SELECTION OF AN OPTIMAL TUNNEL DEVELOPMENT METHOD FOR AN UNDERGROUND MINE TRAVELLING WAY USING AN ANALYTIC HIERARCHY PROCESS

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

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DECLARATION

I have read the University of the Witwatersrand Student Academic Misconduct Policy (SAMP). I hereby declare that the work I am submitting for assessment is my original work and that I have not plagiarised, misrepresented or colluded with any other person or source. I have properly acknowledged, cited and referenced all the sources that I have used in my work. I also declare that where artificial intelligence (AI) tools have been used they have only been used as a means of guidance and that the ideas and arguments presented in my work are my original thoughts and interpretations. I also acknowledge that any academic misconduct will result in serious consequences, such as a reduced grade, a fail mark, or disciplinary action according to the SAMP. I understand that the School of Mining Engineering may investigate academic misconduct including using similarity and AI detection software to check the originality of my work and I undertake to abide by the decision of any such investigation.

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ABSTRACT

This research study was conducted at the Marikana Operations (Marikana) which are situated within the Western Limb of the Bushveld Complex (BC) located in the North West province of South Africa. The Marikana Operations mine platinum group metals (PGM) using conventional underground mining methods. The Marikana Operations are owned by Sibanye-Stillwater. The PGM conventional underground mining entails extracting a shallow-dipping narrow reef horizon which is accessed via a network of development workings. Within this layout, a travelling way is an inclined tunnel that connects lateral development workings with the workings on the reef horizon.

At Marikana the conventional hand-held mining method is used to excavate travelling ways. However, there was a trial process completed that proved the viability of the inverse drop raising method of excavating travelling ways at Marikana. With more than one viable tunnelling method being available for travelling way development, the need arose to select an optimal travelling way development method for Marikana. The selection is a multi-criteria decision-making (MCDM) process because it requires the simultaneous consideration of several factors when evaluating the different alternatives or options.

Commonly applied tunnelling techniques were reviewed leading to the selection of both the hand-held drill and blasting method and the inverse drop raising method as applicable to the conventional underground mining environment and specifically to travelling way development. Thereafter, Multi Criteria Decision Analysis (MCDA) techniques were reviewed, and the Analytic Hierarchy Process (AHP) was selected as the MCDA technique to be used as the selection tool for the research, due to its several advantages such as the ability to detect inconsistencies in judgements and provision to remedy the inconsistencies.

After the application of AHP, the inverse drop raising method scored 7.2% higher than the hand-held method with a 53.6% versus 46.4% score. The inverse drop raising method was therefore selected as the optimal method to develop travelling ways at Marikana.

With the approach that both these methods are currently being executed at Marikana, the inverse drop raising method is nearly twice as expensive as the conventional hand-held method. If PGM prices become a constraint, the method might not be sustainable if executed the way that it is done at the Marikana Operations from a cost perspective. It is suggested that further research should be done to see how the method can be executed more cost-effectively.

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1 INTRODUCTION

1.1 Overview of Chapter 1

Chapter 1 introduces the research topic and presents background information on the case study mine and its location. Additionally, the chapter provides the problem statement that motivated this study, highlighting the key issues that were addressed. Furthermore, it puts forth the research question that guided the investigation, along with the aim and objectives of the research study. To provide an overview of the report structure, Chapter 1 concludes by outlining the subsequent chapters that make up the research report, giving readers guidance on what to expect in the report. By establishing these introductory elements, Chapter 1 sets an outline for the research and provides a framework upon which the subsequent chapters were built.

1.2 Background

The drive to zero harm is a commonly accepted principle in the South African mining industry. The need to constantly improve safety conditions remains a focal point that can be seen in published mining articles, in value statements of mining companies and can be heard in mining-related conversations throughout the mining industry. The transition to zero harm must have equal consideration as any pressures to achieve production targets, whilst striving to maintain operational excellence. This need to constantly improve working conditions must be applied when reviewing or selecting an optimal method of mining.

The mining industry uses various techniques to develop underground tunnels and excavations. Apart from safety and economics, technical factors including orebody characteristics, excavation dimensions, and support installation requirements all form part of the factors considered when selecting an excavation technique. These factors vary between mining sites and must be evaluated simultaneously when selecting the best alternative from a set of alternatives, thus, necessitating the use of Multi-Criteria Decision Analysis (MCDA) techniques (Balusa & Jayanthu, 2017).

In mining, the process of underground tunnelling exposes major geological structures. Each of these geological structures has potential risks. Employees that are tunnelling through these structures must be kept safe and in conducive working conditions. One of the tunnels developed in an underground mine is a traveling way.

This study was motivated by the need to minimise the potential for serious injuries and potential production losses that occur during and after travelling way development in mines that use the conventional underground mining method. In the conventional mining layout, a travelling way is a tunnel that allows workers to access primarily the reef horizon and stoping section of the mine. It is used for the supply of services going into the stopes such as compressed air, water, and electrical cables. Travelling ways are generally located between the stepover and the cross-cut and is an inclined excavation developed from the cross-cut to the on-reef mining area. Travelling ways must be of sufficient size to allow for ventilation flow and be able to accommodate the required equipment, infrastructure, and consumables that must be transported to the working areas.

In the South African context, a travelling way is challenging to excavate in the conventional layout as it is traditionally excavated with hand-held machines at a maximum inclined angle of 34.5º. This designed inclination is set with the aim of reaching the reef horizon as quickly as possible but to remain below the 35º limit which will define an excavation as ‘’steeply inclined’’ according to the South African Mine Health and Safety Act (MHSA) (1996). Steeply inclined excavations are associated with an array of requirements and limitations, and this is the reason that travelling ways are designed to be below the 35º threshold on inclination. Regulations in the MHSA (1996) that apply to steeply inclined excavations include reference to Sections 7.3.2, 7.5.1, 7.5.2, 7.5.3, 7.7.2, 16.12, 16.13 and 16.14. These regulations manage a variety of safety risks including material transport, ladderway requirements and the need for inclined excavations to be kept properly closed by a fence or barrier.

At a designed inclination of 34.5º, a travelling way falls below the steeply inclined definition and the rules on steeply inclined excavations do not apply. However, at an inclination of 34.5º, it remains difficult to clearly identify geological features that are exposed and to determine the required roof support for the exposed geological structures. It is also challenging to safely bar down an inclined excavation as the rocks and material have the potential to dislodge and roll down along the footwall and potentially injure people working in the excavation.

Figure 1.1 illustrates the basic development layouts of the Marikana Operations (Marikana), showing the area from the haulage, which is mined below the reef plane, along the cross-cut and up to the raise and winze position which is on the reef plane. Typically, a travelling way at Marikana Operations is approximately 15 metres in length, three metres wide and 1.8 metres high.

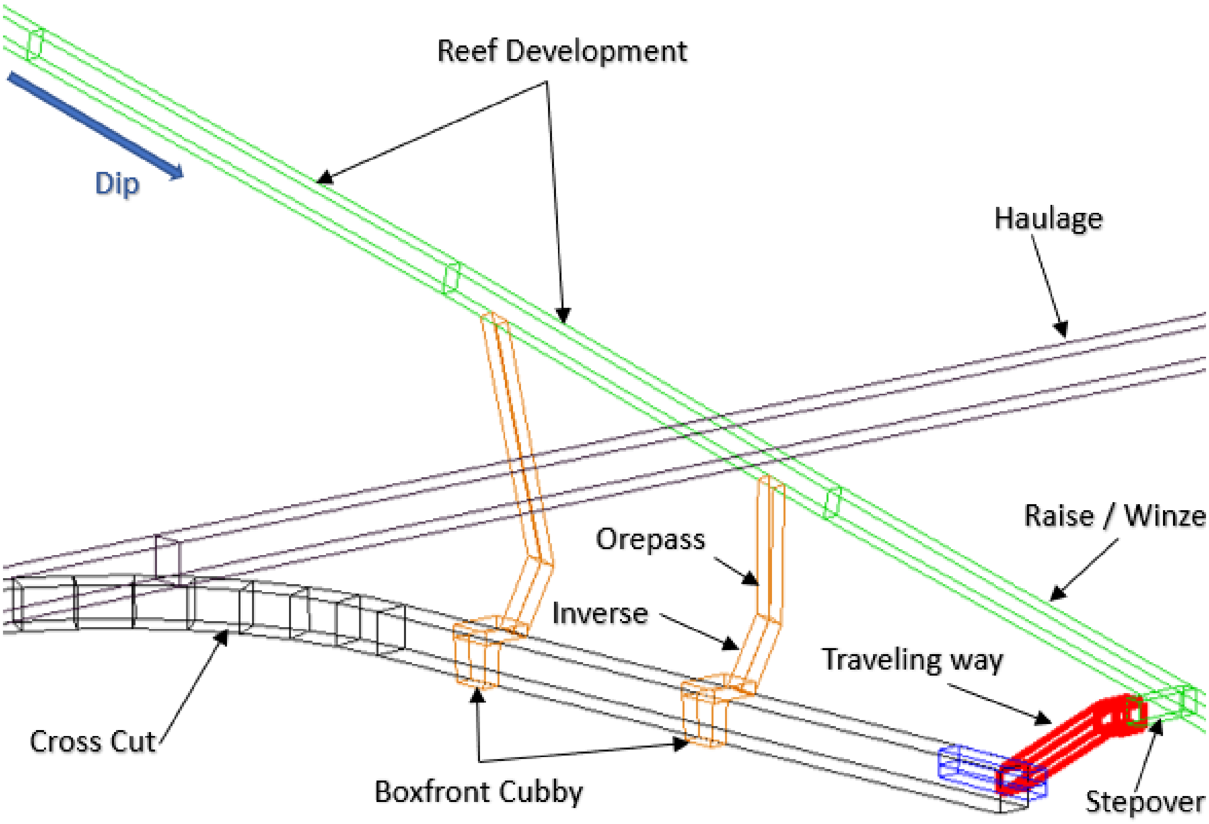

Figure 1.1: Isometric view of Marikana Operations primary development layout

The Sibanye-Stillwater Marikana Operations were used as case study mines. The tunnelling methods used at those mines, as well as other alternative tunnelling methods, were reviewed in the study. The Marikana Operations are situated within the Western Limb of the Bushveld Complex (BC). They are located in the North West Province of South Africa between the towns of Rustenburg and Brits and are situated about 80 km west of Tshwane and 100 kilometres northwest of the city of Johannesburg (Sibanye-Stillwater, 2021a).

Figure 1.2 shows an overview of the Marikana Operations. The data sources for the research study were the Saffy and E3 shaft operations as highlighted by the dashed encirclements in Figure 1.2. The combination of these two shafts is referred to as the Marikana East operation.

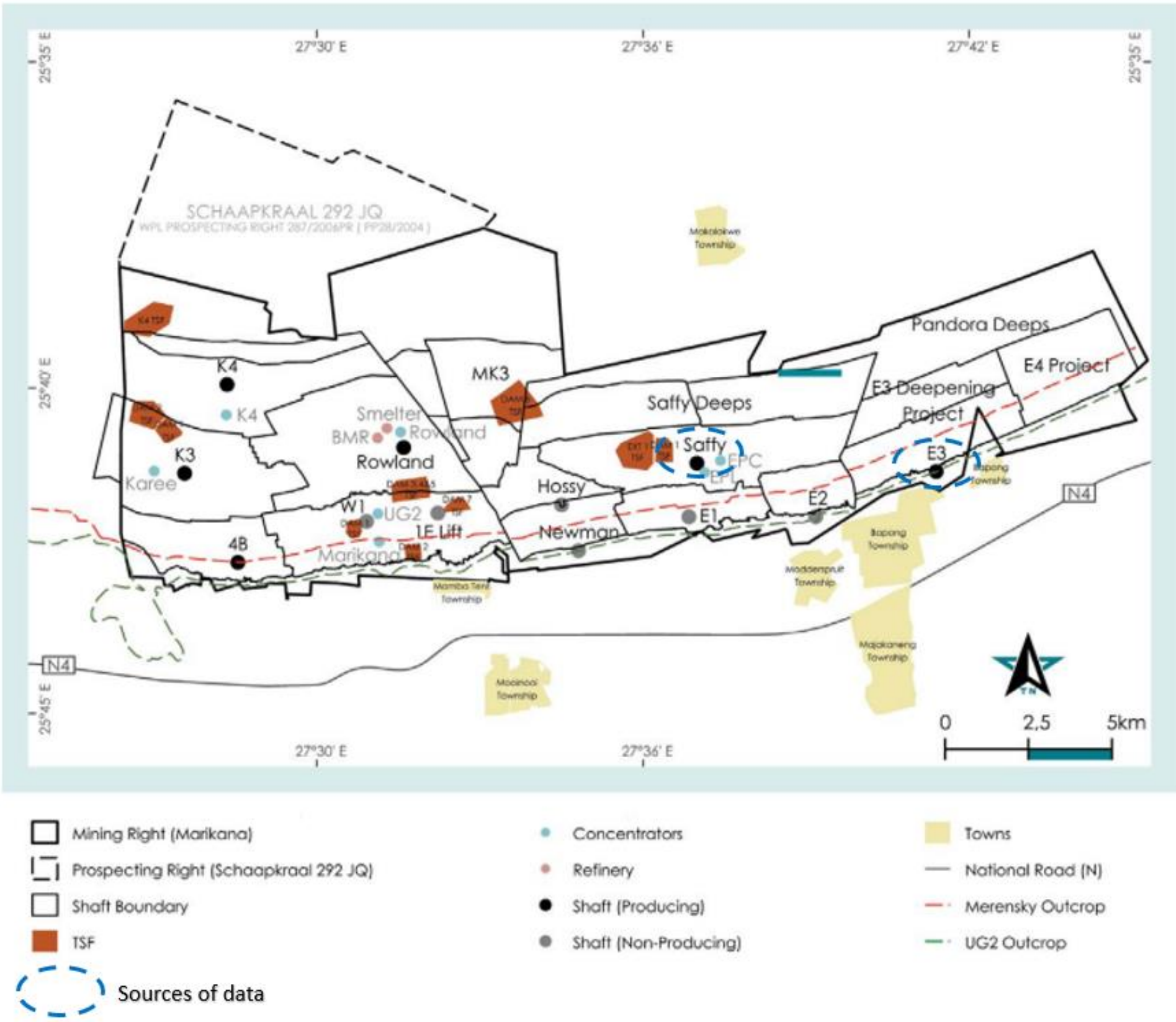

Figure 1.2: Close-up map showing the location of the Marikana Operations

(Source: Adapted from Sibanye-Stillwater, 2021a)

Marikana consists of various operations that include both decline and vertical shafts that have mainly been mined conventionally using mining methods such as the scattered breast, up-dip, and down-dip mining methods. All the mining methods have relatively similar development layouts and require the development of a travelling way to connect the horizontal development with the reef plane.

