SELECTING AN OPTIMAL ROCK TRANSPORTATION SYSTEM AT TROJAN MINE USING THE ANALYTIC HIERARCHY PROCESS

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

Johannesburg, 2020

DECLARATION

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

Signed:

Philip T. Karembera

This 6th day of August year 2020

ABSTRACT

Trojan nickel mine's Mineral Reserves within the current mining area (35/0 lift) are getting depleted due to extraction, with a remaining life of 3.2 years at the projected Life of Mine (LOM) plan extraction rate of 40,000 tpm. To extend the LOM of Trojan mine, 37/0 lift and 39/0 lift are currently being developed to replace 35/0 lift, which will add an additional two years to Trojan mine's life at the projected LOM plan ramp up depletion rate of about 65,000 tpm. Eventually, Trojan mine has plans to further ramp up to the plant capacity of 90,000 tpm as it targets to extract deeper levels of the deposit. However, the 37/0 lift and 39/0 lift Mineral Reserves have low grade ore averaging 0.71% nickel and the ore is transferred through 37/0L and 39/0L haulages, respectively. Since these two haulages are located at elevations lower than that of 35/0 lift, it implies that the extraction of 37/0 lift and 39/0 lift Mineral Reserves will be done at an increased operating cost. In addition to the low ore grade and higher operating cost at an increased depth, the price of nickel has been relatively low, with the current forecast nickel price being US$12,000 per tonne of nickel in concentrate. The price of nickel once soared by 400% to a record high of US$54,000 per tonne of nickel in concentrate in May 2007, and dropped to just under US$9,000 per tonne in October 2008 and has remained subdued ever since. In order to optimise value from the extraction of the low grade ore from lower levels coupled with increased cost due to increased extraction depth and lower nickel price, an optimal rock transportation system has to be selected. The selected transport system will eventually be used in 37/0L, 37/0L and future main haulages.

The operating cost of rock transportation at Trojan mine accounts for about 20% of total mining cost. In all upper levels up to 35/0L rail haulage has been the sole means of transporting rock from chutes to main ore and waste passes but no formal study has been conducted at the mine to investigate the viability of other alternative rock transportation systems such as belt conveyor or truck systems. It was therefore the aim of this study to analyse and select the optimal rock transportation system to use in the all future haulages at Trojan mine.

To do this analysis, the Analytic Hierarchy Process (AHP) was used to select the optimal rock transportation system amidst multiple conflicting criteria. An AHP model was developed in Microsoft Excel® and used to rank the selected transportation alternatives against three major categories of evaluation criteria namely; economic, environmental and technical. The AHP technique uses matrix and vector algebra as the basis of its methodology framework and therefore the technique was chosen due to its simplicity. In addition to its simplicity, the technique has the ability to detect inconsistency and estimate the degree of inconsistency which means that its results are reliable.

From the AHP analysis, the belt conveyor system was found to be the optimal material transportation system. This was followed by the rail and truck systems. To validate the AHP results, a Discounted Cashflow Analysis (DCF) was done for the three transportation systems. According to the DCF analysis, the belt conveyor system has the highest NPV of US$83.5 million, followed by the truck system with a NPV of US$79.9 million and lastly the rail system with a NPV of US$79.5 million. The DCF results confirmed that the belt conveyor system is the optimal material transportation system. Therefore, it is recommended that the mine uses the belt conveyor system for future haulages. However, it is recommended that the pair-wise comparisons be extended to the senior company executives as they are the key decision makers.

ACKNOWLEDGEMENTS

I give glory to God Almighty who has been directing my path from the beginning of my study journey. Special acknowledgement also goes to the following institution and individuals for their contributions towards this research study:

- Trojan mine for giving me the opportunity to study and allowing me to use the mine as a case study;
- My supervisor, Mr. T. Tholana, for his continual encouragement, guidance, positive comments and priceless effort in proof reading all my draft reports;
- Mr. J. Kasumba (Technical Services Manager, Trojan mine) for the insights he gave me throughout my research;
- My colleagues at Trojan mine who gave me inspiration; and
- My wife, Bernadatte, and kids, Blessed and Beloved, for their support, encouragement and understanding when the research work took me from their presence.

DEDICATION

To my late mother Winnie Beredina Sanyangore who would be overjoyed to see me accomplish more in life.

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LIST OF ABBREVIATIONS

AHP – Analytic Hierarchy Process

BNC – Bindura Nickel Corporation

CI – Consistency Index

CR – Consistency Ratio

dB(A) – A-weighted decibel

DCF – Discounted Cashflow analysis

ELECTRE – Elimination and Choice Translating the Reality

hpd – hours per day

HWOB – Hanging Wall Orebody

LHD – Load-Haul-Dump

LOM – Life of Mine

MADM – Multi-Attribute Decision Making

MAUT – Multi-Attribute Utility Theory

mbs – metres below surface

MCDA – Multi-Criteria Decision Analysis

MCDM – Multi-Criteria Decision Making

MOB – Main Orebody

MODM – Multi-Objective Decision Making

NPV – Net Present Value

ppm – parts per million

PROMETHEE – Preference Ranking Organisation Method for Enrichment Evaluation

RI – Random Index

ROM – Run of Mine

SVR – Sub-Vertical Rock

tpd – tonnes per day

tph – tonnes per hour

tpm – tonnes per month

1 INTRODUCTION

1.1 Chapter overview

This chapter gives background information of the case study mine, the problem statement as well as the aim and objectives of the research. The research scope and the significance of making the right choice when selecting an option to use in underground transportation are also discussed in the chapter. The structure of the report by chapters is also outlined at the end of this chapter.

1.2 Background information

Trojan mine is a nickel mine located in Bindura in the Mashonaland Central Province of Zimbabwe, approximately 100 km north-east of the capital city, Harare (SRK Consulting Limited, 2013). It is owned by Bindura Nickel Corporation (BNC), a subsidiary of ASA Resource. Its location and that of other BNC mines in Zimbabwe is shown in Figure 1.1.

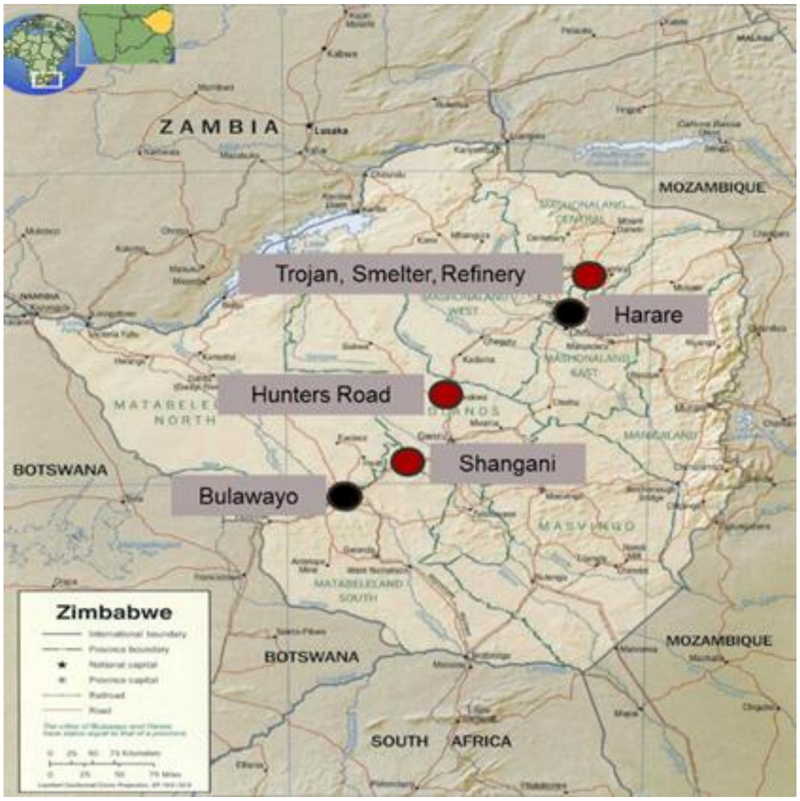


Figure 1.1: Location of BNC properties across Zimbabwe

(Source: Bindura Nickel Corporation, 2018)

There are two major ore bodies mined at Trojan mine and these are the Main Orebody (MOB) and the Hanging Wall Orebody (HWOB), while a discontinuous and smaller massive and near-massive orebody occurs in the footwall as a footwall massive orebody. Ore extraction at the mine is done through sub-level caving mining method. Figure 1.2 shows the configuration of stopes, sublevels and main haulages at Trojan mine.

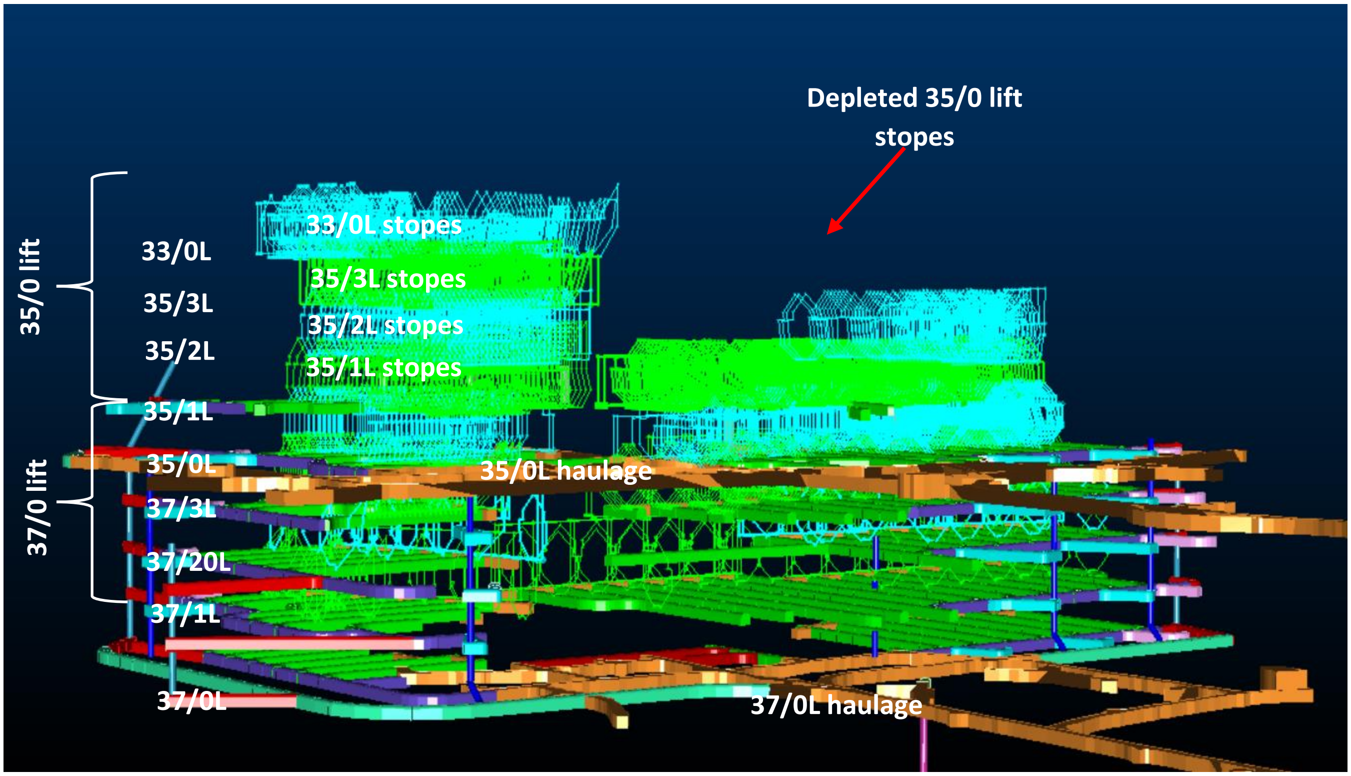


Figure 1.2: A three dimensional view of 35/0 lift and 37/0 lift (stopes and development)

(Source: Bindura Nickel Corporation, 2019)

Figure 1.2 shows two of the main haulage levels namely; 35/0L and 37/0L haulages which are spaced 60.96 m vertically. The 35/0L haulage is equipped with tracks that connect the MOB and HWOB ore bodies to the Sub-Vertical Rock (SVR) shaft. Two 10 t Goodman electric locomotives each pulling eight 3.5 t hoppers operate in the haulage.

