even more incoherent.

Upon observing utilisation numbers for the other pieces of equipment, it can be said that the entire system is in need of a major overhaul. A systems engineering approach needs to be applied at various levels in order to isolate the bottleneck in the system and optimise its processes. The utilisation numbers on the roof-bolters could possibly be attributed to a poor implementation of one or more of the other pieces of equipment in the fleet. The application of a systems engineering approach at a higher level is out of the scope of this study but should be carried out to improve these figures.

On the other hand, the MTBF and MTTR mostly fall within their targets of 40 hours and 4 hours respectively.

[1] used with authorisation

		Availability				
	Target	LHD	Dump Trucks	Drill rigs	Bolters	Access Rigs
17/08 to 23/08	85%	93,5%	89,0%	91,0%	92,0%	91,0%
24/08 to 30/08	85%	92,0%	95,0%	89,0%	82,0%	85,0%
31/08 to 06/09	85%	90,0%	95,0%	92,0%	91,0%	88,0%
07/09 to 13/09	85%	92,0%	100,0%	91,0%	92,0%	87,0%
		Utilization				
	Target	LHD	Dump Trucks	Drill rigs	Bolters	Axess Rigs
17/08 to 23/08	65%	27%	33,0%	7%	10,0%	2%
24/08 to 30/08	65%	24%	14,0%	3%	2,0%	0%
31/08 to 06/09	65%	21%	21,0%	7%	9%	2%
07/09 to 13/09	65%	13,0%	14,0%	8,0%	5,0%	0,0%
		MTTR				
	Target	LHD	Dump Trucks	Drill rigs	Bolters	Axess Rigs
17/08 to 23/08	4,00	2,20	4,60	2,80	3,30	3,10
24/08 to 30/08	4,00	3,04	3,02	6,50	5,40	4,04
31/08 to 06/09	4,00	9,00	3,00	3,00	4,60	5,40
07/09 to 13/09	4,00					
		MTBF				
	Target	LHD	Dump Trucks	Drill rigs	Bolters	Axess Rigs
17/08 to 23/08	45,00	75,00	35,00	71,00	50,50	32,00
24/08 to 30/08	45,00	33,60	63,00	69,00	82,00	49,80
31/08 to 06/09	45,00	42,00	59,50	55,00	60,00	77,80
07/09 to 13/09	45,00					

Figure 5.2: Availability, utilisation, MTBF and MTTR sample data

5.3.3 System deployment and assessment

The roof-bolters along with the rest of the fleet of equipment have been deployed at the mining operation and a high number of unforeseen scenarios have surfaced in addition to the two major events listed in the developed framework, which were "the installation of roof-bolts" and the "breakdown " events. These additional scenarios are an expansion of the breakdown event, since each type of breakdown has to be dealt with in its own specific manner by following a specific protocol.

From work order reports obtained from the control room, it was found that common breakdowns could be grouped into four different categories, each one focused on a particular section of the roof-bolter. This approach would lessen the complexity associated with developing an IDEF3 diagram for each type of breakdown and instead, focus on a more holistic view.Figure 5.4 depicts a mind map representing the 5 categories of breakdowns which are further broken down to the fault in need of repair.