1.3 Problem statement and research question

In an attempt to excavate travelling ways more safely, an inverse drop raising method of tunnelling has been trialled at the Marikana Operations. This method is an alternative to the conventional drill and blast mining technique that is currently in use to establish travelling ways at the operations.

During the development phase of the area from the cross-cut breakaway up to the travelling way position, there is congestion and overlapping of contractor and mining crews. When using the conventional method, the progress of the cross-cut development is stopped for completion of the inverse and boxfront sliping. This is done when the inverse and boxfront positions have been reached. If the inverse is not developed when this position is reached, and done after completion of the cross-cut, all the ventilation and service pipes must be removed and reinstalled after blasting causing further delays in the process. The ventilation and service pipes must be reinstalled to complete the excavation of the travelling way and timber bay. During the time that the inverses are developed the drop raise machinery blocks the rails and access to the cross-cut, thus prohibiting rail-bound cleaning or tramming in the remaining crosscut. Additionally, this method is performed and trialled by a contractor crew with experience in drop raising, inverse mining and long hole drilling. The addition of this crew also potentially relieves crew congestion.

After completion of the cross-cut, the area is then handed over to either a reef development crew or the same contractor crew that developed the inverses, to complete developing the travelling way. The inverse, drop raise and boxfront installations are the only activities in the area that cannot be developed by the mining crews themselves and are performed by a contractor crew. This presents an opportunity to use the contractor crews more efficiently while they are active in the area.

When developing a travelling way with the inverse method the floor of the excavation is smoother and requires less construction. The base does not have to be covered with timber to create a smooth surface for transporting the winches for installation, and other equipment through the travelling way. Additionally, this reduces crew changeovers and congestion by using the same contractor crew as for the inverses and boxfront construction.

No single tunnel development method has currently been selected as the preferred or optimal tunnelling method for travelling ways at the Marikana Operations, thus, raising the research question,

> *"What is the optimal travelling way development method to use at the Marikana Operations?"*

1.4 Research aim and objectives

This study aimed to select an optimal travelling way development method specifically tailored for underground mines that have conventional layouts like those found at the Marikana Operations. This was done using an MCDA technique since the factors considered in the decision are multiple and of different units of measure. This study was conducted with the following objectives:

- Review commonly applied underground mine tunnelling methods.
- Identify and select tunnelling methods applicable to the conventional underground mining environment, specifically to travelling way development.
- Identify and select MCDA techniques applicable to underground tunnelling method selection, specifically travelling way development method selection.
- Apply the chosen MCDA technique/s to selected travelling way development methods and select an optimal travelling way development method.

1.5 Research motivation

Mining method selection is a critical decision that has significant implications for the success and sustainability of mining projects. The choice of mining method directly impacts several key factors, such as safety, productivity, cost efficiency, and the impact on the environment. Therefore, it is crucial to thoroughly investigate and evaluate various tunnelling methods before selecting a suitable tunnelling method.

The primary motivation for this study was to enhance both safety and productivity in the mining of travelling ways in the conventional mining method. Different tunnelling methods present varying degrees of risks to miners, including potential cave-ins, equipment failures, and mining-related injuries. By studying and comparing different tunnelling methods the study identified the optimal option for use at the Marikana Operations.

1.6 Outline of chapters

The research report is structured into five chapters as follows:

- Chapter 1 provided insight into the Marikana Operations mining layout. The chapter also stated the problem, research question, research aim and objectives and research motivation.
- Chapter 2 focuses on the literature review. The chapter reviews literature on the tunnelling methods and MCDA techniques considered in the research study.
- Chapter 3 describes the research methodology which was used in the application of the selected tunnelling methods in Chapter 2 for evaluation using the MCDA technique selected.
- Chapter 4 focusses on selecting an optimal travelling way development method.
- Chapter 5 provides the conclusions and recommendations of the research.

Chapter 2 reviews the different tunnelling methods and MCDA techniques and thereafter selects the relevant methods of tunnelling and MCDA technique that was used as described in Chapter 3.

2 LITERATURE REVIEW OF TUNNELLING METHODS AND DECISION-MAKING TECHNIQUES

2.1 Overview of Chapter 2

Chapter 2 provides a review of both the tunnelling methods and MCDA techniques that are relevant to the research study. Initially, literature on various tunnelling methods suitable for travelling way development in a conventional underground mining layout is reviewed. Subsequently, a specific set of methods is then selected from these options for further analysis. Lastly, an extensive evaluation of different MCDA techniques is done before ultimately choosing and explaining the method applied in the research study.

2.2 Tunnelling methods

Tunnelling is not a process specific to mining but is used in various industries to establish pathways for roads, airways, and pipelines. There are various methods used to develop tunnels and in the mining environment. These methods must be cost-effective and safe to execute. In the mining industry, it is often asked whether mechanised mining methods are more efficient than conventional mining methods. This question was answered in a ranking exercise carried out by Musingwini & Minnitt (2008). In their ranking exercise, the conventional mining method ranked as the most efficient of the methods reviewed.

Rathod & Shah (2013) identified the following commonly used methods of developing tunnels: full-face method, heading and bench method, pilot tunnel method, drill and blast method, tunnel boring machines method, cut-cover method, and the immersed tube method. However, not all the methods are applicable or can be effectively applied to a conventional mining layout. These identified methods are reviewed in Table 2.1 and briefly described thereafter. Table 2.1 compares tunnelling methods, their advantages, limitations, and their applicability to travelling way development and the conventional mining layout.

Table 2.1: Comparison of tunnelling methods used in mining and construction and applicability to travelling way development

Method	Applicable	Advantages	Limitations
Drilling and blasting	Yes	Current mining method in use at Marikana mines. Well-known and widely accepted method, adaptable to various scenarios.	Short advances, multiple blasts cause undue fracturing in the hangingwall and footwall and create an unsmooth floor.
Dropraising	Yes	A well-established and effective method used at Marikana mine to establish ventilation shafts and ore storage excavations.	Needs a top and bottom excavation to tunnel between, limitation on accurate upward drilling (Ferreira, 2003).
Tunnel boring method	No	Uniform muck size, continuous operation, predictable project duration, improved predictable safety performance (Cigla, *et al*., 2015; Gouws, 2015)	Cumbersome and expensive machines, currently not used at Marikana shafts, tunnel boring machines are too big for the current dimensions of the case study mine.
Cut- cover	No	A simple method that can accommodate width changes (Rathod & Shah, 2013).	Applicable to shallow tunnelling excavations only (Rathod & Shah, 2013).
Immersed tube	No	No advantage to travelling way development.	Only used in underwater tunnelling excavations.
Full face	No	No advantage to travelling way development.	Variation of the drill and blast method is not applicable.
Heading and benching	No	No advantage to travelling way development.	The method is slow and used in larger excavations.
Pilot tunnelling	No	No advantage to travelling way development.	Not applicable to the study, uses a pilot tunnel and then the main tunnel excavated parallel to each other.

Table 2.1 outlines the applicability of the various tunnelling methods to travelling way development at Marikana and briefly describes their advantages and limitations. The methods that could apply to travelling way development are briefly reviewed in the next subsections.

2.2.1 Hand-held drill and blast method

The conventional hand-held drilling and blasting method is a variation of the drill and blast method with its origin traceable far back into history (Pickering, 2004). The cycle of the drill and blast method consists of drilling a pattern of drill holes with specialised drilling equipment, charging these holes with explosives, and then detonating those explosives to break the rock (Rathod & Shah, 2013). The process is then repeated after the broken rock is removed and the required rock support is installed within the excavation.

Pickering (2004) explained that this method introduced a lighter pneumatic rock drill that was fitted with an air leg, where scraper winches replaced shovels to move the broken rock, hydraulic prop installation for support and the introduction of tungsten carbide inserts in drill bits. These technologies all formed part of the evolution of the conventional mining method which is also referred to as the Swedish Mining Method (Pickering, 2004). The hand-held drilling and blasting method is applicable to this research study as it is one of the methods used at Marikana.

2.2.2 Drop raising method

The drop raising method is a form of long-hole drilling that falls under the drill and blast method. In this method, long holes are drilled and blasted in an inclined direction. Similar to the hand-held method, the cycle of the drop raising method consists of drilling a pattern of holes, charging these holes with explosives, and then detonating those explosives to break the rock. The difference in the drop raising method comes where larger excavation advances can be developed in a single blast than with the hand-held conventional drill and blast method.

In a case study at Health Steele Mine, a 29 m inverse drop raise was successfully blasted in a single blast (Liu & Tran, 2000). When using the inverse method, drilling accuracy is critical; no corrections can be made to the direction of an excavation once the blast has been taken.

The drilling equipment used in drop raising is mounted on a jig and can be used for drilling both downward and upward holes. A sufficient area is required for the drilling machinery to fit in the excavation where the drilling is taking place. The drop raising equipment is larger than the conventional hand-held rock drills. The drop raising method is applicable to this research study as it is one of the methods used at Marikana.

2.2.3 Tunnel boring method

Like the drill and blast method, the tunnel boring method can be split into several variations. Tunnel boring machines excavate rock using disc cutters mounted on or in the cutter head (Rathod & Shah, 2013). Under compression and rotation of the cutting disc, the rock face is fractured causing rock chips to fall away or through the cutter head. These heads are in some cases referred to as reamers and can either be mounted on the front of a mobile machine or be pulled upwards by a stationary machine through a pilot hole. This practice is commonly used to establish ventilation shafts between pre-developed underground workings and/or the surface of a mine. In this method, no explosives are used as the rock is fractured into chips under compression with the cutter head. The tunnel boring method is non-applicable at Marikana as the method requires cumbersome and expensive machines that are currently not used at Marikana shafts. Additionally, tunnel boring machines are too big for the current dimensions of the travelling ways that are excavated at Marikana.

2.2.4 Rail-bound drilling rigs

Rail-bound drilling rigs are currently being used at Sibanye-Stillwater to do some of the flat-end waste tunnel development. These rigs are not considered as an option for travelling way development in this research as their use requires rail tracks to travel on and the rig cannot negotiate the steep angle of a travelling way.

2.2.5 Cut-cover method

The cut-cover method is a construction technique used in the excavation of tunnels or underground spaces in the engineering and construction sector. This method involves cutting into the ground, creating an open trench or a void, and then covering it with a structural lining. This method offers versatility and efficiency, making it suitable for various ground conditions and enabling fast construction times (Wickham & Tiedemann, 1976). The cut-cover method is non-applicable to the research at

Marikana as the method is only applicable to shallow excavations, since the mining depths at Marikana are at an average depth of around 500m below surface (Sibanye-Stillwater, 2021a).

2.2.6 Immersed tube method

The immersed tube tunnelling method is a widely used technique in the construction of underwater tunnels. The immersed tube method involves the construction of large concrete sections, known as precast segments, which are then submerged and positioned to form a tunnel. The segments are typically constructed in a dry dock or casting yard and transported to the site where they are immersed into position using specialised equipment (Łotysz, 2010). The immersed tube method is non-applicable to the research at Marikana as the method is applicable only to underwater excavations.

2.2.7 Full face method

The full face tunnelling method is a technique used in underground construction projects for continuous excavating of the entire tunnel cross-section in difficult ground conditions. Unlike other methods, such as the drill and blast method, which involve excavating in smaller sections, the full face tunnelling method allows for continuous excavation and support installation. Barla & Barla (2004) mentioned that in Italy the full face method was favoured more than conventional methods when establishing tunnels in difficult ground conditions. This was true, for both deep and shallow tunnelling. The full face tunnelling method is non-applicable to the research at Marikana, where ground conditions are not difficult.

2.2.8 Heading and benching method

The heading and benching tunnelling method is a sequential excavation and support method that has been traditionally used in the construction of small to medium-sized tunnels. Satici (2000) mentioned that this tunnelling process begins with the making of a 'heading', which is essentially a partial excavation of the cross-section at the upper part of the tunnel. This initial excavation provides the opportunity for examination of the ground conditions, enabling a decision on support measures, and the installation thereof before proceeding further. At this point, only a portion of the total cross-sectional area is excavated and supported, thus, providing stability to the excavation. The bottom part of the excavation is thereafter established and referred to as the bench. Although the method might not be the fastest or most efficient method available today for constructing tunnels, it remains an applied method due to its ability to safely handle complex conditions where advanced technologies may fall short (Lane, 1999). The heading and benching tunnelling method is non-applicable to the research as the designed cross sectional excavation size of travelling ways at Marikana can safely be excavated in a single blast.