Closer to the orebody, sublevels are developed from a footwall ramp. These sublevels are vertically spaced at 15.24 m with the production crosscuts offset 7.5 m centre to centre between one sublevel and the next consecutive sublevel and at 15 m spacing within the same sublevel. A vehicle and access ramp that connects sublevels is located in the footwall. A typical main haulage at the mine is equipped with ore and waste chutes to transfer ore and waste, respectively, from the four sublevels above and connected to it. In this report, ore and waste are interchangeably referred to as material or rock.

Most of the production activities at the mine are mechanised. Load, haul and dump (LHD) machines load ore or waste from various draw points and dump into respective ore or waste passes within the sublevel. The material cascades down the ore or waste passes by gravity into pneumatically operated chutes located in the main haulage at the bottom of a lift. Figure 1.3 shows a schematic cross-sectional ore and waste movement design from source to the plant and waste dump, respectively.

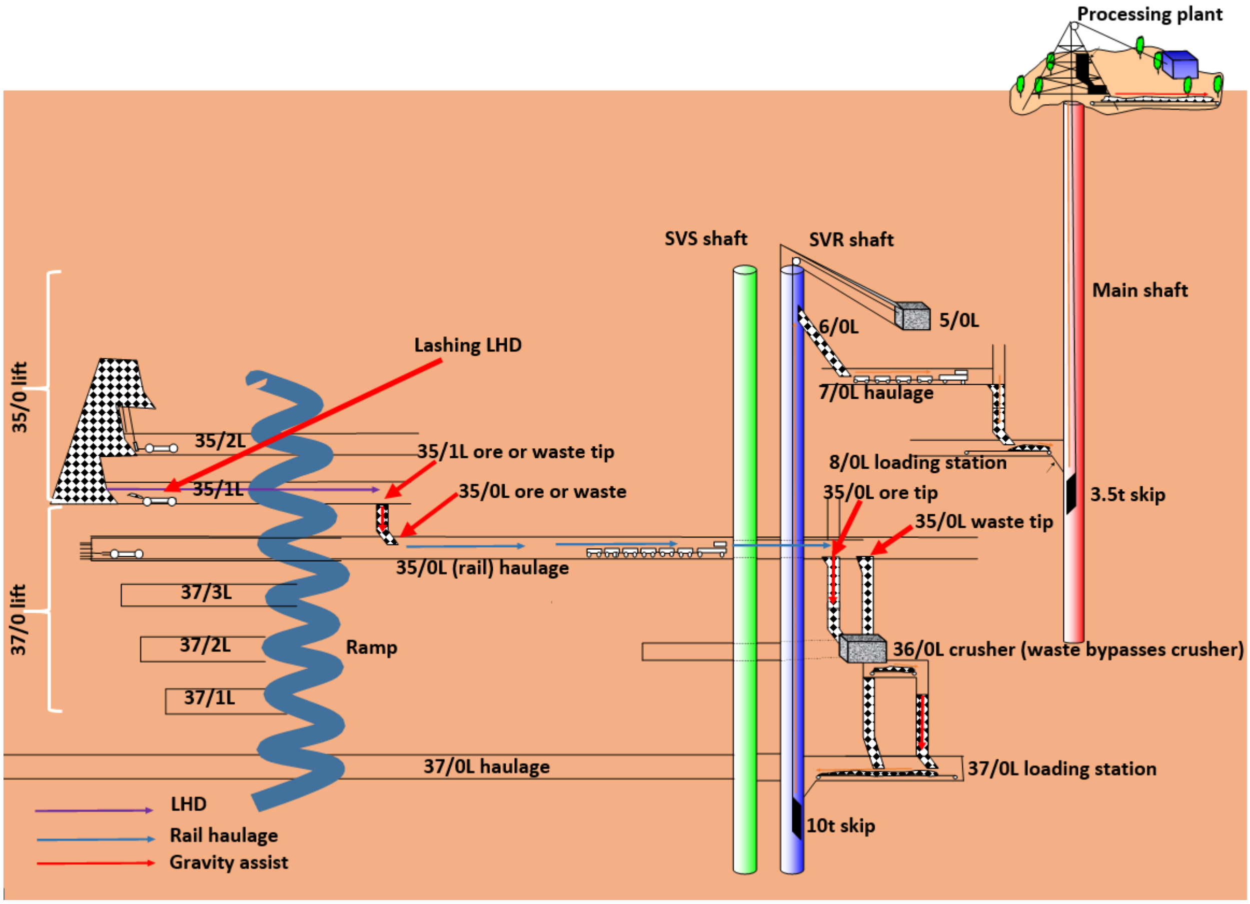


Figure 1.3: Schematic material movement from source to plant at Trojan mine
(Source: Trojan Nickel Mine, 2017)

As indicated in Figure 1.3, material is fed from 35/0 lift sublevels into 35/0 lift passes and cascades down the passes by gravity into 35/0L haulage chutes. Electric locomotives then transfer the material from 35/0L haulage chutes to grizzleys in the 35/0L haulage over a one-way horizontal distance of 919 m. From 35/0L grizzley, ore cascades down by gravity to a Telsmith 42” jaw crusher located at 36/0L (1,011 mbs) where it is crushed. After crushing, it is transferred to the main ore pass via an apron feeder to 37/0L loading station ore chute. On the other hand, waste tipped at the 35/0L main waste grizzley cascades straight down to the 37/0L loading station waste chute. At 37/0L, the material is loaded onto a belt conveyor, ready for loading into measuring flasks and into two 10 t capacity skips in the SVR shaft equipped with a winder which has a hoisting rate of 200 tph (126,000 tpm of rock). The material is hoisted from 37/0L in the SVR to 6/0L (97 mbs) from which it passes through different transfer points as shown in Figure 1.3. Eventually, the material is transferred to surface through the Main shaft equipped with a winder whose hoisting capacity is 200 tph (126,000 tpm of rock). Ore is tipped into a reception bin and discharged onto a belt conveyor to a secondary crusher and to the plant. Waste is discharged from the skips into a separate reception bin where a belt conveyor is used to transport the waste to the waste dump.

1.3 Problem statement and research question

Mineral Reserves above the 35/0L haulage (i.e. in-situ low grade ore in 35/1L, 35/2L, 35/3L and 33/0L sublevels), known as the 35/0 lift (Figure 1.2), are getting depleted due to extraction. The remaining life of the lift is about 3.2 years at the projected LOM plan depletion rate of 40,000 tpm. Therefore, to extend the life of Trojan mine, 37/0 lift and 39/0 lift are being developed to replace the 35/0 lift. This expansion will extend the LOM by an additional two years according to the LOM plan ramp up depletion rate of 65,000 tpm while other future lower levels are being developed. Trojan mine has plans to further ramp up production to match the plant capacity of 90,000 tpm. However, the 37/0 lift and 39/0 lift comprise of equally low grade ore which will be transferred through the 37/0L and 39/0L haulages, respectively. To optimise value from the transfer of this low grade ore, coupled with an increase in depth relative to 35/0L by 60 m and 120 m, respectively, and a relatively lower nickel price averaging US$12,000 per tonne of nickel in concentrate, an optimal rock transportation system must be selected.

In all upper level haulages at Trojan mine, rail haulage has been used as a means of horizontal transportation of material from chutes to the main passes. However, given the increasing depth, low ore grade and a relatively lower nickel price, there is need to evaluate other alternative transportation systems in order to identify an optimal transportation system. The other forms of transportation that can also be used in underground operations are truck and belt conveyor transportation systems but no analysis has been done as yet to determine which one of these three alternative transport systems is optimal for use at Trojan mine. The selected alternative must be one that minimises capital cost, unit operating cost and environmental gas emissions while maximising productivity, flexibility and ensuring the safest working environment. This raises the research question,

> *"What is the optimal rock transportation system to use in main haulages at Trojan mine?"*

1.4 Research aim and objectives

The aim of this research is to select an optimal rock transportation system to use along Trojan mine's 37/0L, 39/0L and subsequently lower haulages against a given set of technical, economic and environmental constraints. The research objectives are to:

- Review literature on underground mine design in general and ore transportation systems in particular;
- Review literature on decision making in mine design and planning as well as the different decision-making techniques;
- Identify alternative underground transportation systems that can be used at Trojan mine;
- Evaluate the alternative transportation systems using the AHP technique;
- Validate the AHP results using the DCF technique; and
- Select the optimal ore and waste transportation system to use at Trojan mine.

The research aims to select an optimal rock transportation system for all lower level haulages at Trojan mine however, data collection and analysis only focusses on 37/0L and 39/0L haulages. Trojan mine has an intention to ramp up production from the current 40,000 tpm to about 90,000 tpm to match the plant capacity and this increase has necessitated the need to optimise rock transportation at the mine. The other processes of the mine cycle such as drilling, blasting, lashing and hoisting are excluded for analysis in this study.

1.5 Research significance

Rock transportation accounts for up to 20% of the total mining cost at Trojan mine and is the third highest cost driver after labour and mining engineering which account for 31% and 28% of total mining cost, respectively. Nickel, like most mineral commodities, is subject to the cyclic nature of metal prices for which miners are price takers. The research will therefore assist the mine in minimising unit operating cost, capital cost and unit energy cost, thereby improving the company's profit margin. Also, there is an increase in awareness on environmentally friendly systems, particularly in the reduction of gas emissions from diesel engines. Therefore, the research will also assist the mine in minimising the negative environmental impacts of dust, gas emissions and noise that are associated with material transportation. In addition, the research will assist the mine in improving productivity, availability and safety during transportation of material.

1.6 Structure of the report

The research report is structured into six chapters. Chapter 1 has outlined the problem statement, background and justification of the research. The research scope, significance and objectives have been discussed in the chapter. The remainder of the report is described below.

Chapter 2 reviews literature on underground mine design and planning and the various modes of rock transportation. The application of MCDA techniques in general and AHP in particular is also discussed in chapter 2 with reference to literature on how it has been applied in the mining industry as a useful MCDA technique.