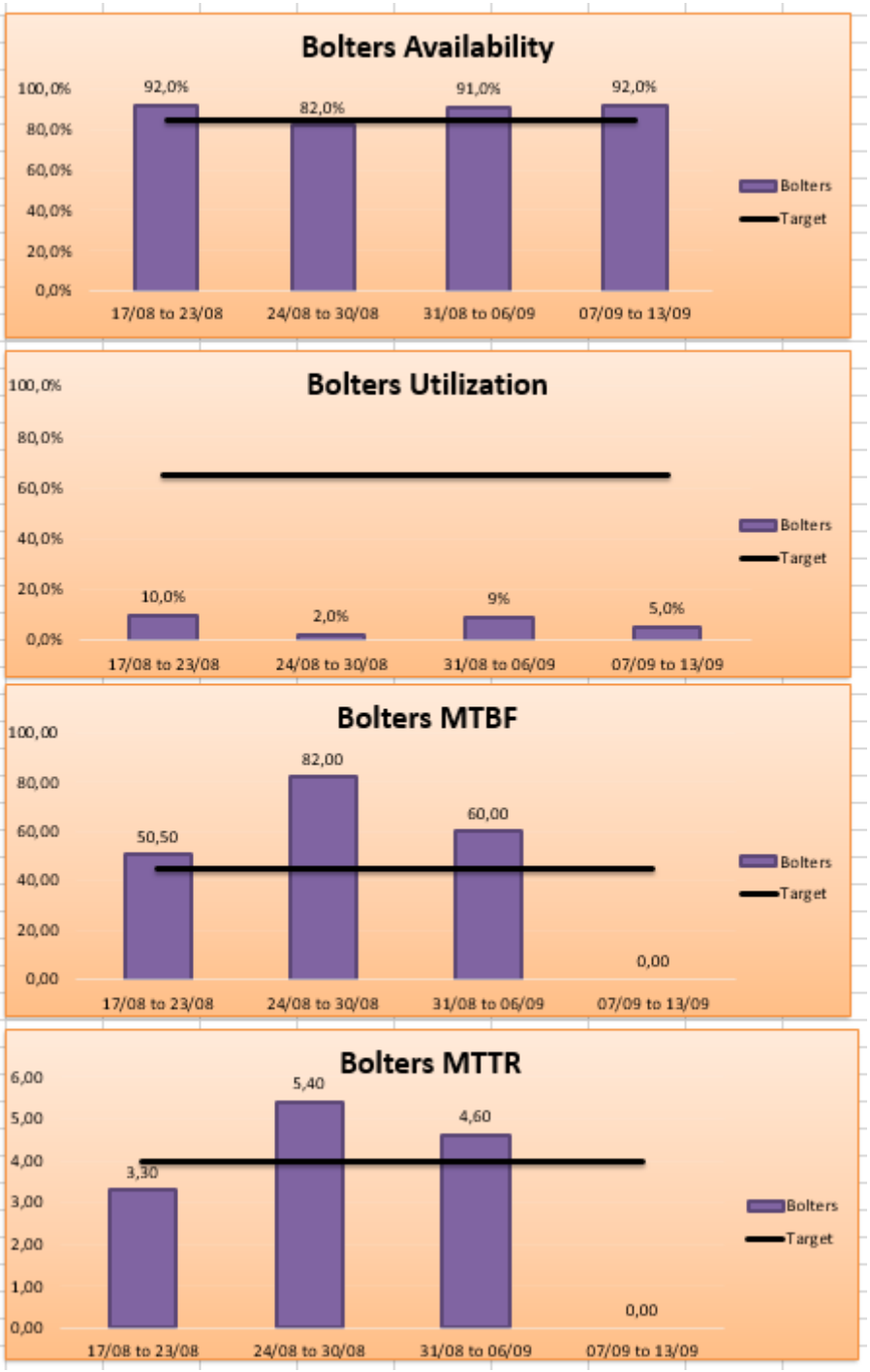

Figure 5.3: Availability, utilisation, MTBF and MTTR sample data

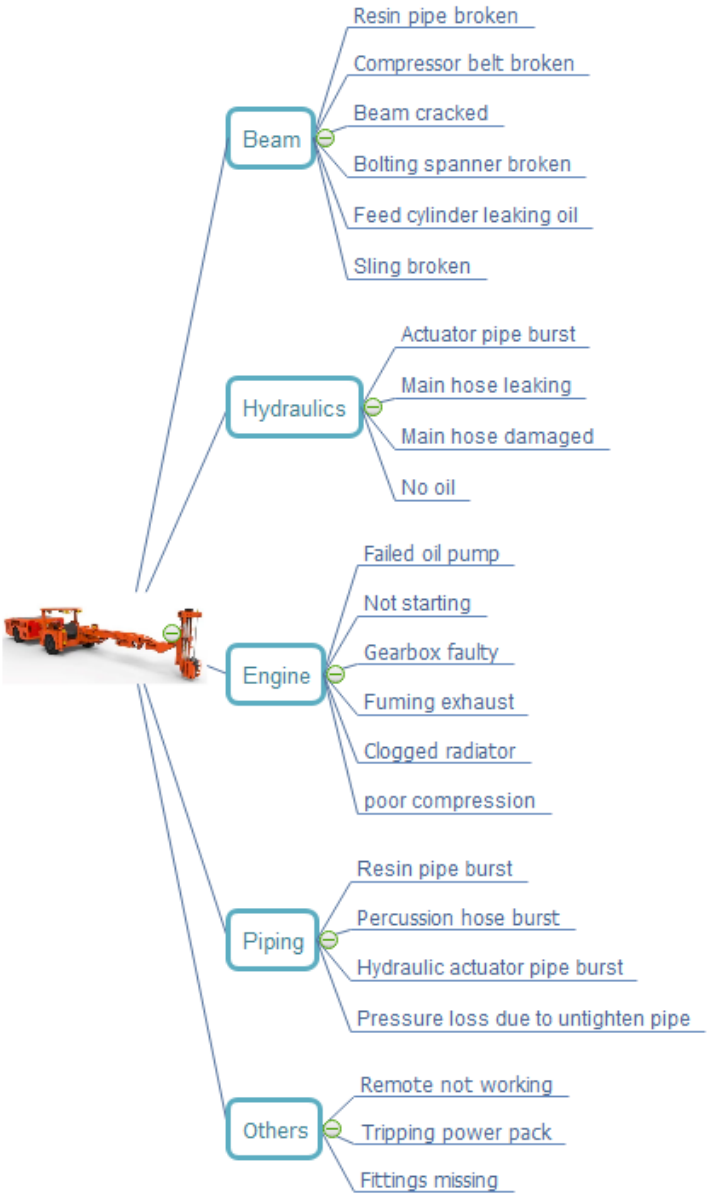

Figure 5.4: Mind map presenting group of common breakdowns on the roof-bolter

Being at an early stage of introducing mechanisation, the investigated mining operation is yet to provide a final assessment of the deployment of its fleet of equipment due to the number of variations occurring at this stage. The mining operation went from employing contractors for the operation and maintenance of the trackless mechanised equipment, to train and employ permanent operators and artisans at the mine. This shift has brought along quite a number of changes that still need to be continually assessed such as implementing and enforcing regulations around equipment.

At the time of conducting this research, some root cause investigation studies conducted by a consulting firm around the equipment and operators performances were ongoing at the mine. The aim of conducting these studies was to improve planning

and scheduling of the resources by understanding how operators and artisans spent time doing work and separate value added to non-value added activities in order to improve efficiency and throughput whilst remaining safe.

Some of the preliminary results around the roof-bolter affirmed the following shortcomings:

- Monthly production is hardly achieved in general due to concerns around bonuses which are believed to be unattainable;
- KPIs vary a lot since bords and pillars sizes are altered to accommodate different sizes of equipment, in which case some re-work will need to be done and additional roof-bolts will have to be installed on the hanging wall. A spacing of 1 m between each roof-bolt is required for 1.5 m long roof-bolts in order to reach the recommended factor of safety (FoS)[2] of 1.6. Alterations in the bords and pillar sizes implies an increase or decrease in the area to be supported and hence a variation in KPI;
- Shortage of resources due to absenteeism, which forces crews to inter-operate equipment in order to meet targets. Such circumstances are a common occurrence and tend to reduce the quality of mining and that of the equipmnt due to inconsistency;
- Potential misunderstanding and lack of cooperation between day shift, afternoon shift and night shift about prioritising each shift's activity at the expense of the others;

5.3.4 Findings (Gap analysis)