2.2.9 Pilot tunnelling method

This technique involves the excavation of a small-diameter tunnel, referred to as the pilot tunnel, which precedes the main bore, to investigate geological conditions before launching the full-scale operation (Jovicic, 2018). It provides a safer working environment, as it exposes potential hazards such as unstable ground or water ingress and implements appropriate mitigation measures ahead of time. Furthermore, this preliminary process can contribute valuable data regarding geotechnical properties and groundwater conditions that aid in planning and design decisions (Jovicic, 2018). The pilot tunnelling method is widely used on various projects ranging from mining applications, road and railway tunnels and hydropower schemes. The pilot tunnelling method is non-applicable to the research as the designed cross sectional excavation size of travelling ways at Marikana can be safely excavated in a single blast.

2.3 Multi-Criteria Decision-Making methods

Mirjat *et al*. (2018) defined Multi-Criteria Decision-Making (MCDM) methods as a range of operations research models designed to tackle decision-making problems with multiple criteria. Through evaluating alternatives across several criteria, MCDM methods enable decision makers to select or prioritise options. These decisions are made by considering trade-offs and compromises between conflicting criteria (Hussain, *et al*., 2018). Multiple Objective Decision Making (MODM) and Multiple Attribute Decision Making (MADM) are the two main branches within the realm of MCDM. The classification range of MCDM methods is depicted in Figure 2.1 with a specific focus on the MADM leg of the representation. The MADM leg shows the different methods for further review, as they constitute the category of MCDM techniques applicable to the selection from a discrete set of alternatives of tunnelling methods using identified criteria.

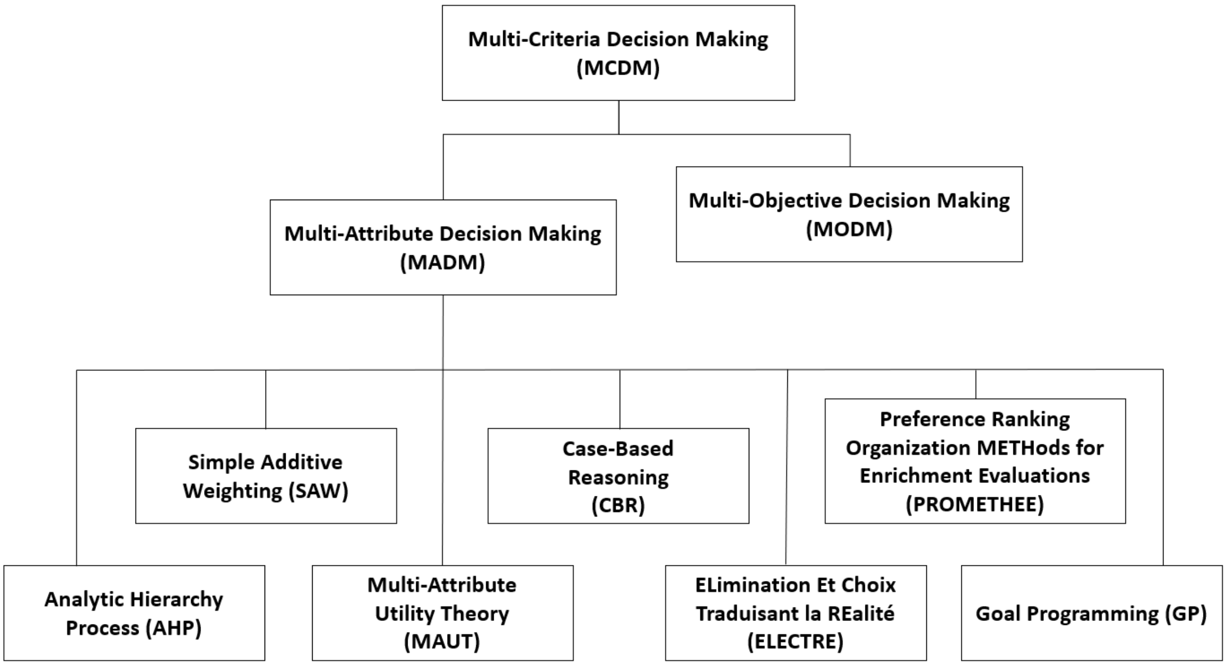

Figure 2.1: Classification of MCDM methods

(Source: Adapted from Hussain, *et al*. 2018)

MODM methods are generally used to solve problems that are multiple objective in nature, and these tend to be a type of mathematical programming method. The primary intent is to identify the most appropriate choice from all available alternatives.

MADM refers to preference decision making, through evaluating and prioritising all alternatives which are often characterised by several conflicting attributes. MCDA techniques fall under this section and are commonly used in the decision-making processes of mine planning and mining method selection. Mahase *et al.* (2016) identified some commonly used techniques which are the Analytic Hierarchy Process (AHP), Simple Additive Weighting (SAW), Multi-Attribute Utility Theory (MAUT), Case-Based Reasoning (CBR), Elimination and Choice Expressing Reality (ELECTRE), Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) and Goal Programming (GP). Velasquez & Hester (2013) noted that when some MCDA techniques are used in combination, they tend to balance the inadequacies of any one technique. Table 2.2 summarises the MCDA techniques. The techniques are arranged from top to bottom by their ease of applicability.

Table 2.2: Analysis of Multi-Criteria Decision-Making methods

Method	Areas of application	Advantages	Disadvantages
Analytic Hierarchy Process (AHP)	Choice problems; ranking problems; sorting problems; mine planning and mining method selection (Mahase, *et al*., 2016; Zlaugotne, *et al*., 2020; Ataei, *et al*., 2008).	Easy to apply in Excel; scalable; hierarchy structure can easily adjust to fit many sized problems; commonly used in mine planning (Zlaugotne, *et al*., 2020).	Interdependence between criteria and alternatives; can lead to inconsistencies between judgment and ranking criteria; rank reversal (Velasquez & Hester, 2013).
Simple Additive Weighting (SAW)	Water management; business management; financial management and mine planning (Mahase, *et al*., 2016).	Easy to apply, ability to compensate among criteria intuitive to decision makers; calculation is simple and can be done in Microsoft Excel.	Estimates revealed do not always reflect the real situation; the result obtained may not be logical (Velasquez & Hester, 2013); Bias as the criteria weights are subjective.
Multi-Attribute Utility Theory (MAUT)	Economics; finance, actuarial; water management; energy management; agriculture and mine planning (Mahase, *et al*., 2016).	Takes uncertainty into account; can incorporate preferences.	Input-intensive, preferences need to be precise (Velasquez & Hester, 2013).
Case-Based Reasoning (CBR)	Vehicle insurance; risk monitoring; engineering design and mine planning (Mahase, *et al*., 2016).	Not data-intensive; requires little maintenance; can improve over time; can adapt to changes in the environment (Velasquez & Hester, 2013).	Sensitive to inconsistent data; requires multiple cases.
ELECTRE	Various areas of application including mine planning (Mahase, *et al.*, 2016).	Takes uncertainty and vagueness into account.	Its process and outcome can be difficult to explain.
PROMETHEE	Various areas of applications including mine planning (Elevli & Demirci, 2004).	Easy to use; does not require the assumption that criteria are proportionate and is simplistic in its inception (Elevli & Demirci, 2004).	Does not provide a clear method by which to assign weights.
Goal Programming (GP)	Production planning, scheduling, health care, portfolio selection, distribution systems, energy planning, water reservoir management and scheduling (Velasquez & Hester, 2013).	Capable of handling large-scale problems; can produce infinite alternatives.	Typically needs to be used in combination with other MCDM methods to weight coefficients.

AHP and SAW are both easy to use and are commonly applied MCDM techniques in mine planning and mining method selection (Velasquez & Hester, 2013). The next sub-sections review these commonly applied MCDM techniques.

2.3.1 Analytic Hierarchy Process

The AHP method was developed by Thomas Saaty in the 1980s at the University of Pittsburgh in the United States of America. AHP has been used globally in many case studies including, strategic planning, benchmarking, prioritisation, and selection decisions. In mine planning, several AHP case studies have been undertaken. A survey done by Mahase *et al.* (2016) noted that a combination of AHP and another method, such as Fuzzy theory, PROMETHEE or SAW, is the most commonly applied MCDA technique(s) used in mine planning. AHP was also used by Ataei *et al.* (2008) and was proven to be an effective mining method selection technique.

The AHP framework comprises a hierarchy that contains different levels, with criteria at each level. Local criteria are specific attributes or aspects related to the decision, and global criteria are broader objectives that incorporate the local criteria and guide the decision. AHP can rank alternative options from most optimal to least optimal and this can easily be accomplished in Microsoft Excel. AHP is a practical assessment tool that is commonly used and well-documented in the mining environment and mining method selection problems.

Ataei, *et al*. (2008) noted that AHP makes it possible to select an optimal method in a more scientific manner that still preserves integrity and objectivity. They also noted that the model is transparent and easy to comprehend in the application by the decision maker. They concluded that for the selection of a mining method, the AHP model is unique in its identification of multiple attributes, has minimal data requirement, and does not consume a lot of time in application (Ataei, *et al*., 2008).

2.3.2 Simple Additive Weighting

SAW aims to evaluate and select the best alternative from a set of options. Churchman & Ackoff (1954) developed the SAW method as a solution to a portfolio selection problem. Tzeng & Huang (2011) viewed SAW as the most intuitive and uncomplicated approach to handling MCDM problems and argued that the linear additive function can represent the preferences of decision makers. They also stated that the preference representation only holds true once the assumption of preference independence or preference separability is met (Gorman, 1968). Due to the simplicity of SAW, the method has become widely recognised, extensively employed and favoured in solving MADM problems. SAW calculates a weighted sum score for each alternative based on their performance across multiple criteria. The SAW method involves the following steps (Taherdoost, 2023):

- Step 1 involves the preparation and setup of the initial matrix. Another part of this step involves defining and assigning weights to each criterion based on their relative importance or priority to the decision maker.
- Step 2 involves normalising the data by converting the raw data for each criterion into a common scale.
- Step 3 involves integrating the values of the criteria and weights and calculating performance scores by multiplying each normalised value with the corresponding weight for the criterion.
- Step 4 involves selecting the best alternative through a review of rankings and selecting the alternative with the highest performance score.

SAW provides an easy approach to grouping different criteria and determining an overall ranking. However, the limitation of SAW is that the method assumes independence of criteria, meaning that the impact of one criterion score is not influenced by the scores of other criteria, thus not considering the interdependencies between criteria. This limitation may hinder the effectiveness of the method in complex decision problems and may require the use of a more sophisticated method (Tzeng & Huang, 2011).

2.3.3 Multiple Attribute Utility Theory

Keeney & Raiffa (1976) considered MAUT to be one of the main analytical tools associated with the field of decision analysis. The MAUT method aims to assist decision makers in evaluating multiple attributes or criteria when making complex decisions. It provides a structured approach for assessing these attributes based on their relative importance and trade-offs between them. The method incorporates subjective judgments from decision makers to quantify preferences and compute overall utility scores for each alternative under consideration. Butler *et al*. (2001) described the steps of MAUT as follows:

- Step 1 involves defining the decision problem at hand, along with the alternatives available and identifying the relevant attributes or criteria that are important for evaluating the alternatives. These attributes should be measurable and reflect the objectives or goals of the decision maker.

- Step 2 involves assigning weights to each attribute based on its relative importance.
- Step 3 involves evaluating how well each alternative performs on each attribute using quantitative measures or subjective assessments provided by experts or stakeholders involved in the decision-making process.
- Step 4 involves developing value functions or utility curves for each attribute. This step involves eliciting preference information from the decision maker or using statistical techniques to estimate utilities based on available data.
- Step 5 involves combining the individual attribute utilities according to their assigned weights to calculate the overall utilities for each alternative.
- Step 6 involves comparing the overall utilities across all alternatives to identify the best option. Sensitivity analyses can also be performed to examine how changes in attribute weights or performance affect the rankings.

2.3.4 Case Based Reasoning

Gupta (1994) defined CBR as an approach to problem solving within the artificial intelligence (AI) space. CBR utilises previous, comparable cases as a basis for finding solutions, adjusting and evaluating existing solutions, and providing explanations for unusual scenarios (Kolodner, 1991). Schank (1982) depicted CBR as a highly valuable and information-rich approach for capturing previous experiences, enhancing current problem-solving techniques, and elevating the overall learning capacities of machines. CBR is a decision-making method that is aligned with how humans learn and remember.

Gupta (1994) argued that CBR seems best suited for decision problems where experience is rich, but knowledge is poor. Gupta explained that problem solving in CBR is system driven with the following three possible outcomes to a new problem presented by the user:

- At first, the system may be able to find an exact match from a past case and solve the current problem.
- The current problem may be solved by the system through extrapolation from solutions of past cases.
- Potentially the current problem might not have a solution within the system.

However, if the proposed solution is successful, then the system will incorporate the findings and the representation of the current case into the case memory of the system (Gupta, 1994).

2.3.5 *Elimination Et Choix Traduisant la Realité*

The ELimination Et Choix Traduisant la REalité (ELECTRE) method is an MCDA technique that was developed by Bernard Roy in the 1960s at the French Operations Research and Decision Support Society (Roy, 1968). It aims to assist in evaluating and ranking multiple alternatives based on several criteria.

Figueira *et al*. (2010) mentioned that over time, different variations of the ELECTRE method have been developed to handle various complexities and limitations. These different variants of the ELECTRE method were developed to address specific limitations or requirements faced during decision-making processes involving multiple criteria and alternatives. They offer flexibility in modelling decision problems, allowing the decision maker to incorporate their preferences and handle various types of uncertainty with efficiency. An overview of the ELECTRE history and the different variations thereof follows.

ELECTRE I was the first version of the ELECTRE method developed by Roy in 1968. It utilises pairwise comparisons between alternatives and assigns binary outranking relations based on predefined thresholds for each criterion. The main objective of ELECTRE I is to identify those alternatives that are superior or inferior to others.

ELECTRE II was thereafter proposed by Roy & Bertier (1971) to overcome the inability that ELECTRE I has in producing a ranking of alternatives (Tzeng & Huang, 2011). Instead of using binary outranking relations, this method employs concordance and discordance indices to rank alternatives relative to each other more accurately. Concordance measures how well an alternative satisfies a particular criterion, while discordance quantifies the degree of disagreement between two alternatives regarding a specific criterion.