Chapter 3 discusses how data was collected and analysed. Chapter 4 discusses the layout design and expected efficiencies of the three selected transportation systems. Chapter 5 presents and analyses the results from the AHP analysis. Validation of the results using the DCF is also done in chapter 5. Finally, conclusions and recommendations are made in Chapter 6.

1.7 Chapter summary

Due to changes in technology and the need to survive in the current negative economic environment, there is always a need to continually optimise mining operations. Trojan mine is accessing deeper parts of the orebody that have low grades during periods of depressed nickel prices. Given that transportation accounts for about 20% of total cost and that the unit transportation cost is likely going to increase with increasing mining depth, the analysis of transport systems to evaluate the most optimal system is imperative. The evaluation of these transport systems takes into consideration economic, environmental and technical factors.

2 LITERATURE REVIEW

2.1 Chapter overview

In order to put this research into perspective, literature on mine design and planning in general, and underground transport systems in particular, is discussed in this chapter. Various rock transportation systems are discussed together with the relevant decision-making techniques applicable to mine design and planning. The relevant evaluation criteria upon which a decision is made are discussed in this chapter as well as the evaluation, formulation and application of AHP as a decision-making technique. Literature on the application of the AHP technique in the mining industry is also reviewed in the chapter.

2.2 Mine design and planning

Mine planning is defined by Kazakidis and Scoble (2003) as a process of developing a depletion or extraction strategy that maximises the economic benefits from an orebody. The process defines the optimal path of orebody depletion that satisfies a company's objectives within the capability of the orebody and comprises of two components namely; design and scheduling. Musingwini *et al.* (2007) defines a mine plan as the integration of a layout (design) and a schedule. Mine design deals with the production of mine layouts that graphically illustrate the relative location of primary and secondary accesses (development design) as well as production areas (stope design) using software such as Datamine's Studio 5D Planner® and Minable Shape Optimiser®. On the other hand, scheduling indicates the sequence and timing of waste and ore extraction over a period of time. Scheduling can be done in the form of a Gantt chart generated software such as Datamine's Enhanced Production Scheduler®. Rupprecht (2003) mentioned that the layouts for underground transportation systems must be efficiently planned and equipped with relevant technology in order to move material safely, quickly and efficiently. The focus of this research is on mine design with particular focus on underground transportation systems. This is because transportation contributes significantly to the Trojan mine's operating cost so optimising transportation will improve the mine's profitability.

2.3 Underground transport systems

Transportation is one of the critical stages in the underground mining cycle involving the transportation of extracted ore to the surface stockpile or processing plant and waste to the surface waste dump (Elevli *et al.*, 2002). Kluge *et al.* (2017) mentioned that the success of a mining project is largely dependent on the selection of the most appropriate transport system since material transportation is a major component of a mining production system.

Dammers *et al.* (2016) categorised underground transportation into two broad categories namely; vertical and horizontal. Vertical transportation can be done by hoisting using a vertical or inclined shaft. de la Vergne (2008) mentioned that horizontal transportation can be done using trucks, rail or belt conveyors. Greberg *et al.* (2016) further stated that for many years, deep underground mines have used a combination of vertical and horizontal systems. These consist of truck haulage, belt conveyors, rail, shafts and ore passes for ore and waste transportation. However, the focus of this study is on horizontal transportation since the key vertical system infrastructure (with sufficient capacity) is already in place at Trojan mine such that as mining continues with depth, it is only haulages that will need to be developed. The three broad horizontal transportation systems are discussed in the next subsections.

2.3.1 Rail system

de la Vergne (2008) mentioned that underground rail transport can be divided into three main categories based on the source of power used. These categories are:

- Diesel locomotives;
- Battery-operated locomotives; and
- Trolley locomotives.

The trolley and diesel locomotives are the two types of rail transport systems that are used at Trojan mine. The trolley locomotive, in particular, is discussed in this study and compared to the truck and belt conveyor systems since it matches the productivity levels of these two transport systems. The trolley locomotive has a relatively high productivity compared to the diesel and battery-operated locomotives as a result of its ability to achieve higher speeds (Northard, 1976). It is equipped with two electric motors which obtain electric current from a live overhead trolley line. The electric current runs from the trolley line to the locomotive engine through a long pole which is continually pressed against the trolley line by means of tension in a spring. The rail haulage system has been widely used as an underground transportation system because of its several advantages. The advantages include:

- Up to 30% lower heat output than a belt conveyor system and much lower heat output than that of a truck system (Rupprecht, 2003);
- No environmental pollution as compared to the truck system whose diesel-powered engines emit harmful gases into the environment (Mahieu, 2017);
- Higher productivity of up to 160,000 tpd in high-capacity hard rock mines (Dammers *et al.*, 2016);
- Good reliability since the system is not as prone to breakdowns as the truck system (de la Vergne, 2008);
- Lower unit operating cost which is more than 10% lower than that of the truck system (Dammers *et al.*, 2016);
- Ability to transport personnel closer to the working face as compared to a belt conveyor system (Rupprecht, 2003);
- Ease of acquisition and procurement of back-up spares as manufacturing is done in Southern Africa (Rupprecht, 2003); and
- Lower noise levels of approximately 80 dB(A) (Ministry of Railways of India, 2015) as compared to trucks whose noise levels can reach 119 dB(A) (Kluge *et al.*, 2017) against an industry threshhold of 90 dB(A) (Rhodesia Government, 1976).

Nonetheless, the rail system also has its disadvantages. Some of its disadvantages are:

- Higher unit operating cost than the belt conveyor system by at least 11% (Kluge *et al.*, 2017);
- Lower flexibility than trucks as the rolling stock is limited to where the tracks and other supporting infrastructure have been laid (Dammers *et al.*, 2016);

- Inability to operate on steeper gradients exceeding 2° as compared to trucks and belt conveyor systems which can operate on gradients of up to 12° and 22°, respectively (Rupprecht, 2003); and
- High investment or capital cost associated with infrastructure (Rupprecht, 2003).

2.3.2 Truck system

Truck haulage has become a dominant means of transportation in underground mines when compared to rail haulage and belt conveyor which have low flexibility and high capital cost (Dammers *et al.*, 2016). Elevli *et al.* (2002) alluded to the fact that two-thirds of underground mines in Australia use the truck haulage system to transport rock.

The truck haulage system involves two phases namely: the transfer of fragmented material from the working face to a dumping point by a LHD machine (for example, from a production stope to an ore pass grizzley) and the transfer of material from the dumping point to the main tip or surface by trucks (Salama and Greberg, 2012). This study focuses on the transfer of material from the dumping point to the main tip. This involves the transfer of fragmented material from ore/waste chutes in a main level to the respective main passes near the rock shaft. The advantages of the truck system are:

- No system interruption as a result of the breakdown of one unit since the system is a batch system and not a continuous system like the belt conveyor system (Aykul *et al.*, 2007);
- High productivity of over 3,000 tpd for the truck system since fleet size can be adjusted to meet required demand (Mahieu, 2017);
- Ability to operate on gradients of up to 12° as compared to the rail system which can operate on gradients not exceeding 2° (Rupprecht, 2003);
- Highly flexible in travel routes since it is not fixed to a particular route as compared to rail and belt conveyor systems (Thomas *et al.*, 1987); and
- Minimal exposure to electrical hazards as compared to the belt conveyor and rail systems (Thomas *et al.*, 1987).

However, there are disadvantages associated with the truck system as well. These include:

- Higher levels of heat output which can be up to 2.6 times the heat output from a similar electric drive unit (de la Vergne, 2008);
- High level of pollution due to the emission of harmful gases as compared to the rail or belt conveyor systems (Dammers *et al.*, 2016);
- Higher unit operating cost by over 10% relative to the rail system (Dammers *et al.*, 2016) and over 20% relative to the belt conveyor system (Kluge *et al.*, 2017);
- Low energy efficiency of the diesel-powered truck of not more than 40% compared to the belt conveyor system whose energy efficiency can be as high as 95% (de la Vergne, 2008);
- A low payload-to-dead ratio of less than $1^{1}/_{2}$:1 compared to the belt conveyor system with a payload-to-dead ratio of about than 4:1;
- Lower payload per cycle as compared to the belt conveyor and the rail systems since payload per cycle is a determinant factor when considering the number of operational units that are required to meet a particular level of production for a batch system (Rupprecht, 2003);
- Higher noise levels of up to 119 dB(A) (Kluge *et al.*, 2017) which exceeds the noise levels of both the rail and belt conveyor systems whose noise levels are approximately 80 dB(A) (Ministry of Railways of India, 2015) and 60 dB(A) (Gladysiewicz, 2011), respectively;
- Inability to operate on steeper gradients exceeding 12° as compared the belt conveyor system which can operate on gradients of up to 22° (Rupprecht, 2003); and
- High capital cost when more units are required to meet a higher level of production (Rupprecht, 2003).

2.3.3 Belt conveyor system

A belt conveyor is basically an endless belt that is tensioned between two drums or pulleys over a set of idlers (Owusu-Mensah, 2010). One of the drums drives the system while the other one acts as a return drum. The drive system is made up of components which are responsible for driving, start-up and braking forces (Dunlop, 2014). The advantages of a belt conveyor system are:

- Lower heat output than trucks (Rupprecht, 2003);
- No environmental pollution as compared to diesel engine trucks whose diesel-powered engines emit harmful gases into the environment (Mahieu, 2017);
- A higher payload-to-dead ratio of about than 4:1 compared to the truck system with a payload-to-dead ratio of less than $1^{1}/_{2}$:1 (de la Vergne, 2008);
- High productivity of above to 5,000 tpd (de la Vergne, 2008);
- Lower unit operating cost which may be as low as one-tenth the unit cost of a haul truck for distances beyond 1 km (de la Vergne, 2008);
- Low noise levels with field tests indicating that emission levels of the system can be reduced to below 60 dB(A) at a distance of 2 m against a threshold of 90 dB(A) (Gladysiewicz, 2011);
- Ability to operate on steeper gradients of up to 22° as compared to trucks and rail systems which can operate on gradients of up to 12° and 2°, respectively (Rupprecht, 2003);
- Ease of automation with low labour requirements as the system is continuous unlike batch systems like the rail or truck systems (de la Vergne, 2008; Bloss *et al.*, 2011);
- Typically higher availability of up to 90% can be achieved (de la Vergne, 2008); and
- Higher energy efficiency of up to 95% since it is driven by an electric motor (de la Vergne, 2008).

On the other hand, the belt conveyor system has its disadvantages. These include:

- The risk of fire due the flammable rubber-based material that the belt is made of (Rupprecht, 2003);
- Lower flexibility than the truck system in that it cannot be easily transferred from one mining area to another when new mining areas are developed (Owusu-Mensah, 2010);
- A potential loss in production since a breakdown in one part of the system stops the entire system given that the system is continuous and any provision for a

backup becomes too costly as this requires a parallel system to be laid down (Dammers *et al.*, 2016);

- High initial capital cost required (Bloss *et al*., 2011); and
- More time is needed for the construction of a belt conveyor system as compared to the time required to run a truck once it arrives (Aykul *et al.*, 2007).

Given the different advantages and disadvantages of each transportation system, it is difficult to conclude on the optimal system. To assist in selecting the optimal transportation system, decision-making techniques must be applied.