The investigation conducted at the mining operation revealed a number of findings from the implementation of the roof-bolter when aligned to the framework. The performance of the roof-bolter was found to be generally poor with a lot of room for improvement. In order to pin-point and identify the areas where improvement can be made, a gap analysis was conducted. The results are shown in Figure 5.5 where an action plan is suggested for moving from a current state to a desired state related to each stage of the roof-bolter implementation at the mining operation. *Desired states* represent the optimal conditions in the implementation based on the systems framework whereas *current states* represent the particular area that needs improvement. Action plans are steps that need to be taken to bridge the gap between these states.

[2]The factor of safety is a ratio of the strength to the stress of the hanging wall structure. A safety factor above 1.2 is recommended to avoid potential FOG.

Stage	Current state	Desired state	Action plan	Impact on production
Requirements & Design	Using COTS roof-bolter	Use of hybrid technology	Develop a set of balanced requirements for a hybrid roof-bolter	Medium
			Design, develop and implement hybrid roof-bolter based on required specifications	Medium
Implemenetation	Reporting based on manual capture on Excel spreadsheets - Error prone	Cloud-based digital reporting	Invest in new digital reporting infrastructure and employees training thereof	High
	Low equipment utilisation	Higher equipment utilisation (Target is set at 60%)	Investigate implementation for other equipment in the fleet using the framework and identify possible bottleneck.	Medium
Deployment & Assessment	Production targets hardly achieved	Reach monthly production targets on a monthly basis	Review and adjust production targets to reasonable figures	High
			Review bonus structure	
	Variations in bord and pillar sizes	Constant bord and pillar sizes to avoid re-work	Maintain constant bord and pillar sizes to reach required factor of safety (FoS)	High
	Unpredictable breakdowns	Identify potential breakdowns before they occur	Introduce predictive maintenace of equipment based on data analytics and sensors	High
	Inter-operation of equipment by untrained operators due to absenteism and resources shortage	Efficient operation of equipment	Provide general training on all types of equpment to every operator	High