ELECTRE III was developed by Roy and supplied yet another variation that improved upon the previous versions. This was achieved by introducing preference modelling through weighted outranking relations. Weights are assigned to criteria based on their importance, allowing explicit preference expression. Moreover, it introduces indifference and preference thresholds, enabling a finer distinction between different levels of performance (Tzeng & Huang, 2011).

ELECTRE IV was developed by Roy & Bouyssou (1983) to handle uncertainties associated with imprecise data or subjective assessments by incorporating fuzzy set theory into the decision-making process. By considering vague or ambiguous information, ELECTRE IV can provide more robust rankings even when precise values are not available (Tzeng & Huang, 2011).

Figueira *et al.* (2010) discussed the long history that ELECTRE applications have had on human decisions and concluded that the field of research on ELECTRE is still evolving. They argued that ELECTRE is still gaining acceptance thanks to new application areas, new methodological and theoretical developments, as well as user-friendly software implementations (Figueira, *et al.*, 2010).

2.3.6 Preference Ranking Organization Methods for Enrichment Evaluations

Brans & Vincke (1985) developed the Preference Ranking Organization METHods for Enrichment Evaluations (PROMETHEE) to solve MCDM problems. They stated that the main aim of the method is for the method to be as easily understood as possible by the decision makers. The method is based on a generalisation of the notion of a criterion. During this period, the concept of fuzzy outranking relation was initially introduced. It involves integrating pairwise comparison measures for alternatives to establish different degrees of relationship between criteria (Tzeng & Huang, 2011). Variations in PROMETHEE are defined by the different relation degrees that are used in the setup, which are a partial preorder for PROMETHEE I, a complete preorder for PROMETHEE II and an interval order for PROMETHEE III on a finite set of feasible solutions (Tzeng & Huang, 2011). Additionally, PROMETHEE IV was developed to be used for cases where the set of feasible solutions is continuous.

Overall, the PROMETHEE group of methods offers a flexible approach for decision makers. However, its limitations should be considered in the application. Disadvantages of the PROMETHEE method include sensitivity to changes in preference models, complexity in assigning criteria weights, and difficulty in handling large-scale problems. PROMETHEE is widely applied but it lacks a strong theoretical underpinning when compared to some methods like AHP and may limit credibility in certain research contexts (Brans & Mareschal, 2005).

2.3.7 Goal Programming

Goal Programming (GP) originated from the field of operational research, specifically from linear programming, which was developed by George Dantzig in the 1940s. Ignazio (1985) argued that even though the method has its roots in the 1950s, it was not until the mid-1970s that GP started to gain significant and widespread attention. GP has demonstrated itself as a highly efficient and effective tool for modelling, solving, and analysing mathematical problems involving multiple goals and conflicting objectives. Additionally, there is growing recognition of the limitations of conventional single-objective mathematical programming methods like linear programming as they often fail to provide reasonable answers or deep insights into actual problem dynamics (Ignizio, 1985). The GP process involves the following steps (Chowdary & Slomp, 2013):

- Step 1 involves identifying and defining the set of objectives or goals to be achieved. These goals can be quantitative (for example, maximise profit, minimise cost) or qualitative (for example, improve customer satisfaction, reduce environmental impact) in nature.
- Step 2 involves prioritising the defined objectives based on their relative importance. This is typically done by assigning weights or importance levels to each objective.
- Step 3 involves formulating a mathematical model that represents the problem and incorporates all the objectives and constraints. The model usually takes the form of a linear or nonlinear optimisation problem.
- Step 4 involves solving the formulated model using various algorithms and techniques to find an optimal solution that satisfies the stated objectives and constraints.
- Step 5 involves evaluating the trade-offs between different objectives. In some cases, achieving one objective may require sacrificing another, and goal programming helps in finding an optimal balance among these conflicting objectives.

In many instances, due to inherent conflicts, it may not be possible to achieve all the desired objectives simultaneously. Therefore, an iterative refinement process is employed where the initial solution is modified until a satisfactory compromise is reached. GP has been widely used in various fields where decision makers face multiple conflicting objectives. GP provides a systematic approach to dealing with complex decision problems with diverse goals (Ignizio, 1985).

2.4 Choice and justification of AHP as the preferred MCDA technique

AHP is the selected MCDA technique utilised in the study. This technique was selected because of its simplicity and common application in mine planning decision-making cases (Ataei, *et al*., 2008). Mahase *et al.* (2016) concluded that an AHP combination of methods was the most frequently used MCDA technique, indicating the efficiency of the AHP method, especially when more criteria and fewer alternatives are evaluated. AHP is easy to apply in Microsoft Excel, is scalable, its hierarchy structure can easily adjust to fit many sized problems and the method is commonly used in mine planning (Zlaugotne, *et al*., 2020). Musingwini & Minnitt (2008) used AHP to rank platinum mining methods. AHP was the chosen method because of its ability to detect inconsistencies in judgements, access to user-friendly software that is available commercially and the ability of AHP to rank alternatives under conflicting criteria. The selection can derive a reliable answer as it is based on pre-defined criteria weights. Additionally, the alternatives are ranked in order of preference.

2.5 Mathematical framework of AHP

The initial step in the AHP application consists of establishing the various criteria within the decision-making process. A pairwise comparison is conducted to determine relative weight of each criterion where the relative weight of C_i over C_j is denoted by w_{ij} and is calculated by Equation 2.1 (Musingwini & Minnitt, 2008):

$$w_{ij} = \frac{1}{w_{ji}} \text{ for different criteria, where } i \neq j \text{ and } w_{ii} = 1 \quad (2.1)$$

A criterion compared to itself has an importance of 1, or w_{ii} = 1, as any criterion, is as important as itself. The relative importance of criteria weights is thereafter used to build a square matrix W, and is expressed by Equation 2.2 (Musingwini & Minnitt, 2008):

$$W = w_{ij} \quad (2.2)$$

The number of criteria in the matrix is denoted by n, with the matrix corresponding to the number of criteria. The generated matrix is thereafter evaluated for transitivity where a relationship is considered transitive if the relative importance is multiplicative (Musingwini & Minnitt, 2008). This transitivity is tested through Equation 2.3 (Musingwini & Minnitt, 2008):

$$\text{If } C_2 = 2C_1 \text{ and } C_3 = 3C_2 \text{ then } C_3 = 6C_1 \quad (2.3)$$

A transitive matrix is considered consistent, however, where humans are involved, there can be inconsistencies in judgement when criteria weights are assigned. The AHP method can help to identify and quantify these inconsistencies (Musingwini & Minnitt, 2008). The degree of transitivity relationship between weights or importance is expressed by Equation 2.4 (Musingwini & Minnitt, 2008):

$$w_{ik} = w_{ij}\, w_{jk} \text{ for all } i, j, \text{ and } k \quad (2.4)$$

A vector matrix (w) of order n, (for n criteria) is calculated as expressed by Equation 2.5 (Musingwini & Minnitt, 2008):

$$W \times w = \lambda_w \qquad (2.5)$$

The vector matrix (w) is termed the eigenvector of the matrix W and the constant λ is the corresponding eigenvalue of the matrix. A matrix is consistent when $\lambda = n$. In the case of an inconsistent matrix, the eigenvector w will satisfy the condition $Ww = \lambda_{max} w$, where $\lambda_{max} \geq n$. The difference between λ_{max} and n indicates the inconsistency in judgment. If $\lambda_{max} = n$, then the judgements were perfectly consistent (Musingwini & Minnitt, 2008).

Various methods exist that can be utilised for eigenvector estimation. Musingwini & Minnitt (2008) selected the geometric mean method and stated that a close approximation of the eigenvector is obtained when the geometric mean method is used to estimate the eigenvector elements. If a typical scale of 1 to 10 is used to indicate relative weights, the difference between reciprocal weights of 0.1 to 10 will have a magnitude of 100. The use of a geometric mean is advantageous compared to an arithmetic mean due to its consideration of the impact of extreme values, which can skew the overall average when using an arithmetic mean (Musingwini & Minnitt, 2008).

The consistency index (CI) is thereafter calculated using Equation 2.6 (Yavuz, 2015):

$$\text{CI} = \frac{(\lambda \max - n)}{(n-1)} \text{ for } n \text{ criteria} \qquad (2.6)$$

where

λ_{max} is the maximum eigenvalue and n is the size or order of the pairwise matrix.

The Consistency Ratio, CR, is calculated to assess whether judgments are reasonably consistent. This involves comparing the calculated CI with judgments made completely at random (Musingwini & Minnitt, 2008). Saaty (1980) conducted simulations with random matrices of increasing order to determine their corresponding CIs and then presented them as RIs. Table 2.3 is based on the work by Saaty (1980) on average random consistency index.

Table 2.3: Average random consistency index

Source: (Saaty & Vargas, 2012, p. 9)

n	1	2	3	4	5	6	7	8	9	10
Random CI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

According to Saaty (1980), a CR greater than 10% indicates too large of inconsistency and that the weighting of criteria should be redone. To the latter, if a CR is equal to 0%, then the judgements used to assign weights to the criteria are said to be perfectly consistent (Musingwini & Minnitt, 2008). The corresponding RI to CI of the matrix is used in the CR calculation that is depicted in Equation 2.7 (Yavuz, 2015):

$$\text{CR} = \frac{\text{CI}}{\text{RI}} \tag{2.7}$$

Once a matrix is of acceptable consistency, the weights of criteria that have been determined are used to determine the efficiencies of the alternatives measured within each criterion. The efficiencies of all alternatives on a criterion, denoted as E_{ij} are then normalised to align the effect that different units of measure have for each criterion. For m alternatives on a criterion, the normalised E_{ij} values are denoted by $E^{N}{}_{ij}$ and is derived by Equation 2.8 (Musingwini & Minnitt, 2008):

$$E^{N}{}_{ij} = \frac{E_{ij}}{\sum_{i=1}^{m} E_{ij}} \tag{2.8}$$

To attain aggregated AHP performance scores the matrix of normalised performance outcomes is multiplied by the eigenvector. This allows the AHP process to rank the alternatives on their aggregated performance scores and make a decision based on the logic that the higher the AHP performance score the more preferable the alternative.

2.6 Rank reversal shortcoming of the AHP

Rank reversal in AHP refers to the condition where the order of ranked alternatives changes when some alternatives are either added or removed from the AHP model. Rank reversal has been studied and documented widely in literature on AHP, highlighting the potential implications it can have on the outcome of the decision-making process.

Saaty & Vargas (2012) examined rank reversal in AHP and found that it can be caused by numerous factors, which include inconsistent judgment patterns, imprecise preference ranking, and sensitivity to minor changes in inputs. They further established that minor alterations in criteria weights or pairwise comparisons may lead to substantial changes in the rankings of alternatives.

Saaty & Vargas (2011) explained that rankings for criteria can change if new criteria are introduced and that the introduction of new factors may alter the order in which the various criteria are ranked. The level of concern may not be as high as anticipated though. The reason for this is that initially, utility theory did not allow for the weighing of criteria and only placed importance on alternatives and their utilities based on different criteria. However, modern utility theorists have adopted methods like AHP by assigning ratings or comparing criteria in some way. At that time, there was no worry about how changes in criteria weights would impact the ranking of alternatives since such weights did not exist at the time.

To mitigate the risk of rank reversal, several approaches have been developed. One approach involves conducting a sensitivity analysis to assess the stability of rankings under different conditions (Saaty, 1994). Sensitivity analysis allows decision makers to identify critical points at which slight changes could result in significant shifts in rankings. Additionally, consistency measures such as the Consistency Ratio (CR) are often used to check the consistency of judgments made during pairwise comparisons. High CR values indicate inconsistency, which may increase the likelihood of rank reversal (Saaty, 1980).

Decision makers should be aware of the impacts of rank reversal on the outcome of AHP scores and how to mitigate the risk it entails. This will ensure enhanced robustness of their decisions and more reliable rankings of alternatives in complex decision problems.

2.7 Expert sample size to determine the number of alternatives and criteria in AHP

During the AHP evaluation, the criteria identification, criteria weighting, and selection of alternatives can be done in various ways. More specifically to method selection are the following examples:

- Naghadehi *et al*. (2009) used a panel of fifteen decision makers to evaluate criteria in a Fuzzy AHP (FAHP) application for a mining method selection problem with thirteen criteria identified.
- Ataei *et al*. (2008) utilised seventeen experts, with different areas of speciality. Using a five-point scale the panel identified and weighted thirteen criteria used in a mining method selection problem solved in AHP.
- Bazzazi *et al*. (2011) identified and weighted seven criteria with an expert panel consisting of six members of different specialities in a mine equipment selection problem.

Based on the varying number of experts used in the three mining case studies above it is clear that there is no prescribed number of experts to be used in the AHP process. It is however important to have a panel of experts with specific knowledge of the field of research.

2.8 Summary of Chapter 2

Various tunnelling methods and decision-making techniques were reviewed in this chapter. For establishing travelling ways, the selected tunnelling methods for comparison are the conventional hand-held drill and blast method and the alternative the inverse drop raising method. The conventional hand-held drill and blast method is the current travelling way tunnelling method used at Marikana. The inverse drop raising method has also been used in some instances at Marikana. No one method has been selected as the preferred between the two alternatives.

Furthermore, to answer the research question stated in Chapter 1, and after a review of various MADM techniques, the AHP was selected to be used in this study. This is because the method has been proven as an effective tool in mining method selection and mine planning-related decision-making problems. The method is easy to apply in Microsoft Excel, is scalable and its hierarchy structure can easily be adjusted to fit problems of different sizes.

The following chapter describes the research methodology outlining the steps taken in setting up the AHP model. Furthermore, the chapter describes the data collection process and how efficiencies were attained within the application of the AHP.