2.4 Decision making in mine planning

Musingwini and Minnitt (2008) identified the comparison of different ore haulage systems as an area where decision making can be applied in the mining industry. Harris (2012) defined decision making as selection of an alternative that has the highest probability of success or effectiveness and best fits laid out goals. Nutt (1991) defined decision making as the selection of an alternative to be implemented. Every decision must be made in the light of criteria which reflect the preferences of the decision maker. Decision making is considered to be one of the major challenges to managers in an organisation. As a result, decision-making skills need to be continually developed since proper decision making can make a huge difference in the performance of a company.

Decision making is a branch of Operations Research that deals with decision problems in the presence of a single criterion or multiple criteria (Triantaphyllou *et al.*, 1998). A decision problem with a single criterion or objective results in a decision maker making a decision by choosing an alternative that has the best value of that objective or criterion. For example, if the objective is to minimise unit operating cost, the decision maker will choose an alternative that has the minimum cost. Single objective decision problems are solved using techniques such as the Decision Tree Analysis. However, most decision problems in mine planning involve multi-criteria objectives. Singla (2016) noted that several of these objectives may be conflicting in nature. For example, if the objective is to minimise both capital cost and unit operating cost for a decision problem with two alternatives being compared against each other, one alternative may have a lower unit operating cost but a higher capital cost. The other alternative may have a higher unit operating cost but a lower capital cost. It would, therefore, not be apparent to the decision-maker as to which alternative to choose from these two alternatives since the criteria are conflicting with each other.

The presence of several objectives which are partly or wholly conflicting leads to Multi-Criteria Decision Making (MCDM). MCDM methods are the focus of this research by virtue of the multi-criteria nature of mine planning decision-making problems. MCDM is divided into two main branches namely: Multi-Objective Decision Making (MODM); and Multi-Criteria Decision Analysis (MCDA). Zimmermann (1991) mentioned that MODM involves selecting an optimal alternative from a decision space that is continuous with an infinite number of alternatives. On the other hand, MCDA, also known as Multi-Attribute Decision Making (MADM), focuses on selecting an optimal alternative from a set of discrete alternatives that are pre-determined. The focus of this research is on MCDA since the number of transport alternatives that can be used at the mine are finite, pre-determined and discrete. In particular, the selection of an optimal transport system involves evaluating various alternatives against a given set of conflicting evaluation criteria.

2.5 Multi-Criteria Decision Analysis

Karande and Chakraborty (2013) highlighted that in the selection of material handling equipment, the decision-making process should utilise a MCDA approach. They mentioned objectives such as minimising cost or maximising productivity or flexibility as some of the objectives to be considered. Musingwini (2010) noted that MCDA techniques have been widely used in the mining industry especially in mine design and planning. Sitorus *et al.* (2019) mentioned that there are four decision problems that can be solved using MCDA techniques. These decision problems are:

- The choice problem in which the MCDA is used to choose the best or optimal alternative from a given set of alternatives. This is applicable to this research study;
- The sorting problem in which alternatives are grouped and ranked from the most preferred to the least preferred group. This normally precedes a choice decision or when more than one alternative is required;

- The ranking problem in which the alternatives are arranged in order of performance either partially or completely; and
- The description problem in which the main features of alternatives are described in order to determine the performance of all or some of them.

2.6 Major MCDA techniques applied in the mining industry

Musingwini and Minnitt (2008) identified four major MCDA methods which have been applied in the mining industry namely; Elimination and Choice Translating the Reality (ELECTRE), Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE), Multi-Attribute Utility Theory (MAUT), and the Analytic Hierarchy Process (AHP). ELECTRE and PROMETHEE are generally classified as outranking methods (Kaya *et al.*, 2019) while MAUT and AHP methods use pair-wise comparison of criteria to arrive at the required solution as illustrated in Figure 2.1.

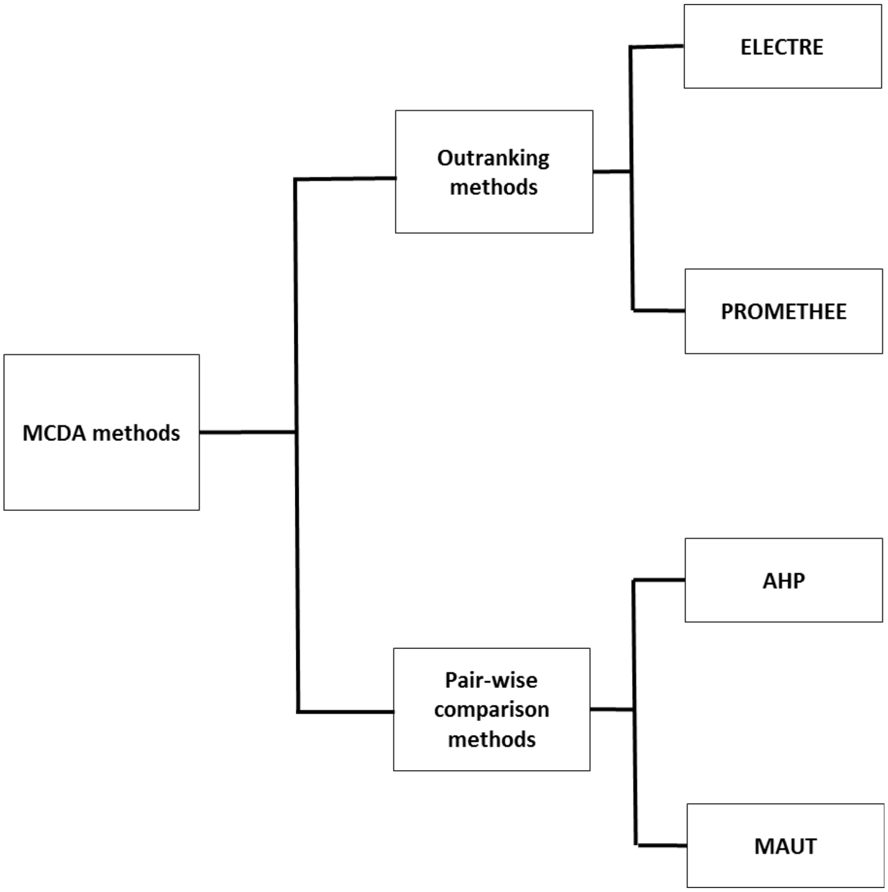


Figure 2.1: Major MCDA methods by category

(Source: Adapted from Mahase, 2017)

Outranking methods are defined by Mahase (2017) as those methods which compare the performance of two alternatives under one criterion. Zhou (1996) described the pair-wise comparison as a technique used in judgement quantification for the evaluation of important relationships among decision elements. In terms of ease of application, Cinelli *et al.* (2014) stated that AHP is the easiest to use among these four methods. This is followed by PROMETHEE and MAUT while ELECTRE is perceived to be relatively difficult.

2.6.1 ELECTRE method

ELECTRE is an outranking where, for example, given alternatives A and B, the aim is to assess whether alternative A outranks or is at least as good as alternative B (Cinelli *et* *al.*, 2014). It is considered to be the most difficult method to apply for decision makers among other MCDA techniques since outranking causes the strength and weaknesses of the alternatives to not be directly identified (Mahase, 2017). This is a major limitation of ELECTRE as opposed to the AHP which is easier to comprehend as explained by Owusu-Mensah and Musingwini (2011) (see Section 2.6.4). Dimitrijevic *et al.* (2014) used ELECTRE and PROMETHEE to select a method of land reclamation at Klenovnik open pit mine in the Kostolac coal basin, from ten alternatives evaluated against 11 criteria. The two methods produced different ratings for the 10 alternatives but agreed on the first rank alternative (alternative A_5) thereby not affecting the best option of reclamation for the Klenovnik open pit mine (Dimitrijevic *et al.,* 2014).

2.6.2 PROMETHEE method

PROMETHEE is a method that uses scaling on the basis of ratios to evaluate alternatives. It can be subdivided into PROMETHEE I (where a partial preorder ranking of alternatives is obtained) and PROMETHEE II (where a complete preorder ranking of alternatives is obtained) (Elevli and Demirci, 2004). It is simpler and easier to use for the decision maker when compared to ELECTRE and eliminates the complication of pair-wise comparisons associated with the ELECTRE method (Geldermann and Rentz, 2005). Elevli and Demirci (2004) used PROMETHEE I and PROMETHEE II to select the most suitable underground ore transport system for a chromite mine in Turkey from five possible ore transport systems and six evaluation criteria. However, Elevli and Demirci (2004) found that the techniques resulted in incomparable alternatives emanating from the weights of the alternatives. This implies that the decision maker should do further evaluation in order to make an informed decision (Macharis *et al.*, 2004). This resulted in Elevli and Demirci (2004) applying PROMETHEE II in order to obtain a complete ranking of the alternatives. Macharis *et al.* (2004) highlighted another key weakness of PROMETHEE which is its failure to provide formal guidelines for weighing, thereby assuming that the decision maker is able to weigh the criteria appropriately. They therefore suggested a new approach which replicates the AHP weighing approach in a PROMETHEE context thus suggesting the supremacy of the AHP over PROMETHEE.

2.6.3 MAUT method

MAUT is a performance aggregation method (Cinelli *et al.*, 2014). The method involves the concept of maximising utility (U) or satisfaction by maximising and minimising desirable and undesirable outcomes, respectively (Musingwini, 2009). Vieira (2005) used MAUT to choose the best mining method from four possible methods to mine ultra-deep tabular gold deposits in the Witwatersrand Basin. Four mining methods were compared on the basis of 49 attributes clustered into five decision criteria.

2.6.4 AHP method

The AHP method was developed by Saaty (1980) with an aim of evaluating criteria in relative terms using an absolute scale. It uses a theory of carrying out measurements through pair-wise comparisons with reliance on expert judgement using a nine-point scale. Saaty (2008) outlined the four major steps required to solve a MCDA problem using AHP as follows:

i. Problem definition and setting out the goal.
ii. Structuring the problem as shown in Figure 2.2, which shows the hierarchical tree structure for solving the problem using AHP. The tree structure makes it easy to comprehend the decision problem.