Figure 5.5: Gap analysis of roof-bolt implementation at the mining operation relative to stages of the framework

The gaps identified in the requirements and design stage of the implementation are regarded as having *"medium"* impacts on production. As stated in section 5.3.1, the trade-off between getting a COTS roof-bolter and developing one based on requirements can be balanced by implementing a hybrid solution. However, it is very common for OEMs to offer roof-bolters which can be adapted to suit the geology of mining operations and at the same time, considering the lead time to produce a roofbolter according to specifications, the COTS has to be the better option. A very refined investigation based on COTS roof-bolters specifications will need to be conducted by the mine before committing to purchasing and implementing a roof-bolter. A systems approach is also recommended for this selection.

With regards to the implementation stage, a more accurate and precise reporting system should be implemented. The ideal system would reduce the number of

transactions between operators and the control room by centralising all the reports. This would also reduce the possibility of errors occuring when capturing data. As for utilisation, it was noted that due to a high percentage in availability ,an investigation around the cycle times of the rest of the fleet needs to be conducted in order to optimise the other processes and reach the targeted utilisation of 60% on the roof-bolter.

The system of interest being the roof-bolter, forms part of a bigger system made of a number of other sub-systems. Each of these sub-systems has a direct or indirect influence on the other and in this case, isolating and optimising the other sub-systems and processes that are linked to the implementation of the roof-bolter would further enhance the implementation. Currently, the system of interest is being negatively affected by the larger system; therefore calling for a more holistic system view.

Finally, the development and assessment stages were regarded as having *"high"* impacts on production. From production targets that need to be achieved, to variations in bord and pillar sizes as well as breakdowns and resources shortage, this stage has to repeatedly be improved since it is an iterative process. Once deployed, the roof-bolter is continuously assessed and optimisation of current states in these stages is an ongoing endeavor. A mining operation can be regarded as an enterprise where, not only financial growth is to be attained, but also where continuous improvement in processes is necessary in order to enable this growth. It is therefore important to continuously review and streamline processes and where possible, apply continuous improvement techniques as used in the manufacturing industry.

5.3.5 Framework SWOT analysis

The implementation framework was developed by deconstructing processes and grouping them in stages aligned to a systems approach. It is important to undertake a SWOT analysis on the developed framework in order to indicate areas where it reached or fails to reach its objectives. Similarly, potential areas which can externally influence the improvement as well as those that represent a risk if implemented, have to be addressed.A SWOT analysis diagram for the developed framework is shown in Figure 5.6.

Leveraging a series of systems engineering tools that have been proven to work in other industries, has to some extend, given the framework the capability to identify and isolate points of failure in the implementation of the roof-bolter at the mining operation. By enabling the identification of actions to be taken in order to increase the throughput of the roof-bolter, it can be said that the developed framework has reached its objectives.

However, the system of interest in this case, is part of a broader system, whose sub-systems directly or indirectly interact with it. These interactions introduce a number of dependencies that necessitate alternative processes to be included in the framework and imply a more in depth deconstruction of processes. The developed framework also fails to consider COTS and hybrid roof-bolters during the requirements and design phase and only focuses on a custom design solution.

Having proven that it is based on a concept that works and that provides constructive feedback on a typical roof-bolter implementation, the developed framework has the potential to be implemented for every piece of mechanised mining equipment and thereof, a holistic framework for the entire fleet can be implemented. It will also be possible to enhance the capabilities of the framework by implementing real-time data analytics which can provide feedback based on how the fleet performs.

The adoption and commitment to apply the developed framework in the industry remains a treat at many levels. From an OEM perspective, the risk of disturbing the current processes in place is quite high and from a mining company perspective, this will involve a disruption in current operations.