3 RESEARCH METHODOLOGY

3.1 Overview of Chapter 3

Chapter 3 describes the methodology that was used in this research and describes the data collection process that went into setting up the hierarchical structure of the AHP model used. After restating the research question, this chapter outlines the step-by-step process followed in the research design. This chapter aids in providing a clear understanding of the methodology of each stage of setting up the AHP framework as well as defining the data collection processes and research design that were followed in Chapter 4.

3.2 Restating the research question

For this chapter to add the needed value to the report it is important to restate the research question before an approach to answering said question can be explained. As stated in Section 1.3, no one tunnelling technique has been selected as the preferred or optimal tunnelling method for travelling ways at the Marikana Operations. This raised the research question: *"What is the optimal travelling way development method to use at the Marikana Operations?"*

3.3 Research design

In Chapter 2, both the AHP and two tunnelling methods were selected to be tested in the remainder of the research. This selection process was carried out in line with the research aim and objectives stated in Section 1.4 and leaves only the application of AHP to the selected tunnelling development methods to select an optimal travelling way development method as the next step.

3.3.1 Brief description of the steps taken in the research

Even though the mathematical framework of AHP was discussed in detail in Section 2.5, it is needed to describe the research design of the study as follows:

- Step 1 was to define the decision problem: This was clearly defined in restating the research question.
- Step 2 was to identify travelling way development techniques and select the optimal method applicable to the conventional underground mining environment.
- Step 3 was to select AHP as the applicable MCDM method to be used for the travelling way development method selection.

- Step 4 was to apply AHP to the conventional hand-held drill and blast method and to the inverse drop raising method of establishing travelling ways in the conventional mining layout.
- Step 5 was to establish the AHP model, which includes, a hierarchical structure, weighted and tested consistent criteria selection and a normalised pairwise comparison. This is all extensively covered in Chapter 4. A workshop with a panel of experts was used to establish the criteria used in the AHP application. These same panel members completed questionnaires to assist in ranking the selected criteria.
- Step 6 was to apply the AHP model with data collected from the Marikana Operations test sites. This step is also extensively covered in Chapter 4.
- Step 7 was to select the optimal travelling way tunnelling method through the AHP ranking results.

3.4 Data collection process

Data was collected through investigation and research done on various mining documentation, mining reports and interactions with experts from the Marikana Operations. The selected criteria have different units of measure and data per criteria was collected from different departments and in different formats.

3.5 Data analysis techniques

Various data analysis techniques were used to derive the different efficiencies per criterion. Some criteria were minimisation criteria while others were maximisation criteria. To obtain the maximum AHP priority scores, it was therefore necessary to use complements of normalised efficiencies for minimisation-type criteria when deriving the AHP priority scores. All the data that was collected had to be interpreted and normalised before the final ranking in the AHP model could take place.

3.6 Summary of Chapter 3

Chapter 3 presented the research design and outlined steps followed in conducting the research. The following chapter deals with the application of the AHP model to select an optimal method of establishing travelling ways at Marikana.

4 SELECTING AN OPTIMAL TUNNEL DEVELOPMENT METHOD

4.1 Overview of Chapter 4

Chapter 4 covers the setup and application of the AHP process. Additionally, the data collection and efficiency of each alternative on the selected criteria is discussed and shown. The chapter answers the research question by selecting an optimal travelling way tunnelling method for application at the Marikana Operations.

4.2 Steps of setting up the AHP model

Steps outlined in the following Section 4.2.1 were followed to establish the AHP model. This section also deals with establishing whether the matrix is of acceptable consistency before moving over to the application of the efficiencies to the AHP model.

4.2.1 Hierarchical structure of the AHP model

The initial step was to design the hierarchical structure of the AHP model. This was done by conducting a workshop involving twelve anonymous specialists from the Marikana Saffy Shaft. The workshop was held on the 29th of July 2023. The specialists' expertise included four mining engineers, two safety specialists and six mining technical specialists. All the experts were involved in implementing both the trial of the inverse drop raising method as well as the conventional hand-held method of travelling way development. This panel size was in line with what was stated in Section 2.7, where there is no prescribed number of experts required in an AHP panel. The panel, however, must have specific knowledge of the area of research or decision to be made.

In the workshop, the panel collaboratively identified six criteria to be used in the AHP application. A letter confirming the occurrence of the workshop is shown in Appendix 1. Figure 4.1 depicts a schematic representation of the AHP hierarchical structure as derived in the workshop, indicating the selected criteria and alternatives.

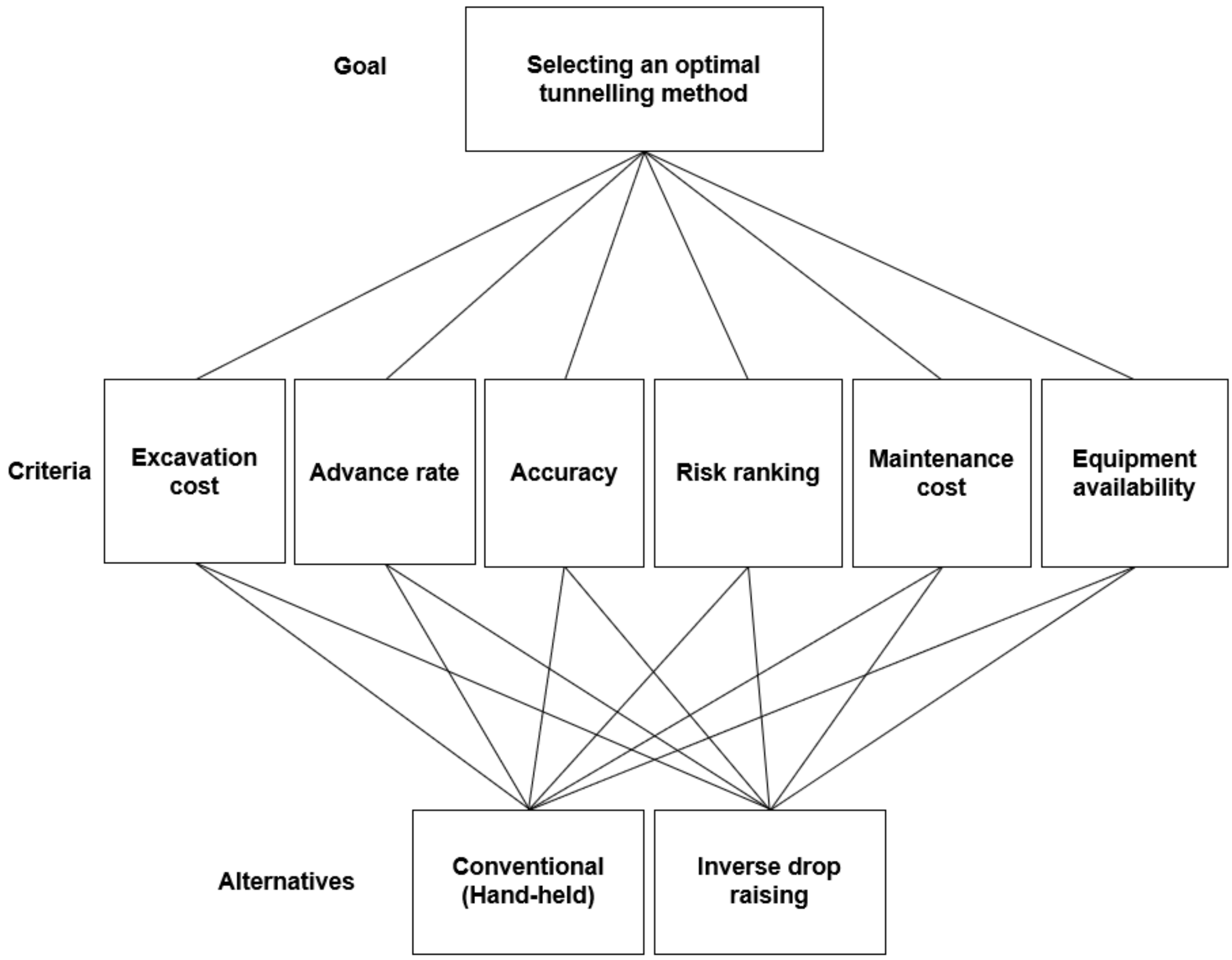

Figure 4.1: AHP schematic design representation of the hierarchical structure

4.2.2 Pairwise comparison matrix and its normalisation

The next step was to create and normalise a pairwise matrix to determine the relative importance of the different criteria concerning the goal. From this step onwards the model was handled in Microsoft Excel. To normalise the pairwise matrix, weights of criteria in the pairwise matrix were derived through questionnaires that were distributed to the experts who attended the workshop.

Figure 4.2 shows an uncompleted sample of the questionnaire that was anonymously completed by the panel members who attended the workshop. The weighting scale that was described in Section 2.5 was used to set up the questionnaires whereafter panel members were tasked to rank the compared criteria by marking the appropriate weight value under the criteria of preference. The 12 copies of the completed questionnaires are shown in Appendix 2. The first questionnaire in Appendix 2 shows that the anonymous participant considered ‘Advance rate’ to be twice as important as ‘Excavation cost’.

Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Figure 4.2: Uncompleted questionnaire

After the questionnaires were answered and returned, the weighting scores were captured and averaged. Where preference or weighting was marked on the righthand side of the questionnaire, the inverse value of that number was captured and thereafter the average of the row entries was captured in column 2 of Table 4.1. For example, in Questionnaire 1 an importance score of two was marked on the righthand side of the questionnaire for comparison of the criteria of ‘Excavation cost’ and ‘Advance rate’, meaning that, Expert 1 viewed ‘Advance rate’ to be twice as important as ‘Excavation cost’. The inverse value, (1 ÷ 2 = 0.5) was captured for the comparison cell in column three row three meaning that Expert 1 viewed ‘Excavation cost’ to be half as important as ‘Advance rate’. This was continued throughout Table 4.1. Table 4.1 represents the averaged weighting scores obtained from the workshop panel members and captured in Microsoft Excel.

Table 4.1: Averaged weighting scores of the completed questionnaires

Questionnaire	**Ave**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Excavation cost	**1.00**	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Advance rate	**0.42**	0.50	0.33	0.33	0.33	0.33	0.50	0.33	1.00	0.33	0.33	0.33	0.33
Accuracy	**0.35**	0.33	0.33	0.33	0.33	0.50	0.20	0.20	0.50	0.33	0.33	0.33	0.50
Risk ranking	**0.24**	0.33	0.20	0.20	0.20	0.20	0.20	0.20	0.25	0.33	0.20	0.20	0.33
Maintenance cost	**0.52**	0.50	0.50	0.50	0.33	0.50	0.33	0.33	2.00	0.25	0.33	0.33	0.33
Equipment availability	**0.50**	0.50	0.33	0.50	0.50	0.50	0.33	1.00	0.50	0.33	0.50	0.50	0.50
Advance rate	**1.00**	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Accuracy	**0.46**	0.50	1.00	0.50	0.33	0.33	0.33	0.33	0.33	0.50	0.33	0.50	0.50
Risk ranking	**0.33**	0.20	0.33	0.20	0.20	0.20	0.20	0.20	0.50	0.50	0.20	0.25	1.00
Maintenance cost	**0.53**	0.33	0.50	0.33	0.33	0.50	0.50	0.50	1.00	1.00	0.50	0.50	0.33
Equipment availability	**0.78**	3.00	1.00	0.50	0.33	1.00	0.33	0.33	0.33	0.50	0.50	1.00	0.50
Accuracy	**1.00**	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Risk ranking	**0.35**	0.50	0.33	0.20	0.20	0.20	0.33	0.20	0.50	1.00	0.20	0.20	0.33
Maintenance cost	**1.74**	2.00	2.00	3.00	1.00	1.00	3.00	1.00	2.00	2.00	3.00	0.33	0.50
Equipment availability	**2.13**	2.00	2.00	3.00	3.00	3.00	3.00	2.00	2.00	2.00	2.00	0.50	1.00
Risk ranking	**1.00**	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Maintenance cost	**4.25**	3.00	5.00	5.00	5.00	5.00	3.00	5.00	4.00	3.00	5.00	5.00	3.00
Equipment availability	**4.00**	3.00	5.00	4.00	5.00	5.00	3.00	5.00	2.00	3.00	5.00	5.00	3.00
Maintenance cost	**1.00**	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Equipment availability	**1.29**	1.00	2.00	0.50	2.00	2.00	2.00	2.00	0.50	0.50	1.00	1.00	1.00

The averaged scores shown in the second column were thereafter transferred into a square matrix in Table 4.2, whereafter they were normalised to attain a normalised weighting per criterion. Table 4.2 represents the average weighting scores captured from the questionnaires that were compiled in the square matrix. To populate Table 4.2 the second column values of Table 4.1 were first populated to attain all the values above the diagonal of the matrix indicated by the grey cells with a value of 1. The values in the grey cells indicate that a criterion is as important as itself, as it was mentioned in Section 2.5. Like Table 4.1, the inverse values of the comparison cells were thereafter calculated to populate the cells below the matrix diagonal. As an example, the weighting score for ‘Excavation cost’ to ‘Equipment availability’ highlighted in green was 0.500, meaning that ‘Excavation cost’ is half as important as ‘Equipment availability’. Therefore, the inverse value highlighted in yellow, (1 ÷ 0.500 = 2.000) was captured for the ‘Equipment availability’ to ‘Excavation cost’ comparison cell, meaning that ‘Equipment availability is twice as important as ‘Excavation cost’. This was continued for all lower diagonal values in Table 4.2.