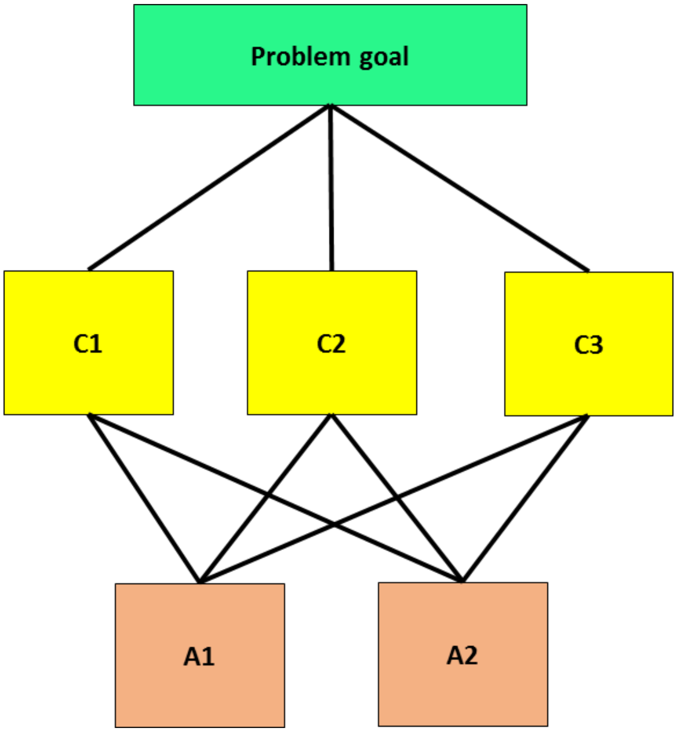


Figure 2.2: Hierarchical tree structure for solving a MCDA problem using AHP

(Source: Despodov *et al.*, 2011)

As illustrated in Figure 2.2, the hierarchical tree consists of the decision goal at the top, criteria C1, C2 and C3 (and where necessary sub-criteria in the middle) and alternatives A1 and A2 at the bottom.

iii. Construction of pair-wise matrices from the top level to the bottom level. Elements in a particular level of the hierarchy are compared to each other with respect to each element they are linked to in an immediate upper level. This is done following the hierarchy from the second level of criteria (C1, C2 and C3) to the last level of alternatives (A1, A2 and A3). Priorities obtained from comparisons are used to weigh the priorities in the level immediately below.

iv. The process of weighing and aggregating is continued until the final AHP scores are obtained, resulting in ranking of alternatives with respect to the goal.

Owusu-Mensah and Musingwini (2011) mentioned that the advantages of the AHP method is that it has the ability to:

- Detect inconsistency in judgment and the degree of inconsistency resulting in the reliability of the method and the ultimate results;
- Use basic matrix and vector algebra in its methodology for solving problems and can therefore be easily configured in Microsoft Excel® for computation; and
- Rank alternatives from the most preferred to the least preferred option when conflicting criteria or objectives are involved.

The AHP method is relatively easy to apply as highlighted by Cinelli *et al.* (2014) who indicated its ease of application when compared to other MCDA techniques. However, there are three major limitations associated with the AHP. The first limitation is that the method only works if the criteria weights matrix is a positive reciprocal matrix (Coyle, 2004). This is satisfied if criterion $\boldsymbol{C_i}$ is x times as important as criterion $\mathbf{C_j}$ and correspondingly criterion $\boldsymbol{C_j}$ is $1/x$ times as important as criterion $\mathbf{C_i}$. Secondly, when the scale for measuring the relative importance of criteria with respect to each other is changed, say from a scale of 1 to 9 to a scale of 1 to 29, the weight vector will also change. This might, in some cases, affect the final decision (Coyle, 2004). Lastly, the number of pairwise comparisons increases rapidly as the number of criteria to be compared increases following a power function, $\frac{n(n-1)}{2}$, where n is the number of criteria (Musingwini and Minnitt, 2008). For example, three criteria require only three pair-wise comparisons while nine criteria require 36 pair-wise comparisons.

The AHP method has found considerable application in the mining industry relative to the other MCDA techniques. Acaroglu et al. (2006) highlighted that the AHP technique has widespread use in mining and geology. Because of its wide application in the mining industry and the ease of its application using Microsoft Excel®, AHP has been selected in this study to select the optimal transport system to use at Trojan mine.

2.7 Mining industry applications of the AHP technique

Musingwini and Minnitt (2008) mentioned that AHP is the most preferred cost effective MCDA technique for solving multi-criteria mining engineering decision problems. It has been used in different mine design and planning problems that include mining method selection, mining equipment selection, mining support system selection, mining projects location selection and in mining transport system selection.

2.7.1 AHP application in mining method selection

Bitarafan and Ataei (2004) used an AHP based fuzzy multiple attribute decision-making method and fuzzy dominance method to select the optimal mining method for extracting the No. 3 Anomaly at the Gol-Gohar iron mine in Iran. Seven mining methods were evaluated against 15 criteria in the case study. Musingwini and Minnitt (2008) used AHP to rank the efficiency of four selected mining methods based on eight criteria for the narrow reef tabular platinum deposits of the Bushveld Complex. Karadogan *et al*. (2008) selected the most suitable underground mining method for the Ciftalan Lignite mine in Turkey using AHP based fuzzy Multi-Attribute Decision Analysis methodology.

2.7.2 AHP application in equipment selection

Dessurealt and Scoble (2000) used AHP to decide on whether to purchase new drill-monitoring technology, maintain status quo, or retain drillers and surveyors to work more safely and productively on the basis of six criteria. Bascetin (2003) used AHP to select optimal loading and hauling equipment at an open pit coal mine in Western Turkey from four alternatives based on 21 criteria. Acaroglu *et al.* (2006) used AHP to select the most suitable boom type tunneling roadheader machine for the excavation of gallaries out of three alternatives based on 14 criteria. Aghajani-Bazzazi *et al.* (2009) used AHP and Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) methods to select an optimal equipment suite for the removal of overburden in surface iron ore and coal mines from five alternative equipment suites based on seven criteria. Adebimpe *et al.* (2013) used a combination of AHP and Technique for Order Preferences by Similarity to an Ideal Solution (TOPSIS) to select mine equipment for Ajabanoko Iron ore deposit in Nigeria. Javad and Mohammad (2014) used AHP to select the best primary crusher for Golegohar Iron mine in Iran from a set of eight alternatives based on six criteria. Yavuz (2015) used AHP and Yager’s method to select equipment for an open pit mine in Turkey from four alternatives based on four main criteria and 21 sub-criteria.

2.7.3 AHP application in underground support system selection

Kazakidis *et al.* (2004) used AHP to select the best rock bolt support system from 14 alternatives using 10 criteria. They also used AHP to select the best option to improve tunneling advance rates from five options based on seven criteria and to select the mine with the highest production performance risk from eight mines in a mining company based on five criteria. Also, Kluge and Malan (2011) used AHP to compare the use of backfill support and a conventional support system on the basis of 10 evaluation criteria for a platinum mining project.

2.7.4 AHP application in transport system selection

Despodov *et al.* (2011) demonstrated the application of the AHP method in the selection of a transportation system using a software known as Expert Choice. Owusu-Mensah and Musingwini (2011) used AHP to select the optimal transport system for Obuasi mine in Ghana from four alternatives based on three main criteria and 15 sub-criteria.

2.7.5 Other AHP application in mining

Ataei (2005) used AHP to select the best location of an alumina-cement plant in Iran from five possible locations on the basis of five criteria. Yavuz (2008) used AHP and compared it with the Fuzzy Multiple Attribute Decision Making (FMADM) method to select the best site for the location of a natural stone processing plant from four alternatives based on four main criteria and 15 sub-criteria. Hamilton (2018) used AHP to rank three brownfield mining projects in Africa belonging to AngloGold Ashanti on the basis of four main criteria and 12 sub-criteria. Musingwini (2009) used AHP to determine the optimum level and raise spacing in the Bushveld Complex platinum reef resulting in the adoption of a solution with short cross-cut mining layouts from a total of 15 different layout alternatives compared against 12 techno-economic criteria.

2.8 The AHP model

According to Musingwini and Minnitt (2008), the mathematical procedure of the AHP model is structured into the following five steps:

1. Criteria pair-wise comparisons involving comparing one criterion against another by assigning weights. For a problem with *n* criteria, an n x n criteria pair-wise comparison square matrix is formed and denoted as shown by Equation 1:

$$\mathbf{W} = (w_{ij}) \qquad \textbf{Equation 1}$$

The weights are based on a scale that ranges from 1 to 9 as shown in Table 2.1.

Table 2.1: The fundamental scale of absolute numbers

(Source: Saaty, 2008)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

As mentioned by Musingwini (2009), the scale is a measure of a criterion's relative importance over another. The relative weight of criterion C_i over C_j is denoted by w_{ij} whereas that of C_j over C_i is denoted by w_{ji}. Musingwini (2009) mentioned that the axiom of reciprocity that the AHP observes gives rise to Equation 2:

$$w_{ij} = \frac{1}{w_{ji}} \; for\ all\ i \neq j, \text{ and } w_{ij} = 1 \; for\ all\ i = j \qquad \textbf{Equation 2}$$

The square matrix, **W**, is called a reciprocal matrix since the relative weight of one criterion over the other is equal to the inverse of the second over the first. As an example if criterion C_1 is twice as important as criterion C_2, it follows logically that criterion C_2 is half as important as criterion C_1. In addition, if criterion C_1 is twice as important as criterion **C_2**, and criterion ***C_2*** is five times as important as criterion ***C_3***, then by the axiom of transitivity, criterion ***C_1*** is ten times as important as criterion ***C_3*** if judgements are to be consistent. The number of pair-wise comparisons for a matrix of order n are calculated using Equation 3:

$$\text{Number of pair-wise comparisons} = \frac{n(n-1)}{2}$$ **Equation 3**

According to Equation 3, a six criteria problem requires 15 comparisons while a nine criteria problem requires 36 comparisons. Musingwini and Minnit (2008) mentioned that AHP produces more reliable results when the number of criteria does not exceed nine due to the general limitations of human beings on abstract thinking.

2. Normalisation of the criteria pair-wise comparison matrix, **W**, to create a dimensionless matrix of ratios which are comparable. After the matrix is normalised, an eigenvector, ***w***, is calculated. The elements of the eigenvector are the arithmetic or geometric mean of the corresponding row elements of the normalised matrix. The eigenvector is a criteria weights vector as it shows the relative weight of each criterion and the ranking of the criteria.
3. Determining the Consistency Index, CI, using the following three steps:
    i. Calculating the weight sums vector, ***w_s***, using Equation 4:

    $$w_s = \mathrm{W}w = \{\text{cons.}\}.w$$

    $$\{\text{cons.}\} = w_s \,.\, \frac{1}{w}$$ **Equation 4**

    Where {cons.} is the consistency vector

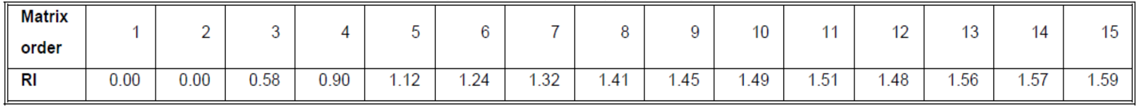
    ii. Calculating the average of the elements of the consistency vector to give the eigenvalue, $\lambda_{\max}$.

    iii. Finally, the Consistency Index, CI, is calculated using Equation 5:

    $$CI = \frac{\lambda_{\max} - n}{n-1}$$ **Equation 5**
4. Determining the Consistency Ratio, CR, by first identifying the Random Index, *RI*. The RI was determined by Saaty (1980) for matrices of order between 1 and 15 and these are shown in Table 2.2.

Table 2.2: Random Index (RI) for n-ordered matrix

(Source: Saaty, 1980)



Matrix order	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

The Consistency Ratio, CR, is calculated using Equation 6:

$$CR = \frac{CI}{RI}$$ **Equation 6**

CR is a measure of how consistent judgments are relative to a large samples of purely random judgments. If CR is less than or equal to 0.1, then the comparisons are considered to be inconsistent but reliable. If CR is greater than 0.1, then the judgements are regarded as too inconsistent to be relied upon such that the assignments of pair-wise comparisons would require to be done again. A CR of 1 suggest that the judgements are completely too random to be trusted whereas a CR of 0 means the judgements are perfectly consistent. From Equation 6, a CR of 0 is obtained if $\lambda_{max} = n$.