Figure 5.6: SWOT analysis of the developed framework

5.4 Summary

The case study investigated was identified as a mining operation situated in the western limb of the Bushveld complex in the Rustenburg area. The developed framework based on the systems approach was then measured against the current implementation at the mining operation for each of the systems stages.

The system requirements and system design stages at the mining operation revealed to have taken an approach based on COTS components, which has advantages as well as drawbacks when compared to the proposed QFD approach based on a custom design.

The system implementation stage was in line with the framework, although a number of issues were identified specifically around data capture and reporting.

The system deployment and assessment stage was found to have an increased number of scenarios around the breakdown category compared to those of the developed framework, which increased the level of complexity in redrawing the IDEF3 model. The mining operation was still at an early stage of introducing mechanisation, hence a final assessment would be premature at this point in time. Root cause investigation studies aiming at improving productivity and planing are ongoing at the mining operation.

A gap analysis based on findings from the on-site investigation was conducted, emphasising action plans to bridge the gap between current and desired states for each stage of the implementation at the mine related to the framework.

Finally, a SWOT analysis of the developed framework was presented, which highlights internal (strengths and weaknesses) and external (opportunity and threats) factors related to the framework in order to provide a clear assessment of the framework.

The following chapter will summarise the report and provide a general conclusion as well as recommendations for future work.

Chapter 6

Conclusion and recommendations

6.1 Summary

The aim of the research presented here was to develop a framework based on a systems approach for the implementation of a roof-bolter in an underground platinum mine section based on a systems approach. The developed framework's primary function is increase the level of success when implementing a roof-bolter in a platinum mine, while also identifying points of failure in a typical implementation process. The objective of the research was to evaluate whether a systems approach would enhance the level of success of implementation of the roof-bolter in an underground platinum mine.

A background on the mining industry's shift to mechanisation was presented and the concept behind systems engineering and what it entails was provided. An introduction to the geology of South African platinum mines was given and techniques around hanging wall roof-support were also covered.

Systems engineering tools that have previously been successfully applied to various industries were introduced. These tools were used to deconstruct the implementation process into four stages. Each stage was analysed for the roof-bolter and the system's implementation framework was deduced.

A case study was conducted comparing the proposed framework and the implementation of the roof-bolter at the investigated mining operation. As a result of this comparison, a gap analysis was conducted. Finally, a SWOT analysis on the developed framework was presented.

6.2 General conclusions

The developed framework assessed and managed to identify areas in each stage of processes where improvements could be implemented, indicating different levels of

impact on production. The systems engineering tools that were used to develop the framework had previously been applied to other industries with a high level of success and therefore, had a high potential for success.

It is therefore safe to say that the developed framework has achieved its purpose although it displayed a number of pitfalls that were covered in the SWOT analysis in section 5.3.5.

However, a single case study represents a constraint and the framework should be tested on a reasonable number of mines that have had different types of implementation. The relative size of the sample used to validate the framework cannot transform a single case into a macroscopic study. Being a qualitative study, Ishak & Bakar (2014) affirm that choosing a single case study as a mean to validate the framework should imply that the sample used (implementation of the roof-bolter at the particular mining operation) has to represent an extreme or unique case. Issues found in the gap analysis do not necessarily apply as a holistic representation of other mining operations.Due to time constraints, a validation based on multiple case studies was not accomplished.

6.3 Recommendations and future work

The concept of implementing a piece of mining equipment following a systems approach presents high potential for not only implementing equipment with a higher potential of success, but also for smooth running of mining operations once equipment has been deployed. The current state of the South African mining industry which is driven by a high level of economic uncertainty and depletion of resources, calls for a more optimised extraction process with minimal room for error. The study here presented can serve as a pilot to a further investigation, expanion and implementation of a number of variations of the framework.

The qualitative aspect of the research can be spanned across multiple operations in order to draw a holistic conclusion or generate a framework adaptable to any possible mining operation.

Expanding the implementation, deployment and assessment stages by looking in depth at processes and implementing value stream mapping (VSM) to each stage would further allow to identify and eliminate non-value-adding activities or processes towards a more optimised framework.

Perhaps in the future, a consolidated mine operations planning software based on various systems engineering tools, could be developed for deploying and implementing mechanised equipment more efficiently and being able to detect and mitigate

potential risks of failure. Such a software application would establish a direct link between the OEM and the mining operation and would not only guarantee a successful implementation but also a sustainable equipment lifecycle.

Bibliography

Akao, Y. (2004), *Quality Function Deployment: Integrating Customer Requirements Into Product Design*, Productivity Press, New York, NY.