Table 4.2: Square matrix with averaged weighting scores

Pairwise Matrix	**Excavation cost**	**Advance rate**	**Accuracy**	**Risk ranking**	**Maintenance cost**	**Equipment availability**
Excavation cost	1.000	0.417	0.353	0.238	0.521	0.500
Advance rate	2.400	1.000	0.458	0.332	0.528	0.778
Accuracy	2.835	2.182	1.000	0.350	1.736	2.125
Risk ranking	4.211	3.013	2.857	1.000	4.250	4.000
Maintenance cost	1.920	1.895	0.576	0.235	1.000	1.292
Equipment availability	2.000	1.286	0.471	0.250	0.774	1.000
Sum	**14.365**	**9.791**	**5.715**	**2.405**	**8.809**	**9.694**

The next step was to normalise the matrix to attain criteria weights that are normalised. Table 4.3 represents the normalised pairwise matrix. In this normalisation process, each column value in Table 4.2 was divided by the sum of all the elements in that column to populate Table 4.3. As an example, the weighting score for ‘Excavation cost’ to ‘Excavation cost’ is divided by the column total (1 ÷ 14.365 = 0.070) out of Table 4.2 and captured in yellow in Table 4.3. This calculation was done for the remaining entries of Table 4.3 and now has the resulting normalized matrix completed with each column adding up to a value of one. The resulting row averages were then calculated to attain the criteria weights indicated in the far-right column of Table 4.3.

Table 4.3: Normalised matrix with averaged criteria weights

Normalised Matrix	Excavation cost	Advance rate	Accuracy	Risk ranking	Maintenance cost	Equipment availability	Criteria Weight (Average of row entries)
Excavation cost	0.070	0.043	0.062	0.099	0.059	0.052	0.064
Advance rate	0.167	0.102	0.080	0.138	0.060	0.080	0.105
Accuracy	0.197	0.223	0.175	0.146	0.197	0.219	0.193
Risk ranking	0.293	0.308	0.500	0.416	0.482	0.413	0.402
Maintenance cost	0.134	0.194	0.101	0.098	0.114	0.133	0.129
Equipment availability	0.139	0.131	0.082	0.104	0.088	0.103	0.108
Total	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

The criteria at this stage were not sorted in any preference and are shown as it was at this stage of the process. It is important to note that normalisation does not change the relative relationships between elements within a row or column but only scales their values proportionally so that they sum up to 1. These criteria weights were used in further steps of calculating the CR with the methods as discussed in Section 2.5.

4.2.3 Eigenvector calculation

In this step, the CR was calculated to check if the weighted values were reliable and were reflecting consistent judgements or acceptable judgements. To calculate the weighted sum values per criteria as shown in Table 4.4, the non-normalised row values in Table 4.2 were multiplied by the criteria weights in Table 4.3. For example, out of Table 4.4 the column C row 8 value for 'Equipment availability' multiplied by the criteria weight for 'Excavation cost' out of column C row 11 was multiplied to populate column C row 18 (2.000 x 0.064 = 0.128) indicated in yellow. This calculation was then repeated as indicated in the notes on formulae used in Table 4.4. These row values were then added up to calculate the weighted sum value per criteria in column J rows 13 to 18 of Table 4.4.

In order to calculate the λ column values, the weighted sum values per criteria was divided by the criteria weights per criterion. For example, out of Table 4.4 the weighted sum value for 'Equipment availability' in column J row 18 divided by the criteria weight for 'Equipment availability' in column J row 8 calculated to the λ value for 'Equipment availability' in column L row 18 (0.661 ÷ 0.108 = 6.123) indicated in green. This calculation was then repeated as indicated in the notes on formulae used in Table 4.4 for column L rows 14 to 18. The λ column values, or ratio per criteria values was used in a lambda max (λ_{max}) calculation.

The λ_{max} calculation, also known as the maximum or principal eigenvalue, is a key step in the AHP methodology that aids to determine the consistency of pairwise comparisons made. To calculate, from Table 4.5, the average of the λ values was determined. To do so the sum of the λ column values was divided by n (n = 6) and equated to a λ_{max} value of 6.155 (36.931 ÷ 6 = 6.155). Table 4.4 shows the non-normalised values from Table 4.2 and the results of the process that was followed to calculate the weighted sum values per criterion and the λ values.

Table 4.4: Weighted sum and ratio per criterion calculation

	A	B	C	D	E	F	G	H		J		L
1		**Pairwise Matrix (From Table 4.2)**										
2		**Pairwise Matrix**	Excavation cost	Advance rate	Accuracy	Risk ranking	Maintenance cost	Equipment availability		**Criteria Weight**		
3		Excavation cost	1.000	0.417	0.353	0.238	0.521	0.500		0.064		
4		Advance rate	2.400	1.000	0.458	0.332	0.528	0.778		0.105		
5		Accuracy	2.835	2.182	1.000	0.350	1.736	2.125		0.193		
6		Risk ranking	4.211	3.013	2.857	1.000	4.250	4.000		0.402		
7		Maintenance cost	1.920	1.895	0.576	0.235	1.000	1.292		0.129		
8		Equipment availability	2.000	1.286	0.471	0.250	0.774	1.000		0.108		
9		**Total**	**14.365**	**9.791**	**5.715**	**2.405**	**8.809**	**9.694**		**1.000**		
11		**Criteria Weight (From Table 4.3)**	0.064	0.105	0.193	0.402	0.129	0.108				
12			Excavation cost	Advance rate	Accuracy	Risk ranking	Maintenance cost	Equipment availability		**Weighted Sum Value**		**λ (Ratio per criterion)**
13		Excavation cost	0.064	0.044	0.068	0.095	0.067	0.054		0.392		6.135
14		Advance rate	0.153	0.105	0.088	0.133	0.068	0.084		0.632		6.039
15		Accuracy	0.181	0.228	0.193	0.141	0.224	0.229		1.196		6.202
16		Risk ranking	0.269	0.315	0.551	0.402	0.547	0.432		2.516		6.260
17		Maintenance cost	0.123	0.198	0.111	0.095	0.129	0.139		0.795		6.172
18		Equipment availability	0.128	0.134	0.091	0.100	0.100	0.108		0.661		6.123
19		**Total**	**0.918**	**1.024**	**1.102**	**0.967**	**1.134**	**1.047**				
		Notes on formulae										

	Cell	Formula	Comments
21	**Cell**	**Formula**	**Comments**
22	C13	C3*C11	The formula is copied down for cells C14 to C18
23			The same formula copied for columns D to H and rows 13 to 18
24	J13	SUM (C13:H13)	The formula is copied down for cells J14 to J18
25	L13	J13/J3	The formula is copied down for cells L14 to L18

Table 4.4 represents the Microsoft Excel view of the values and calculations done to calculate the ratio per criterion or λ values. After calculating the weighted sum values a ratio per criterion was calculated by dividing the relevant weighted sum value by the corresponding criteria weight. The CI was thereafter calculated using Equation 2.6, and the CR was calculated using Equation 2.7 as described in Section 2.5. These calculations are shown in Table 4.5. Table 4.5 is a representation of the consistency ratio calculation carried out in Microsoft Excel.

Table 4.5: Consistency ratio calculation

	Excavation cost	Advance rate	Accuracy	Risk ranking	Maintenance cost	Equipment availability	**Weighted Sum Value**	λ
Excavation cost	0.064	0.044	0.068	0.095	0.067	0.054	0.392	6.135
Advance rate	0.153	0.105	0.088	0.133	0.068	0.084	0.632	6.039
Accuracy	0.181	0.228	0.193	0.141	0.224	0.229	1.196	6.202
Risk ranking	0.269	0.315	0.551	0.402	0.547	0.432	2.516	6.260
Maintenance cost	0.123	0.198	0.111	0.095	0.129	0.139	0.795	6.172
Equipment availability	0.128	0.134	0.091	0.100	0.100	0.108	0.661	6.123
Total	**0.918**	**1.024**	**1.102**	**0.967**	**1.134**	**1.047**		**36.931**

n = 6

RI = 1.25 (from Table 2.3, where n = 6)

n-1 = 5

λ max = 6.155

$$\text{CI} = \frac{(\lambda \max - n)}{(n-1)} = \frac{6.155-6}{(6-1)} = 0.031$$

and

$$\text{CR} = \frac{\text{CI}}{\text{RI}} = \frac{0.032}{1.25} = 2.48\,\%$$

The RI value of 1.25 for n = 6 was derived from the random consistency index shown in Table 2.3. The CR thereafter calculated to 2.48% which falls below the 10% consistency threshold of the AHP process. According to Saaty (1980), the CR should be less than 10% for the weighting of the criteria to be considered of acceptable consistency. If the value is greater than 10% the weighting of criteria should be redone. Once the matrix was of acceptable consistency, the AHP process of decision making was continued, and a ranking of alternatives was obtained. Table 4.6 shows the calculated criteria weights of the six criteria selected. The criteria in Table 4.6 are arranged and sorted from highest to lowest according to their weights. Table 4.6 indicates the six selected criteria and their respective weights.

Table 4.6: Criteria weight representation arranged from highest to lowest

Criteria	**Criteria Weight**
Risk ranking	0.402
Accuracy	0.193
Maintenance cost	0.129
Equipment availability	0.108
Advance rate	0.105
Excavation cost	0.064
Total	**1.000**

After the model and its judgements had been proven to be of acceptable consistency, the efficiency of each of the criteria to each of the alternatives was determined and normalised. To determine efficiencies to the different criteria it is important to first understand how the alternative methods are executed and applied at the Marikana East case study mines. The following sub-section describes the application of the drop raising method and the hand-held drill and blasting method to travelling way development at Marikana.

4.3 Description of the alternatives as practised at Marikana

Before the different criteria per alternative can be discussed it is important to look at how the two alternative methods are practised and implemented at Marikana. This is important as the efficiencies used and described in the research are directly related to how the methods were executed at Marikana and might not be executed similarly at a different mine.

An example of differences in approach is that the drop raising practice is executed by a contractor crew at Marikana and this might not be the case at other mines. The cleaning in turn is done by the mine crews themselves even though the blasting is done by a contractor. Table 4.7 depicts the basic variations and similarities of how the alternative methods are executed at the case study mines.

Table 4.7: Alternative tunnelling method variances and similarities

Method	**Hand-held method**	**Drop raising method**
Supervision allocation	Marikana crew	Contractor crew, contractor supervision
Drilling crew allocation	Hand-held reef or waste crew, Marikana crew	Drop raise crew, contractor crew
Blasting crew allocation	Hand-held reef or waste crew, Marikana crew	Drop raise crew, contractor crew
Cleaning method	Rail-bound mechanical loader, Marikana operator	Rail-bound mechanical loader, Marikana operator
Support crew	Hand-held reef or waste crew, Marikana crew	Hand-held reef or waste crew, Marikana crew
Advance per blast	1.5m – 1.8m, 10 blasts to complete a 15m travelling way	5.0 m, as per rock engineering recommendations, 3 blasts to complete a 15m travelling way
Drilling frequency	Daily after each blast, clean and support installation and stop when reef is intersected	Once for the full travelling way length, the crew stops at 20m or when the reef is intersected
Equipping	Marikana crew	Contractor crew, contractor supervision
Material	Supplied and transported by Marikana	Supplied and transported by Marikana
Equipment	Supplied and transported by Marikana	Supplied by the contractor, transported by Marikana

4.4 Data for analysis per criterion in the AHP model

During the workshop with the panel of experts, six criteria were identified for analysis and comparison. The next sub-sections describe each of these criteria including how the methods scored within the criterion respectively. The criteria are discussed in descending order of weights, starting with the criterion that attained the highest weighting as shown in Table 4.6.

4.4.1 Risk ranking

Risk ranking is the process of assessing and prioritising risks based on their potential impact and likelihood of occurrence. It involves evaluating the severity or consequence of a risk if it were to materialise, as well as the probability or chance of that risk occurring.

The data collection process for the risk ranking criteria was conducted through a risk ranking exercise carried out by anonymous senior mining experts and was facilitated by the author. The exercise included risk rankings of 15 hazardous activity areas, functions or processes that are carried out when developing a travelling way using the identified tunnelling methods.

To obtain a risk ranking for the identified tunnelling methods the Sibanye-Stillwater Safety, Health and Environmental (SHE) Risk Matrix was used (Sibanye-Stillwater, 2021b). This is a 5 x 5 risk matrix used by Sibanye-Stillwater as part of a standard systematic operational risk management process. The 5 x 5 risk ranking matrix, also known as the probability-impact matrix or likelihood-consequence matrix, is a commonly used tool in risk management. Further, it can serve as a supplementary tool in evaluating the possible damage or disruption brought about by various risks. It does not have a specific origin or reference to a single source. The matrix has been developed and adapted by various organisations and experts over time.

Figure 4.3 shows the Sibanye-Stillwater Safety, Health and Environmental Risk Matrix that was used to rank the risk between the alternative methods. Figure 4.3 was obtained from the Sibanye-Stillwater Safety, Health and Environmental (SHE) Microsoft Excel document (Sibanye-Stillwater, 2021b).