5. The efficiencies of all alternatives on each criterion, E_{ij}, are determined and normalised in order to eliminate the effect of different units of measurement (Musingwini and Minnit, 2008). If there are **m** alternatives on a particular criterion, the normalised E_{ij} outcomes denoted by E^{N}_{ij} with respect to that criterion are calculated using Equation 7:

$$E^{N}{}_{ij} = \frac{E_{ij}}{\sum_{i=1}^{m} E_{ij}}$$ **Equation 7**

The matrix of normalised performance values is then multiplied by the eigenvector to obtain the final AHP priority score. The AHP priority scores are then ranked according to preference, using the logic that the higher the AHP score of an alternative, the more preferable the alternative. This implies that the alternative attaining the highest score is the most preferred.

2.9 Chapter summary

Mine design and planning is a key process for a mining operation. The process consists of sub-processes including the design of material transportation systems. Material transportation is categorised into vertical and horizontal transportation. The horizontal transportation of material underground, in particular, can be done through track bound, trackless or belt conveyor systems. Material handling systems have been identified as one of the areas where decision making can be applied in the mining industry.

Decision problems can be single objective or multi-objective. Single objective problems are decision problems that result in a decision maker making a decision by choosing an alternative that has the best value of that objective. On the other hand, multi-criteria objective problems are characterised by the presence of several objectives which are partly or wholly conflicting. However, most decision problems in mine design and planning involve multi-criteria objectives resulting in the need to solve them using MCDM techniques. There are many MCDM techniques including the AHP. AHP was selected for this study to select an optimal transportation system due to its relative simplicity and ability to detect for inconsistency as well as estimate the degree of inconsistency in human judgements. It uses basic matrix and vector algebra in its methodology which can be readily configured in Microsoft Excel®. Eventually, alternatives can be ranked from the most preferred to the least preferred option when conflicting criteria or objectives have to be satisfied. The use of the AHP technique to develop a model that was used to select the optimal transport system is described in the next chapter.

3 DATA COLLECTION AND THE ANALYTIC HIERARCHY PROCESS MODEL DESCRIPTION

3.1 Chapter overview

This chapter describes the methodology that was used in this study to select the experts who participated to complete to the AHP questionnaires and how the nine evaluation criteria were chosen. The chapter also describes the AHP model that was used in this study and how the data was analysed in order to select the optimal transportation system.

3.2 Selection of experts and evaluation criteria

In order to carry out the research using data from Trojan mine, a permission letter was granted by the mine. The permission letter is shown in Appendix 8.1. Five experts who work at the mine were chosen based on their knowledge and experience in underground transportation systems. They were selected to act as participants to complete a questionnaire. Since the research involved human participants who were required to complete questionnaires to select the evaluation criteria and to do the pair-wise comparisons, a research ethics approval was obtained from the University of the Witwatersrand research office before conducting the research. The ethics clearance certificate is shown in Appendix 8.2. The five experts that were chosen are:

- One mine planning engineer from the Technical Services Department with 15 years mining experience in mining and planning collectively;
- One chief surveyor with at least 14 years of experience in survey and planning;
- One mechanical engineer with at least five years mining related engineering experience;
- One electrical engineer specialising in fixed plant with at least 10 years mining related engineering experience; and
- One ventilation officer from the Technical Services Department with 14 years mining experience in mining and planning collectively.

The team of experts was deemed to have sufficient experience and knowledge of underground transportation systems and therefore qualified to carry out the pair-wise comparison judgements as required by the questionnaire. Their pair-wise comparison views and judgements were thus assumed to represent the views and judgements of Trojan mine. A Participant Information Sheet was generated and presented to the five experts as shown in Appendix 8.3. The experts agreed to participate in the research by signing consent forms. The five consent forms are shown in Appendix 8.4. In order to select the relevant evaluation criteria for the AHP model, a questionnaire was designed and presented to the five experts individually. The questionnaire had a total of 24 criteria under three main categories namely: economic, environmental and technical, extracted from a list of possible criteria proposed by Samanta *et al.* (2002). The sample of the questionnaire is shown in Appendix 8.5.

The experts were required to rank these criteria, category by category, through applying a weight against each criterion from 0 to 10. A weight of “0” meant that the criterion was considered not important at all while a weight of “10” meant it was very important for consideration in selecting a transport system. An option was also included for the experts to include those criteria which had been left out but which they considered important for consideration, as well as to apply weights to such. The average scores were considered and the top three criteria under each category were used in the AHP model to make a total on nine evaluation criteria. The number of criteria was set to nine in line with the limitations of human judgements when it comes to abstract thinking in solving a MCDA problem as explained in Section 2.8. Appendix 8.6 shows the five questionnaires completed by the five experts to select the evaluation criteria. The scores were consolidated and the mean scores were calculated. The consolidated scores are shown in Appendix 8.7.

Table 3.1 shows the top three evaluation criteria for each category that were chosen by the experts and ranked in accordance with their mean scores. Table 3.1 was developed from data in Appendix 8.7.

Table 3.1: Evaluation criteria and their respective scores and rankings

Category	Criteria	Mean score	Ranking
Economic	Capital cost	9.4	1
	Unit operating cost	8.4	2
	Unit energy cost	7.6	3
Environmental	Emissions	7.2	1
	Noise	6.4	2
	Dust	6.4	2
Technical	Safety	8.8	1
	Availability	8.8	1
	Productivity	7.6	2

As shown in Table 3.1, a total of nine criteria were selected for application in the AHP model. The choice of an equal number of criteria under each category was done to ensure that there is equal contribution by the main categories in order to avoid bias as suggested by Hamilton (2018). The AHP problem was structured into a hierarchal tree structure as shown in Figure 3.1.

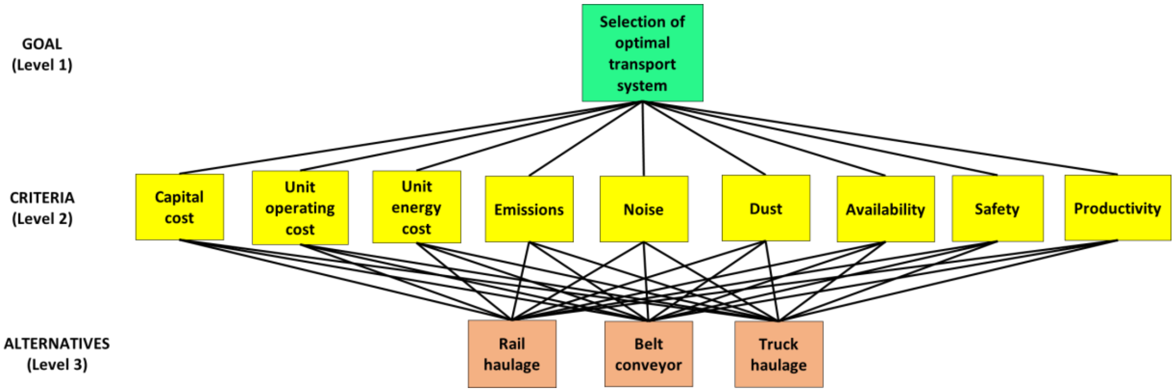


Figure 3.1: AHP Hierarchy for Trojan mine's horizontal transportation system

As illustrated in Figure 3.1, the hierarchical tree structure consists of the decision goal at the top namely "Selection of optimal transportation system" and this is located on level 1. This is followed by the nine evaluation criteria on level 2 namely capital cost, unit operating cost, unit energy cost, gas emissions, noise, dust, availability, safety and productivity. The three alternatives namely rail haulage, belt conveyor haulage and truck haulage are located at the bottom of the structure representing level 3. The criteria were mapped into three broad categories of economic, environmental and technical as illustrated in Figure 3.2.

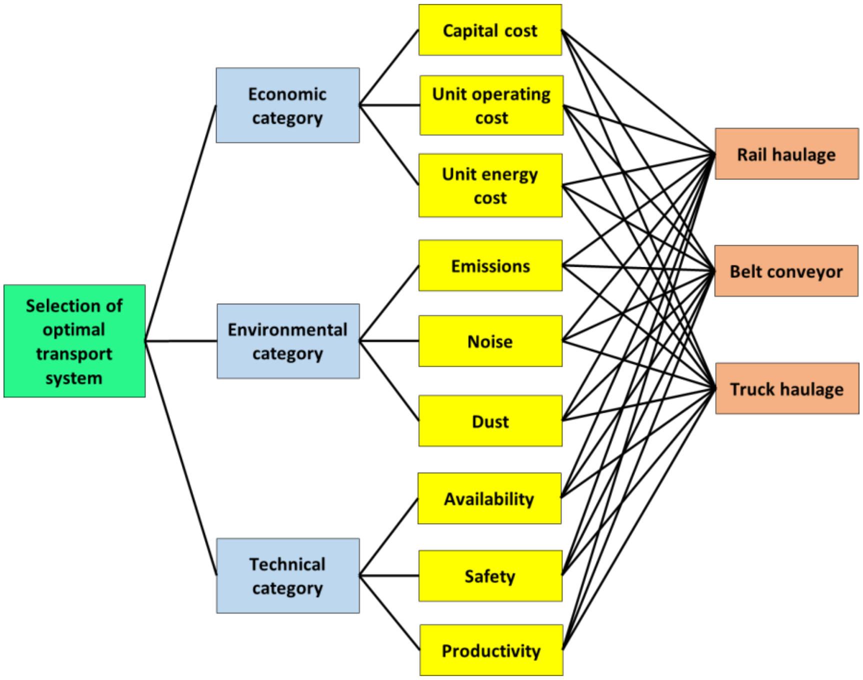


Figure 3.2: Relationship between goal, main categories, criteria and alternatives

It can be seen from Figure 3.2 that the importance of each main category can be determined once the weights of the criteria leading to it have been determined. For example, the total weight of the availability, safety and productivity criteria will amount to the weight of the technical category.

3.3 AHP model description

The AHP model was developed in Microsoft Excel®. The AHP steps that were used in the AHP model study are described in following five steps:

i. The judgements from the individual experts' criteria pair-wise comparisons with respect to the goal of selecting an optimal transportation system through relative scoring as provided in the questionnaire were entered into a 9 x 9 matrix. The five individual matrices from the five experts were normalised and the Consistency Index, CI, for each matrix was computed using Equation 5 (Section 2.8). The Consistency Ratio, CR, for each of the matrices was determined using Equation 6 (Section 2.8). The CR values were interpreted as explained in Section 2.8.

ii. The five individual pair-wise comparison matrices were then aggregated into a single composite matrix by taking the geometric means of all corresponding cell entries across all the individual experts' matrices.

iii. The aggregated pair-wise comparison matrix was then normalised by first computing the sum of each column of the aggregated pair-wise comparison matrix and dividing each corresponding entry by the column sum. The average of each row in the normalised matrix gives the aggregated weights for the criteria or eigenvector, $\boldsymbol{w}$. Each criterion weight is an indication of the relative importance of each criterion. The weight sums vector, $\boldsymbol{w_s}$, and the consistency vector, {cons.}, were computed using Equation 4 as discussed in Section 2.8. The average of the elements of the consistency vector gives the eigenvalue, λ_{max}.

iv. The Consistency Index, CI, for the aggregated normalised matrix was computed using Equation 5 (Section 2.8). The value of n in Equation 5 is equal to the number of criteria under consideration while the value of the Random Index, RI, is determined from values for matrices of order between 1 and 15 which were determined by Saaty (1980) as shown in Table 2.2. The Consistency Ratio, CR, for the aggregated normalised matrix was computed using Equation 6 (Section 2.8). If CR was less than or equal to 0.1 and not equal to zero, then the pair-wise comparisons were considered to be inconsistent but reliable.

v. The efficiency scores for the three alternatives with respect to each evaluation criterion relating to transport selection were determined. They were normalised using Equation 7 (Section 2.8) since the different criteria have different units of measurement. The normalised efficiency scores were then normalised with the criteria weights to obtain the overall AHP priority score. The AHP priority scores were then ranked according to preference, using the logic that the higher the AHP score of an alternative, the more preferable the alternative. This implies that the alternative attaining the highest score is the most preferred.