Al-Chalabi, H., Hoseinie, H. & Lundberg, J. (2016), Monte carlo reliability simulation of underground mining drilling rig, *in* 'Current Trends in Reliability, Availability, Maintainability and Safety - Lecture Notes in Mechanical Engineering', Springer, Cham, pp. 633–643.

Balt, E. J. P. (2007), *Cost management of the availability and utilization of mining earth moving equipment*, University of Pretoria. Master of Science Thesis.

Baxter, R. (2015), 'Future of the south african platinum mining industry'. [Accessed July 20th, 2017].
URL: *http://www.lbma.org.uk/assets/events/Conference%202015/Presentations/Baxter.pdf*

Birolini, A. (1994), *Quality and Reliability of Technical Systems: Theory - Practice - Management*, $\mathrm{Springer}_{V}erlag, BerlinHeidelberg, GmbH.$

Bohlmann, H. R., Dixon, P. B., Rimmer, M. T. & Van Heerden, J. H. (2015), 'The impact of the 2014 platinum mining strike in south africa: An economy-wide analysis', *Economic Modelling* **Volume 51**, 403–411.

Burge Hughes Walsh Limited (2009), 'Systems engineering tools techniques'. [Accessed September 15th, 2017].
URL: *https://www.burgehugheswalsh.co.uk/systems-engineering/tools.aspx*

Callow, D. J. (2006), 'The impact of mining conditions on mechanized mining efficiency', *The Journal of the Southern African Institute of Mining and Metallurgy* **Volume 106**, 821–830.

Canbulat, I. (2008), 'Evaluation and design of optimum support systems in south african coileries using the probabilistic design approach'. PhD Thesis.

Cawthorn, R. G. (2010), 'The platinum group element deposits of the bushveld complex in south africa', *Platinum Metals Review* **Volume 54**, 205–215.

Chamber of Mines of South Africa (2016), 'Integrated annual review 2016 - area of focus: Safety'. [Accessed September 22nd, 2017].
URL: *http://chamberofmines.org.za/reports/2016/download/CM-IR16-focus-safety.pdf*

Classen, J. O. (2015), 'Application of systemic flow-based principles in mining', *The Journal of the Southern African Institute of Mining and Metallurgy* **Volume 115**, 747–754.

Conradie, C. D. (2018), *Investigating the values and fears of mechanisation in the South African gold and platinum industry*, North-West University. Master of Business Administration Dissertation.

Defense Acquisition University Press (2001), Systems engineering fundamentals, Technical report, Department of Defense - Systems Management College, Virginia.

Dettmer, H. W. (2005), 'An introduction to the systems approach'. [Accessed March 30th, 2017].
URL: *http://www.tocca.com.au/Documents/Introduction*$_t o_t he_S ystems_A pproach_c$*.pdf*

Ferreira, P. H. (2012), A perspective on underground support technologies in southern african platinum mines to reduce safety risks and enhance productivity, The Journal of the Southern African Institute of Mining and Metallurgy, Sun City, pp. 445–482.

Fourie, F., Valicek, P., Krafft, G. & Sevenoaks, J. (2014), Narrow reef mechanized mining layout at anglo american platinum, *in* 'The 6th International Platinum Conference - Platinum Metal for the Future', The Southern African Institute of Mining and Metallurgy, pp. 261–279.

Fourie, H. (2015), Improvement in the overall efficiency of mining equipment: a case study, Vol. Volume 116, The Journal of the Southern African Institute of Mining and Metallurgy, pp. 445–482.

Franklin, C. E. (2008), 'Optimisation of a mechanised platinum mining section'.

Harisson, G. A. (2008), Anglo platinum extra low profile (xlp) mechanized equipment implementation - an update, *in* 'Third International Platinum Conference, Platinum in Transformation', The Southern African Institute of Mining and Metallurgy, pp. 293–296.

Hartley, J. F. (1994), *Quantitative Methods in Organizational Research: A Practical Guide - Case studies in organizational research*, SAGE Publications.

Hattingh, T. S., Sheer, T. J. & Du Plessis, A. G. (2010), Human factors in mine mechanization, *in* 'The 4th International Platinum Conference, Platinum in transition 'Boom or Burst", The South African Institute of Mining and Metallurgy, pp. 255–258.

Henning, P. & Ferreira, P. (2010), 'In-stope bolting for safer working environment', *The Journal of the Southern African Institute of Mining and Metallurgy* **Volume 110**, 47–52.