Sibanye-Stillwater Safety, Health and Environmental (SHE) Risk Matrix

					Severity	General Description	Safety	Health	Environment
5 (Low)	10 (Medium)	15 (High)	20 (High)	25 (High)	5 Catastrophic	Consequences are severe and could not be managed. The operation may not recover	Multiple Fatalities	Irreversible impact on health with loss of quality of life of a numerous group / population or multiple fatalities	Long term irreversible liability / Significant loss of biodiversity
4 (Low)	8 (Medium)	12 (Medium)	16 (High)	20 (High)	4 Significant	Consequences are severe and manageable to some extent, but the operation would recover.	Fatality	Irreversible impact on health with loss of quality of life or single fatality	Irreparable damage to a natural resource
3 (Low)	6 (Low)	9 (Medium)	12 (Medium)	15 (High)	3 Moderate	Consequences would be significant, but manageable to a large extent.	Serious Injury	Reversible impact on health (with lost time) with a temporary disability or loss of quality of life	Medium to Serious reparable damage
2 (Low)	4 (Low)	6 (Low)	8 (Medium)	10 (Medium)	2 Low	Consequences would be visible yet fully managed.	Lost Time Injury	Reversible impact on health (with lost time) with no disability or loss of quality of life	Minor damage / Minor reversible effects
1 (Low)	2 (Low)	3 (Low)	4 (Low)	5 (Low)	1 Negligible	Consequences would be minimal.	Minor (medical treatment or first aid case)	Temporary discomfort	Insignificant / Non Conformance
1 - Rare	2 - Unlikely	3 - Possible	4 - Likely	5 - Almost Certain					

Probability / Time Frequency / Likelihood				
1 - Rare	2 - Unlikely	3 - Possible	4 - Likely	5 - Almost Certain
>20 Years	5-19 Years	1-4 Years	Monthly	Weekly
Could conceivably occur but would be extremely remote	Could possibly occur but would be rare	Could occur but infrequently	Known to occur / would not be surprising	Occurs often / is to be expected

Score	Rating	Description
15-25	High (Catastrophic)	Risk with potential to lead to collapse of business and is fundamental to the achievement of objectives OR Risk which can be endured but which may have a prolonged negative impact and extensive consequences. Immediate action and commitment from senior management required.
7-14	Medium (Moderate and Significant)	The risk may harm the objectives and functions resulting in loss of effectiveness and reputation to the department/operation. Management responsibility must be specified and accountability defined.
1-6	Low (Low and Negligible)	Event which can be managed by routine processes and procedures.

Figure 4.3: Sibanye-Stillwater SHE risk matrix

(Sibanye-Stillwater, 2021b)

To compare the risk ranking of the alternative methods a risk ranking exercise of the alternative tunnelling methods as practised at the Marikana Operations was conducted. This risk ranking exercise is shown in Appendix 3. Similar to the mentioned workshop, this ranking exercise was conducted with senior mining experts at Marikana. The results from this risk ranking exercise are shown in Table 4.8 and are ranked as per Figure 4.3.

Table 4.8: Risk ranking results

Risk #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Risk Rating – Hand-held drill & blast	3	4	9	9	6	6	12	6	9	12	9	2	6	12	12	117
Risk Rating - Inverse Drop Raising	3	6	6	6	6	6	6	6	6	4	6	2	6	12	12	93

4.4.2 Accuracy

For the criterion of accuracy, the efficiency measure and term accuracy refer to how precise a method was executed when comparing planned dimensions with measured survey dimensions. This accuracy between the methods differs due to the nature of the shorter versus longer drill holes and the deflection of drill steels that occurs when longer holes are drilled. According to the mining experts, deflection on the drop raising method starts after 15 metres and has a negative effect after 20 metres when drilled at the 34.5º inclination. The current practice at the case study mines is to have a flat portion of 3m in a travelling way every 15 to 20 meters when the travelling way exceeds 25 meters in total length. However, this does not fall within the designed layout at the case study mines as there is a drive to have longer cross cuts and shorter travelling ways to accommodate more hoppers in the cross cut. The average designed travelling way length at Marikana East is 15 metres.

When using the hand-held method to drill a travelling way, the bottom drill holes tend to be drilled too flat, thus damaging the floor of the travelling way, resulting in a staggered floor profile. The drop raising method in turn has a smoother floor, roof and sides compared to the hand-held method due to the nature of the longer drill holes that constantly follow the gradient of the excavation.

The unit of measure for the accuracy used in the research was expressed as a percentage. This was measured on the roof, floor and sides of the excavation and is the variance between the actual dimensions being smaller or larger than the designed dimensions. The final percentage efficiency used was thereafter calculated by subtracting the overall combined percentage from 100% to get the accuracy percentage. As an example, where the overbreak on the hand-held method was 4.58%, the calculation is as follows.

100% - 4.58% = 95.42% accuracy for the hand-held method.

The sample sizes for comparison of the accuracy of the methods were 17 travelling ways for the drop raising method and 28 travelling ways for the hand-held method. The accuracy efficiency scores for the methods were 97.93% for the drop raising method and 95.42% for the hand-held method. The accuracy sample information for the travelling way dimensions can be seen in Appendix 4.

4.4.3 Maintenance cost

Maintenance cost refers to costs that are incurred at a travelling way during the entire lifespan of the travelling way and are expressed in rand per metre. The alternative methods do not have the same result in overbreak and mining accuracy resulting in more maintenance and equipping needed for staggered floors. In a conventional travelling way excavation, the floor of the equipment side is covered in timber to create a smooth surface for winches and equipment to be pulled up on. However, this is not needed for the drop raising method as the floor of the excavation is smooth enough to drag the equipment directly on the rock surface. There are in some cases only minor cement alterations needed in the equipping stage. This saves costs on timber that does not have to be replaced after winches are pulled up the travelling way as the heavy winches damage the timber which then needs to be replaced or repaired. The timber cost is the only cost where there is a difference in maintenance cost as the other cost making up the maintenance cost between the alternative methods are the same. A travelling way mined with the hand-held method will have its timber replaced twice in the lifespan of the travelling way resulting in a maintenance cost 209% more than a travelling way mined with the drop raising method at R341 per metre compared to R711 per meter for the hand-held method. These costs were derived from the finance departments of the case study mines.

4.4.4 Equipment availability

For the criteria of equipment availability, the efficiency measure used was equipment uptime and is expressed as a percentage. This metric represents the amount of time that equipment is operational and available for use and is expressed as a percentage of the total scheduled operating time. To calculate this efficiency the total available operating hours minus the downtime or maintenance time was determined. The resulting value was then divided by the total scheduled operating hours and multiplied by 100 to get the equipment uptime percentage.

For example, the hand-held machines have a scheduled operating time of 60 hours to complete a travelling way. The hand-held machines however experience an average of 2.5 hours of unplanned downtime and breakdowns during this available 60 hours. The equipment uptime was then calculated as follows: (60 – 2.5) / 60 x 100 = 95.8%

This calculation was repeated for both alternative sets of equipment. The alternative availability efficiencies results were 95.8% for the hand-held method and 95.2% for the drop raising method.

4.4.5 Advance rate

For the criterion of advance rate, the efficiency measure of metres per month (m/month) was used. In this criterion, the efficiency comparison was made between the possible advance per month a travelling way can advance in a 22-shift working month if all available time was sufficiently utilised for each of the alternative methods. This calculation included the setup times, cleaning duration and support installation up until the equipping process or flat portion at the top of the travelling way can commence. Table 4.9 depicts a daily schedule of the main activities of the alternative methods.

Table 4.9: Advance rate schedule of the alternative methods

Method	**Hand-held method**	**Drop raising method**
Day 1	Transporting, equipping and winch-bed preparation	Transporting & setting up of equipment
Day 2	Equipping and winch-bed preparation	Setting up of equipment
Day 3	Equipping and winch installation	Setting up and alignment of equipment
Day 4	Equipping and winch installation	Drilling day 1 (7 of 44 holes)
Day 5	1.5 m advance, 1st blast	Drilling day 2 (14 of 44 holes)
Day 6	1.5 m advance, 3.0 m cumulative advance	Drilling day 3 (21 of 44 holes)
Day 7	1. 5 m advance, 4.5 m cumulative advance	Drilling day 4 (28 of 44 holes)
Day 8	1.5 m advance, 6.0 m cumulative advance	Drilling day 5 (35 of 44 holes)
Day 9	1.5 m advance, 7.5 m cumulative advance	Drilling day 6 (42 of 44 holes)
Day 10	1.5 m advance, 9.0 m cumulative advance	Drilling day 7 (44 of 44 holes), removal of equipment
Day 11	1.5 m advance, 10.5 m cumulative advance	Removing of equipment, 2.0 m advance, 1st blast
Day 12	1.5 m advance, 12.0 m cumulative advance	5.0 m advance, 7.0 m cumulative advance
Day 13	1.5 m advance, 13.5 m cumulative advance	5.0 m advance, 12 m cumulative advance
Day 14	1.5m advance, 15.0m cumulative advance	3.0m advance, 15m cumulative advance
Day 15	Last cleaning day	Last cleaning day
m/month	**15 m in 15 days = 22 m/month**	**15 m in 15 days = 22 m/month**

Table 4.9 describes the alternative method schedules and the number of days it takes to complete a 15 metre long travelling way. At the bottom of the table an efficiency score of advance per month is indicated for each of the methods.

4.4.6 Excavation cost

For the criterion of excavation cost the total cost of excavating a travelling way was used as the efficiency measure. This was totalled up for each of the alternative methods and thereafter rescaled for confidentiality reasons. The rescaling was done by setting the contractor equipping cost under the drop raising method to an arbitrary value of R10 000 and thereafter indexing each of the other costs to this base. This rescaling does not affect the final efficiency score as all the values were adjusted and their relation to the total per method remained the same.

With the drop raising method being performed by contractor crews the cost of the method ranked significantly higher than the alternative. Table 4.8 shows the basic breakdown of the cost variance between the alternative methods. The data in Table 4.8 was derived from the finance departments of the case study mines.

Table 4.10: Cost efficiencies of the alternative methods

Travelling way developed by mine, hand-held method	**Description**
R31 691	Crew labour costs
R10 730	Supervision portion
R20 354	Material
R62 776	**Total hand-held cost**
Travelling way developed by a contractor, drop raising method	
R92 597	Contractor costs
R20 354	Material
R10 000	Equipping to mine standard, construction
R122 952	**Total contractor cost**

4.5 Application of the efficiencies to the AHP model

Once the efficiencies per criterion were determined, the efficiencies were tabled and summed to be used in the normalisation process. The normalised efficiencies were thereafter used in calculating a final score per alternative. Table 4.11 displays the efficiencies that were tabled and summed pre normalisation process.

Table 4.11: Table of efficiencies

Criterion	**Risk ranking**	**Accuracy**	**Maintenance cost**	**Equipment availability**	**Advance rate**	**Excavation cost**
Criterion requirement / **Mining method**	minimise	maximise	minimise	maximise	maximise	minimise
Hand-held drill & blast	117	95%	711	95.8	22	R 62 776
Inverse drop raising	93	98%	341	95.2	22	R 122 952
Sum	210	193%	1052	191	44	R 185 728

To calculate the normalised efficiencies the actual efficiencies from Table 4.11 were divided by the sum of the actual efficiency score. In the normalised efficiency table, Table 4.12, the efficiencies should add up to one. In the case of a maximisation criterion, the calculation of the efficiency was as follows. For example, for the criterion of ‘Equipment availability’, the calculation for the normalised hand-held efficiency was calculated by dividing the efficiency for ‘Equipment availability’ by the sum value of the criteria (95.8 ÷ 191 = 0.502) as indicated in yellow. In the case of a minimisation criterion, the calculation of the efficiency was used as follows. For example, for the criterion of ‘Risk ranking’, the calculation for normalised hand-held efficiency was calculated by the value of one minus the ‘Risk ranking’ efficiency divided by the sum value of the normalised efficiencies of that criterion (1 - (117 ÷ 210) = 0.443) to convert a minimisation case to a maximisation case through using its compliment and is indicated in green. These calculations were repeated to populate Table 4.12. which shows the normalised efficiencies of the alternative methods.

Table 4.12: Normalised table of efficiencies

Criterion / Mining method	Risk ranking	Accuracy	Maintenance cost	Equipment availability	Advance rate	Excavation cost
Hand-held drill & blast	0.443	0.494	0.324	0.502	0.500	0.662
Inverse drop raising	0.557	0.506	0.676	0.498	0.500	0.338
Sum	1.000	1.000	1.000	1.000	1.000	1.000

The final step was to then calculate an overall AHP score per alternative tunnelling method based on the normalised efficiencies from Table 4.12 and the weighting values from Table 4.6. This was done in Table 4.13 by multiplying the normalised efficiency values per criteria with the criteria weight shown and taken from Table 4.6. These row values were thereafter added up to attain a final score per alternative method. As an example, to calculate the row value to be totalled for the hand-held method under 'Risk ranking', the normalised efficiency value for the hand-held method under the criterion of 'Risk ranking' was multiplied by the criteria weight under 'Risk ranking' and calculated to the value of 0.178 (0.443 x 0.402 = 0.178) as indicated in yellow. This calculation was done for the remaining row entries in the table. The row entries were thereafter totalled to get the final AHP priority score per alternative method. Table 4.13 shows the final AHP priority score calculation for the alternative tunnelling methods.

Table 4.13: Totalled AHP score calculation

Criterion / Mining method		Risk ranking	Accuracy	Maintenance cost	Equipment availability	Advance rate	Excavation cost	
Normalised Efficiencies	Hand-held drill & blast	0.443	0.494	0.324	0.502	0.500	0.662	
	Inverse drop raising	0.557	0.506	0.676	0.498	0.500	0.338	
Criteria Weights from Table 4.6		0.402	0.193	0.129	0.108	0.105	0.064	
Row values to be totalled	Hand-held drill & blast	0.178	0.095	0.042	0.054	0.052	0.042	Row total 0.464
	Inverse drop raising	0.224	0.098	0.087	0.054	0.052	0.022	Row total 0.536

Totalled AHP Scores

Mining method	AHP Score
HH drill & blast	0.464
Inverse drop raising	0.536

The final AHP scores for the alternative methods indicate that the inverse drop raising method scored higher with a score of 54% versus 46% for the hand-held drill and blasting method. This makes the inverse drop raising method the optimal method for use at the Marikana East Operations.

4.6 Summary of Chapter 4

The AHP was used to determine which of the alternative tunnelling methods is the optimal travelling way development method for use at the Marikana Operations. The alternative methods reviewed and tested were the conventional hand-held drill and blast method and the inverse drop raising method. The chapter covered the process followed and the calculations made in the AHP application as well as the data analysis performed to allocate efficiency scores per criterion. The next chapter, Chapter 5, concludes the research study and provides recommendations and suggestions for further research.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Overview of Chapter 5

Chapter 5 covers the conclusions and recommendations of the research study. The chapter summarises the findings of the research and provides suggestions for further research and improvements based on these findings. The chapter helps to explain the significance and implications of the research, as well as guide future researchers or stakeholders in solving similar problems. In this chapter, an overview of the key conclusions is drawn, and recommendations are made that can contribute to advancing knowledge and practice in the field of mining engineering and mining method selection.