3.4 Chapter summary

The team of experts for pair-wise comparison was chosen based on their past experience as their opinions were deemed to represent the opinions of the company with respect to optimum transport system selection. Through this methodology, information was gathered relating to alternatives in question and the associated criteria. The expected efficiencies of the three transport alternatives which were aggregated with the experts' criteria weights are described in the next chapter.

4 ALTERNATIVE TRANSPORT SYSTEMS DESIGN AND EFFICIENCIES

4.1 Chapter overview

This chapter discusses the layout design and expected efficiencies of the three alternative transport systems namely; rail, belt conveyor and truck transport systems. The layout formed the framework of all the three systems. The expected efficiencies under consideration are in relation to the nine criteria that were selected by a team of experts under the three main categories of criteria namely: economic; environmental; and technical as discussed in Chapter 3.

4.2 Typical main haulage level layout at Trojan mine and capacity models

The typical layout of the main haulage is similar for all main tramming levels at Trojan mine. Figure 4.1 shows the typical transport route for the three transport systems displayed as a continuous green line.

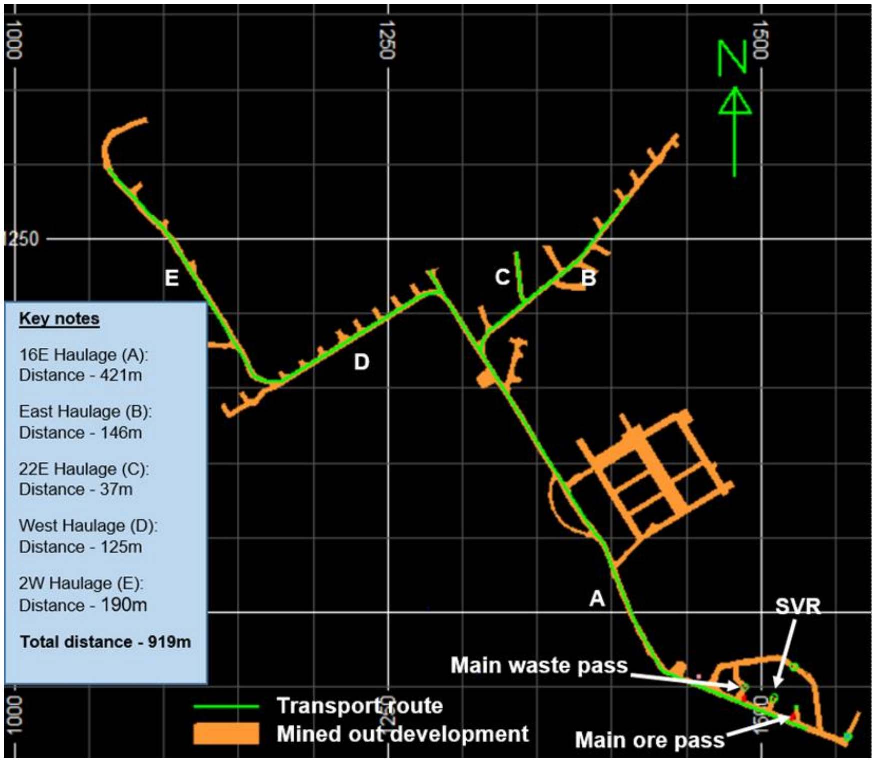


Figure 4.1: The generic transport system layout and associated tramming distances

As shown in Figure 4.1, the three transport systems are designed to run along the entire path that connects the main level haulage chutes to the main ore and waste passes. The main haulage level comprises of five haulage segments namely: 16E haulage (A); East haulage (B); 22E haulage (C); West haulage (D); and 2W haulage (E). The total distance covered by these haulages is 919 m. Table 4.1 is a summary of the haulages by name, location and purpose with regards to the chutes they are connected to.

Table 4.1: Summary of the haulage configuration in a typical main haulage level

Haulage Name	Location	Purpose
16E haulage (A)	• Runs from the dust raise around the shaft area then northwards at an azimuth of 330° along the 16E easting	• Connects all the other haulage branches to the shaft main tips • Transfers material from 18E chute in the footwall of MOB
East haulage (B)	• Branches off 16E haulage towards the east	• Transfers material from 24E and 33E chutes on the footwall of the MOB • Serves as access to 22E haulage
22E haulage (C)	• Branches off northward from the east haulage along the 22E easting	• Transfers material from 22E chute on the footwall of the MOB
West haulage (D)	• Branches off 16E haulage towards the west	• Transfers material from 10E and 3E chutes on the footwall of the MOB western extension • Serves as access to 2W haulage
2W haulage (E)	• Branches off northward from west haulage along the 2W easting	• Transfers material from 3S and 8S chutes on the footwall of the HWOB

Each transport system is designed to handle at least 187.5 tph which is equivalent to at least 90,000 tpm in line with the projected LOM extraction rate as mentioned in Section 1.5. The design elements of each of the transport systems are discussed in the next subsections.

4.2.1 Rail transport system layout design and capacity

The rail will be floor mounted on concrete sleepers and secured by corch screws to provide a 24” gauge track on a grade of -1:200 towards the shaft to allow for good water drainage. At any given point, two consecutive main levels are required to be operational such that the required rolling stock will be distributed equally among the two operational main levels. In this study, 37/0L and 39/0L haulages have been considered as they are the next consecutive main haulage levels to replace 35/0L haulage. Table 4.2 shows the rail system rolling stock requirements based on the LOM schedule and processing plant capacity design.

Table 4.2: Rail transport system's plant capacity and rolling stock requirements

Parameter	**Value**
Required monthly throughput	90,000 tpm (guided by LOM schedule and plant design capacity)
Number of operational days per month	30 days/month (6/3 shift cycle basis)
Required daily throughput	Tonnes per day = 90,000 tpm/(30 days/month) = 3,000 tpd
Effective working hours per day	16 hpd
Required hourly productivity	Required hourly productivity = 3,000 tpd/16 hpd = 187.5 tph
Granby car capacity	5 t/granby car
Granby cars per cycle	10 granby cars/cycle
Locomotive train cycles per hour	2 cycles/locomotive/h
Locomotive train hourly productivity	Locomotive train hourly productivity = 5 t/granby car x 10 granby cars/cycle x 2 cycles/loco/h = 100 t/locomotive/h
Number of locomotives required	Number of locomotives required = 187.5 tph/(100 t/ locomotive /h) = 2 locomotives (one per main level)
Number of spare locomotives required	2 spare locomotives (one per main level) required
Number of granby cars required	Number of granby cars required = 10 granby cars/locomotive x 2 locomotives = 20 running granby cars
Number of spare granby cars required	**6 spare granby cars required**

According to Table 4.2, the required rolling stock comprises of four by 10 t Goodman electric locomotives (two running electric locomotives and two spare ones) and 26 by 5 t granby cars (20 running granby cars and six spare ones) distributed equally over two main levels. Each locomotive is capable of pulling ten by 5 t granby cars thereby enabling the two operational locomotives to allow the rail transport system a production capacity of 96,000 tpm which is able to meet the minimum required extraction capacity based on the LOM schedule and the processing plant capacity of 90,000 tpm. The derived quantities of rolling stock units were essential in the computation of the rail system's initial capital outlay as an efficiency measure in Section 4.3.

4.2.2 Belt conveyor transport system layout and belt sizing

Appendix 8.8 shows the belt conveyor system sizing and costing for the five haulage flights, A to E (Figure 4.1). According to Appendix 8.8, the required flights have a minimum motor rating of 30 hp for 22E Haulage with a required belt length of 97 m and a maximum motor rating of 100 hp for 16E Haulage with a required belt length of 481 m. The overall system's production capacity will be 1,072 tph and will be enough to meet the minimum required extraction capacity of 187.5 tph. The belt conveyor system will be installed over two main consecutive haulages (37/0L and 39/0L haulages) since a particular lift is designed to be replaced gradually by the next consecutive lower lift during extraction, hence the need to equip two main levels for them to run concurrently. As a result, a total of 10 flights have been considered and the derived sizes and quantities of components of the 10 flights were essential in the computation of the belt conveyor system's initial capital outlay as an efficiency measure.

4.2.3 Truck transport system layout design and capacity

The truck haulage system is designed to run along the entire path that connects the main level haulage chutes to the main passes. The truck system route is similar to that of both the rail and belt conveyor transport systems (Figure 4.1). The trucks will run over 37/0L and 39/0L haulages just like in the other two transport systems. Figure 4.2 shows the preferred truck model, a Sandvik TH320 underground truck from Sandvik Mining and Construction.

Figure 4.2: The Sandvik TH320 underground truck

(Source: Sandvik Mining and Rock Technology, 2019)

The Sandvik TH320 shown in Figure 4.2 is a narrow 20 metric tonne truck designed for hard rock mines and fitting in a 3 m by 3 m tunnel. It has a maximum forward speed of 27.8 km/h and is well adapted to long spiral ramps with gradients of up to 1:5 (Sandvik Mining and Rock Technology, 2019). The Sandvik TH320 truck in particular was chosen among other brands since it can fit well in the 3.5 m by 3.5 m tunnels at Trojan mine since it has been used before at the mine. Table 4.3 shows the truck system requirements based on the LOM schedule and processing plant capacity design.

Table 4.3: Truck transport system requirements and associated capacity

Parameter	**Value**
Required monthly throughput	90,000 tpm (guided by LOM schedule and plant design capacity)
Number of operational days per month	30 days/month (6/3 shift cycle basis)
Required daily throughput	Tonnes per day = 90,000 tpm/(30 days/month) = 3,000 tpd
Effective working hours per day	16 hpd
Required hourly productivity	Required hourly productivity = 3,000 tpd/16 hpd = 187.5 tph
Truck cycle time	20 minutes/load
Truck cycles per hour	Truck cycles per hour = 60 minutes/(20 minutes/load) = 3 loads/h
Truck payload capacity	20 t/load/truck
Truck hourly productivity	Truck hourly productivity = 20 t/load/truck x 3 loads/h = 60 t/h/dump truck
Number of trucks required	Required trucks = 187.5 tph/(60 t/h/truck) = 3.125 dump trucks = 3 dump trucks
Number of spare trucks required	= 1
Total number of trucks required	Total trucks required = (3+1) trucks = **4 trucks**

According to Table 4.3, the fourth truck will be underutilised since three trucks yielding 180 tph can almost satisfy the required productivity of 187.5 tph. Given that an allowance of 10% can be made on the truck payload, three trucks would suffice. Therefore, the fourth truck would be required to be procured as spare to create flexibility in the event of planned maintenance or breakdown among the three operational trucks. The three operational trucks give the truck haulage system a capacity of 198 tph which is above the 187.5 tph threshold when a 10% allowance is considered on the truck payload. The required truck complement required to meet the minimum required extraction capacity based on the LOM schedule and the processing plant capacity of 90,000 tpm is therefore four trucks (three running and one spare). The derived complement of trucks was used in the computation of the truck system's initial capital cost.