Hochreiter, R. C., Kennedy, D. C., Muir, W. & Woods, A. I. (1985), 'Platinum in south africa (metal review series no. 3)', *The Journal of the Southern African Institute of Mining and Metallurgy* **Volume 85**, 165–185.

Hoek, E. (2007), 'Practical rock engineering'. [Accessed December 10th, 2017].
URL: *https://www.rocscience.com/documents/hoek/corner/Practical-Rock-Engineering-Full-Text.pdf*

Horberry, T. J., Limerick, R. B. & J., S. L. (2011), *Human Factors for the Deign, Operation, and Maintenance of Mining Equipment*, Taylor and Francis Group, LLC, Boca Raton, FL.

Ishak, N. M. & Bakar, A. Y. A. (2014), Developing sampling frame for case study: Challenges and conditions, Vol. Volume 4, World Journal of Education, pp. 29–35.

Jenkins, G. A. (1967), 'Systems and their optimisation'. [Accessed August 30th, 2017].

Kekana, W. O. (2018), *Implementation of a GHH Roof Bolter Machine at Merensky Shaft (Booysendal Platinum Mine) - A Case Study*, University of the Witwatersrand. Master of Science Thesis.

Kolokoto, T. J. & Yimaz, H. (2013), 'An investigation into introducing a new support element at khomanani 2: resin bolts or 1.5m in-stope roofbolts', *The Journal of the Southern African Institute of Mining and Metallurgy* **Volume 113**, 335–344.

Lisle, J. (2017), 'Mining indaba conference 2017: The outlook fir the south african mining sector'.

Marek, A., Thorley, S., Dawson, L. & Pickering, R. (2012), Mechanized bolting - on-board drilling automation and a change in the support regime in low-profile mechanized mining, *in* 'Platinum 2012', The Southern African Institute of Mining and Metallurgy, pp. 49–64.

Mayer, R. J., Menzel, C. P., K., P. M., deWitte, P. S., Blinn, T. & Perakath, B. (1995), *Information Integration for Concurrent Engineering (IICE) IDEF3 Process Description Capture Method Report*, Knowledge Based Systems, Inc, College Station, TX. [Accessed August 19th, 2017].
URL: *https://pdfs.semanticscholar.org/2b4f/202bc011dd3a930791ac8655bff00ea63974.pdf*

Mayer, R. J., Painter, C. M. K. & deWitte, P. S. (1992), *Systems and their Optimisation*, Knowledge Based Systems, Inc, College Station, TX.

[Accessed August 12th, 2017].
URL: *http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.114.9568&rep=rep1&type=pdf*

McIntyre, W. W. (2009), *Lean and Mean Process Improvement*, Book Surge Publishing, Jacksonville, FL.

Mine Health and Safety Council (2014), 'South african mining industry journey to zero hard 2003-2013'. [Accessed August 28th, 2017].
URL: *http://www.sacollierymanagers.org.za/docs/MHSC_Journey to Zero Harm A5 Handbook print draft v5 F*

Minnitt, R. (2014), 'Sampling in the south african mineral industry', *The Journal of the Southern African Institute of Mining and Metallurgy* **Volume 114**, 63–81.

New Concept Mining (2017), 'Hydrabolt'. [Accessed October 28th, 2017].
URL: *http://www.ncm.co.za/hydrabolt.html*

Pickering, R. G. B. & Ebner, B. (2001), Hard rock cutting and the development of a ontinuous mining machine for narrow platinum reefs, *in* 'Third International Platinum Conference 'Platinum in Transformation", Vol. Volume 102, pp. 19–24.

Pickering, R. G. B. & Leon, F. (2008), The implementation of mechanized breast mining and the development of xlp equipment, *in* 'Third International Platinum Conference 'Platinum in Transformation", The Southern African Institute of Mining and Metallurgy, pp. 269–275.

Reid, P. P., Compton, W. D., Grossman, J. H. & Fanjiang, G. (2005), *Building a Better Delivery System: A New Engineering/Health Care Partnership*, The National Academies Press, Washington, DC.

Resemin (2015), 'Small bolter 88: Roof bolter for small sections'. [Accessed December 19th, 2017].
URL: *http://www.resemin.com/en/pdf/33e75ff09dd601bbe69f351039152189-Bolter%2088%20(English)Rev.%*20160920*.pdf*

Robbins, R. J. (2000), 'Mechanization of underground mining: a quick look backward and forward', *International Journal of Rock Mechanics and Mining Sciences* **Volume 37**, 413–421.