5.2 Conclusions

Through the application of AHP, the research question stated in Section 1.3 was answered by selecting an optimal travelling way development method to be used at the Marikana Operations. In the final AHP scores, the alternative tunnelling methods scored close to each other indicating that even though an optimal method could be selected the methods are both usable at the Marikana Operations. The inverse drop raising method scored 53.6% and the conventional hand-held method scored 46.4%, thus making the inverse drop raising method the optimal method by a margin of 7.2%.

The research highlights the fact that the inverse drop raising method carries a lower risk to stakeholders than the alternative method. Additionally, the method is more accurate and requires less equipping and maintenance for the duration of use in the excavation. The criteria of risk ranking obtained the highest weighting score from the panel of experts and indicates the importance of safety and the drive to zero harm to the members of the mining community. In this criterion, the optimal method also scored higher, proving that the inverse drop raising method holds less risk to miners and stakeholders.

On the criterion of advance rate both the methods scored at the same rate, proving that neither of the methods holds an advantage when mining 15 metre long travelling ways. This might however change if longer or shorter travelling ways were to be mined and will have to be investigated in such cases.

One significant takeaway from the research is that even though the excavation cost and maintenance cost criteria obtained smaller weightings from the workshop panel, these were the criteria where the method efficiencies differed the most. It is important to note that in a price-constrained environment, the excavation cost weighting might not change, but basic budget constraints can make the inverse drop raising method less preferred if not done more cost-effectively.

5.3 Recommendations

With the way that both these methods are currently being executed at the Marikana Operations, the inverse drop raising method is close to twice as expensive as the conventional hand-held method. If metal prices drop, the cost of the method might not be sustainable if executed the way that it is done at the Marikana Operations. Therefore, it is recommended that should the Marikana Operations choose to use the inverse drop raising method as the preferred travelling way development method as recommended by this study, the mine should investigate a way of executing the method more cost effectively. It is suggested that, as an alternative to the use of a contractor, further research should also be done on the viability of training and employing hybrid in-house mining crews to execute the development of travelling ways with both the hand-held and the inverse drop raising method. By doing so the required skills and equipment will not be supplied by a contractor and has the potential of being executed more cost effectively. Alternatively, renegotiations with the contractor that is performing the inverse drop raising method should be commenced to decrease the cost of the method as executed at Marikana.

5.4 Suggestions for future research work

The drop raising method is a widely used method of excavating rock transfer passes in the mining environment. The equipment suite can however be used for various other applications and the viability thereof must be tested site specific. This was apparent in the research, proving the method as a viable and preferred method for the application of travelling way development at Marikana, but the viability of the method must be tested at other underground platinum mines. Like this, there is a wide variety of other methods that can be used, modified and tested for application in different fields.

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6 Appendix 1: Letter from the mine confirming the workshop

we are one
Sibanye Stillwater

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Subject: *Confirmation of Workshop for Defining AHP Criteria to the MSC research of Mr. B Meyer.*

To whom it may concern.

I am writing to confirm that a workshop was successfully conducted to aid Mr. B Meyer with the following research topic: "Selection of an optimal tunnel development method for an underground mine travelling way using an Analytic Hierarchy Process".

I am pleased to inform you that the workshop took place on 29 July 2023 at the Saffy Shaft planning boardroom. The objective of the workshop was to establish clear and comprehensive criteria using the AHP framework, which would guide the research process of the stated topic effectively. We had a panel of experts who specialize in mining, mine planning, safety and other mining technical departments.

Through collaborative efforts and collective expertise, the panel was able to outline a set of six criteria specifically tailored to address the intricacies of the research topic. After the workshop anonymous weighting tick sheets were handed out for completion by the attendees of the workshop.

Yours sincerely,

Saffy Shaft
Abie Letsholo
27 SEP 2023
Manager Operations UG
Sibanye Stillwater
SA PGM Segment

Abie Letsholo

www.sibanyestillwater.com

Directors: B Mathebula, NR Mugovhani, RA Stewart and JD van Aswegen
Alternate Director: AJ Murdoch-Eaton
Company Secretary: LD Matlosa

7 Appendix 2: The twelve completed questionnaires

1

Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9

2

Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

3

Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

4

Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9

5

Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	✓3	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	✓2	3	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	✓5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	✓2	3	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	✓2	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	2	✓3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	✓5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	✓2	3	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	✓1	2	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	✓5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	✓1	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	✓3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	✓5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	✓5	4	3	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	✓2	1	2	3	4	5	6	7	8	9

6

Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

7

Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

8

Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	~~4~~	5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	5	~~4~~	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	5	4	3	~~2~~	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

9

Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

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Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

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Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	~~4~~	5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	~~5~~	4	3	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9

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Excavation cost									Advance rate							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Accuracy							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Excavation cost									Risk ranking							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Excavation cost									Equipment availability							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Advance rate									Accuracy							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Advance rate									Risk ranking							
9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9

Advance rate									Maintenance cost							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Advance rate									Equipment availability							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Accuracy									Risk ranking							
9	8	7	6	5	4	3	2	1	2	~~3~~	4	5	6	7	8	9

Accuracy									Maintenance cost							
9	8	7	6	5	4	3	2	1	~~2~~	3	4	5	6	7	8	9

Accuracy									Equipment availability							
9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9

Risk ranking									Maintenance cost							
9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9

Risk ranking									Equipment availability							
9	8	7	6	5	4	~~3~~	2	1	2	3	4	5	6	7	8	9

Maintenance cost									Equipment availability							
9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9

8 Appendix 3: Risk ranking exercise

				Risk Rating - HH drill & blast					Risk Rating - Inverse Drop Raising					
#	Activity / Area / Function / Process	Sub - Activity / Area / Function / Process	Likelihood	Safety	Health	Environment	Earnings / Capital at Risk	Inherent Risk Rank (Max Impact)	Likelihood	Safety	Health	Environment	Earnings / Capital at Risk	Residual Risk Rank (Max Impact)
1	Transporting of material	Nipping points	3 - Possible	1 - Negligible	1 - Negligible	1 - Negligible	1 - Negligible	3(Low)	3 - Possible	1 - Negligible	1 - Negligible	1 - Negligible	1 - Negligible	3(Low)
2	Transporting of material	Weight	2 - Unlikely	2 - Low	2 - Low	1 - Negligible	2 - Low	4(Low)	3 - Possible	2 - Low	2 - Low	1 - Negligible	1 - Negligible	6(Low)
3	Transporting of material	Slopes / angles	3 - Possible	3 - Moderate	2 - Low	1 - Negligible	2 - Low	9(Medium)	3 - Possible	2 - Low	2 - Low	1 - Negligible	1 - Negligible	6(Low)
4	Site preparation / Setup of equipment	RBE / mashinery inte	3 - Possible	3 - Moderate	3 - Moderate	1 - Negligible	1 - Negligible	9(Medium)	3 - Possible	2 - Low	2 - Low	1 - Negligible	1 - Negligible	6(Low)
5	General Safety	General Safety	3 - Possible	2 - Low	2 - Low	1 - Negligible	2 - Low	6(Low)	3 - Possible	2 - Low	2 - Low	1 - Negligible	2 - Low	6(Low)
6	General Safety	Possitioning / Clearance	3 - Possible	2 - Low	2 - Low	1 - Negligible	1 - Negligible	6(Low)	3 - Possible	2 - Low	2 - Low	1 - Negligible	1 - Negligible	6(Low)
7	Drilling	Drilling of traveling way at incline	4 - Likely	3 - Moderate	2 - Low	1 - Negligible	2 - Low	12(Medium)	3 - Possible	2 - Low	2 - Low	1 - Negligible	1 - Negligible	6(Low)
8	Drilling	Establishing cubby / Traveling way break, flat portion @ 12-20m up	3 - Possible	2 - Low	2 - Low	1 - Negligible	1 - Negligible	6(Low)	3 - Possible	2 - Low	1 - Negligible	1 - Negligible	1 - Negligible	6(Low)
9	Blasting operations	Sequence of blasting, Charging up	3 - Possible	3 - Moderate	2 - Low	1 - Negligible	3 - Moderate	9(Medium)	3 - Possible	2 - Low	1 - Negligible	1 - Negligible	1 - Negligible	6(Low)
10	Drilling operations (opening of blocked pre-drilled holes)	Misfires	4 - Likely	3 - Moderate	3 - Moderate	1 - Negligible	3 - Moderate	12(Medium)	2 - Unlikely	2 - Low	1 - Negligible	1 - Negligible	2 - Low	4(Low)
11	Ground conditions	Hanging wall and side wall	3 - Possible	3 - Moderate	3 - Moderate	1 - Negligible	1 - Negligible	9(Medium)	2 - Unlikely	3 - Moderate	3 - Moderate	1 - Negligible	1 - Negligible	6(Low)
12	Ventalation	Ventalation layout	2 - Unlikely	1 - Negligible	1 - Negligible	1 - Negligible	1 - Negligible	2(Low)	2 - Unlikely	1 - Negligible	1 - Negligible	1 - Negligible	1 - Negligible	2(Low)
13	Water	Water Usage	3 - Possible	2 - Low	2 - Low	1 - Negligible	1 - Negligible	6(Low)	3 - Possible	2 - Low	2 - Low	1 - Negligible	1 - Negligible	6(Low)
14	Roling Rocks/ Slip and Fall	Related to rocks falling from the incline	3 - Possible	4 - Significant	4 - Significant	1 - Negligible	1 - Negligible	12(Medium)	3 - Possible	4 - Significant	4 - Significant	1 - Negligible	1 - Negligible	12(Medium)
15	Barring	FOG	3 - Possible	4 - Significant	4 - Significant	1 - Negligible	4 - Significant	12(Medium)	3 - Possible	4 - Significant	4 - Significant	1 - Negligible	4 - Significant	12(Medium)

9 Appendix 4: Accuracy sample information

Drop raise method accuracy efficiencies

Workplace	Total metres	Actual Width	Actual Height	Plan Width	Plan Height
Travelling way 1	10.9	3.0	1.8	3.0	1.8
Travelling way 2	14.6	3.0	1.8	3.0	1.8
Travelling way 3	11.5	3.4	2.0	3.0	1.8
Travelling way 4	3.1	3.0	2.0	3.0	1.8
Travelling way 5	8.6	3.0	1.8	3.0	1.8
Travelling way 6	6.1	3.0	1.8	3.0	1.8
Travelling way 7	10.6	3.0	1.8	3.0	1.8
Travelling way 8	3.8	3.0	1.8	3.0	1.8
Travelling way 9	5.1	3.0	1.8	3.0	1.8
Travelling way 10	15.7	3.0	1.8	3.0	1.8
Travelling way 11	7.3	3.0	1.8	3.0	1.8
Travelling way 12	1.3	3.0	1.8	3.0	1.8
Travelling way 13	5.2	3.0	1.8	3.0	1.8
Travelling way 14	5.6	3.0	1.8	3.0	1.8
Travelling way 15	5.9	3.0	1.8	3.0	1.8
Travelling way 16	5.3	3.0	1.8	3.0	1.8
Travelling way 17	4.9	3.0	1.8	3.0	1.8
Average dimensions		**3.024**	**1.824**	**3.000**	**1.800**
Overbreak %		**0.78%**	**1.29%**		
Overall overbreak				**2.07%**	

Hand-held method accuracy efficiencies

Workplace	Total metres	Actual Width	Actual Height	Plan Width	Plan Height
Travelling way 1	7.7	3.0	1.8	3.0	1.8
Travelling way 2	16.6	3.1	1.8	3.0	1.8
Travelling way 3	8.4	3.0	1.8	3.0	1.8
Travelling way 4	12.2	3.0	1.8	3.0	1.8
Travelling way 5	6.1	3.0	2.2	3.0	1.8
Travelling way 6	5.6	3.0	1.8	3.0	1.8
Travelling way 7	8.3	3.0	1.8	3.0	1.8
Travelling way 8	7.0	3.0	1.8	3.0	1.8
Travelling way 9	13.7	3.1	1.8	3.0	1.8
Travelling way 10	7.2	3.0	1.8	3.0	1.8
Travelling way 11	7.6	3.0	1.8	3.0	1.8
Travelling way 12	6.8	3.0	2.2	3.0	1.8
Travelling way 13	16.5	3.0	1.9	3.0	1.8
Travelling way 14	14.4	3.0	1.8	3.0	1.8
Travelling way 15	10.0	3.0	1.8	3.0	1.8
Travelling way 16	7.7	3.0	1.8	3.0	1.8
Travelling way 17	6.5	3.0	1.8	3.0	1.8
Travelling way 18	10.0	3.2	2.4	3.0	1.8
Travelling way 19	10.1	3.2	1.8	3.0	1.8
Travelling way 20	18.7	3.0	1.8	3.0	1.8
Travelling way 21	17.8	3.0	1.8	3.0	1.8
Travelling way 22	9.0	3.1	2.0	3.0	1.8
Travelling way 23	11.9	3.0	1.8	3.0	1.8
Travelling way 24	8.6	3.0	1.8	3.0	1.8
Travelling way 25	5.2	3.0	1.8	3.0	1.8
Travelling way 26	9.4	3.0	1.8	3.0	1.8
Travelling way 27	13.0	3.1	1.8	3.0	1.8
Travelling way 28	5.5	3.0	2.0	3.0	1.8
Average dimensions		**3.029**	**1.868**	**3.000**	**1.800**
Overbreak %		**0.94%**	**3.63%**		
Overall overbreak				**4.58%**	