Rosing, M. V., Scheer, A. W. & Scheel, H. V. (2015), *The Complete Business Process Handbook - Body of Knowledge from proces Modeling to BPM Volume 1*, Morgan Kaufmann and Elsevier, Waltham, MA.

Rowland, T. (2014), 'South deep: A world class orebody in perspective'. [Accessed July 20th, 2017].

URL: *hhttps://www.goldfields.com/pdf/investors/shareholder-information/transcripts/2014/south-deep-a-world-class-ore-body-in-perspective-sd/presentation-transcript.pdf*

SANDVIK (2006), 'Robolt xlp technical specifications'. [Accessed July 10th, 2017].
URL: *http://www.miningandconstruction.sandvik.com/sandvik/9082/Internet/S002630.nsf/Alldocs/*

SANDVIK (n.d.), 'Ds211l-v low-profile bolter:technical specifications'. [Accessed June 6th, 2017].
URL: *https://www.rocktechnology.sandvik/globalassets/products/underground-drill-rigs-and-bolters/pdf/ds211l-v-specification-sheet-english.pdf*

Schouwstra, R. P. & Kinloch, E. D. (2000), 'A short geological review of the bushveld complex', *Platinum Metals Review* **Volume 44**, 33–39.

Sellers, E. J., Roberts, M. K. C., Lamos, R., Roberts, D. P. & Watson, B. P. (2016), 'The use of tendon support in tabular stopes'. CSIR Mining Technology, Research number SIM 020208.

Simpson, W. R. & Sheppard, J. S. (1993), 'The impact of commercial off-the-shelf (cots) equipment on system test and diagnosis', *Proceedings from the International Test Conference* pp. 30–36.

Singh, N. (2017), 'Weathering the 'perfect storm' facing the mining sector', *The Journal of the Southern African Institute of Mining and Metallurgy* **Volume 117**, 223–229.

Skyes, W. (1990), Validity and reliability in quantitative market research: A review of the literature, *in* 'Journal of the Market Research Society', pp. 289–328.

Spearing, A. J. S. & Heyett, A. (2014), 'In situ monitoring of primary roofbolts at underground coal mines in the usa', *The Journal of the Southern African Institute of Minining and Metallurgy* **Volume 144**, 791–800.

Stacey, T. R. & Wesseloo, J. (2004), 'Updated stress database for south africa', *Proceedings of the International Symposium on In-situ Rock Stress* pp. 46–471.

study.com (2006), 'Business process model and notation: Process examples'. [Accessed September 11th, 2017].
URL: *https://study.com/academy/lesson/business-process-model-and-notation-process-examples.html*

Tapke, J., Muller, A., Johnson, C. & Sieck, J. (n.d.), 'House of quality: Steps in understanding the house of quality'. [Accessed June 14th, 2017].
URL: *http://www.public.iastate.edu/ vardeman/IE361/f01mini/johnson.pdf*

Van Schoor, M., Du Pisani, P. & Vogt, D. (2006), High-resolution, short-range, in-mine geophysical techniques for the delineation of south african ore bodies, Vol. Volume 102, South African Journal of Science, pp. 355–360.

Vogt, D. & Hattingh, T. (2016), 'The importance of people in the process of converting a narrow tabular hard rock mine to mechanization', **Volume 116**, 265–274.

Walden, D. D., Roeldler, G. J., Forsberg, K. J., Hamelin, R. D. & Shortell, T. M. (2015), *Systems Engineering Handbook - A Guide for System Life Cycle Process and Activities*, fourth edn, Wiley, San Diego, CA.

Wertz, J. R. & Larson, W. J. (2008), *Space Mission Analysis and Design*, Microcosm Press and Springer, New York, NY.

Willis, R. H., Cixon, J. R., Cox, J. A. & Pooley, A. D. (2004), A framework for the introduction of mechanized mining, *in* 'International Platinum Conference 'Platinum Adding Value", The Journal of the Southern African Institute of Mining and Metallurgy, Sun City, pp. 117–124.

Yin, R. K. (1984), *Cas study research: Design and methods*, SAGE, Newbury Park, CA.

Appendix A

Resemin Small Bolter 88 Datasheet

Appendix B

Sandvik DS211L-V Low-Profile Bolter Datasheet