4.3 Efficiencies of the transport alternatives

The next subsections focus on the expected efficiencies of the alternatives with respect to each of the nine criteria. These efficiencies were aggregated and used together with the criteria pair-wise comparison judgements in the AHP model to rank the alternatives as discussed in Chapter 5.

4.3.1 Capital costs of the transport alternatives

The zero base approach was used to determine the capital cost of each transport system. This approach involves:

- Obtaining relevant quotations for items for each transport system from equipment suppliers. For this study, quotations were sourced from New Enterprise Trading (2019a), New Enterprise Trading (2019b) and Sandvik Mining and Construction (2019);
- Entering the items’ quotations into a costing template; and
- Calculating the capital cost requirement for each system in order to get the expected efficiencies for use in the AHP model.

Figure 4.3 shows the capital costs of the rail, belt conveyor and truck transport systems. Figure 4.3 was developed from data in Appendix 8.8, Appendix 8.9 and Appendix 8.10 which shows the capital cost estimated for the belt conveyor, rail and truck transport systems, respectively.

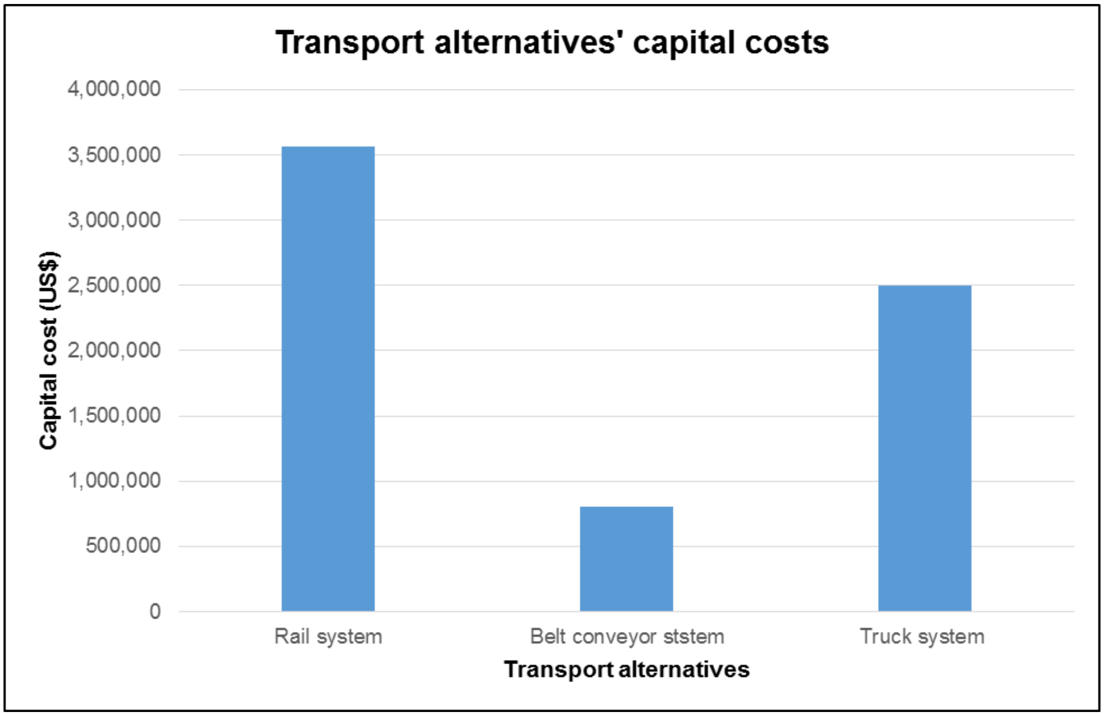


Figure 4.3: Capital costs of the transport alternatives

It can be seen from Figure 4.3 that the capital cost of installing the rail system is the highest at US$3,563,690. This is followed by the truck system at US$2,497,675 and the lowest is the belt conveyor system at US$802,313. If the decision was based on minimising capital cost only, the belt conveyor system would be the optimum system.

4.3.2 Unit operating costs of the transport alternatives

Figure 4.4 shows the unit operating costs for the three transport alternatives. Figure 4.4 was developed from data in Appendix 8.11 which shows the unit operating and energy costs for the rail, belt conveyor and truck transport systems. The data was obtained from the actual performances of the alternatives at Trojan for the financial year 2018 to 2019.

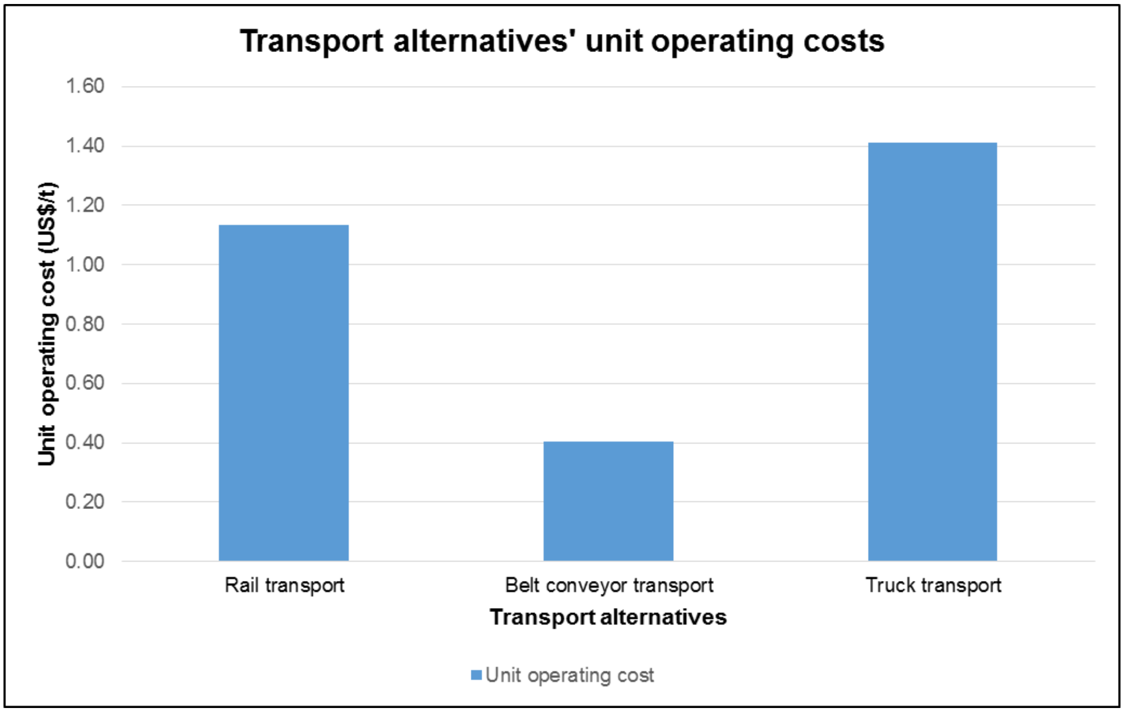


Figure 4.4: Unit operating costs of the transport alternatives

Figure 4.4 shows that the truck system has the highest unit operating cost of US$1.41/t followed by the rail and belt conveyor transport systems at US$1.13/t and US$0.40/t respectively. If the decision was based on minimising unit operating cost only, the belt conveyor system would be the optimum system.

4.3.3 Unit energy costs of the transport alternatives

Figure 4.5 shows the unit energy costs for the three transport alternatives. Figure 4.5 was developed from data in Appendix 8.11 which shows the unit operating and energy costs for the rail, belt conveyor and truck transport systems.

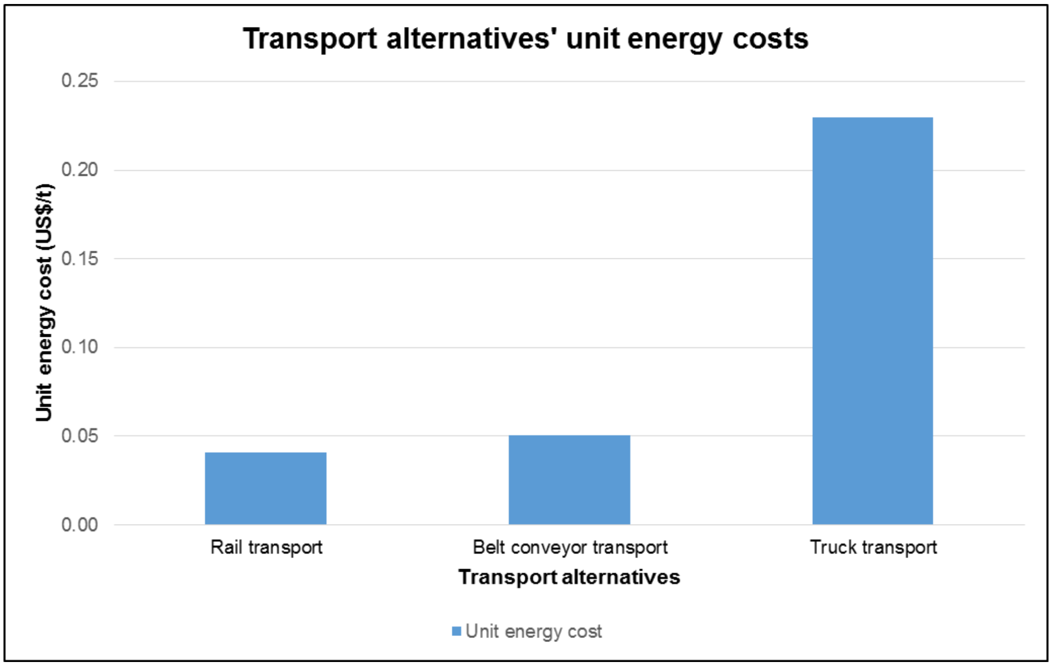


Figure 4.5: Unit energy costs of the transport alternatives

Figure 4.5 shows that the truck system has the highest unit energy cost of US$0.23/t followed by the belt conveyor and rail transport systems at US$0.05/t and US$0.04/t, respectively. If the decision was based on minimising unit energy cost only, the rail transport system would be the optimum system.

4.3.4 Relative noise levels of the transport alternatives

Table 4.4 shows the relative environmental efficiencies for the three transport alternatives. Table 4.4 is an extract of the last column of Appendix 8.12 for the rail, belt conveyor and truck transport systems. Figure 4.6 shows the relative performance of each of the three transport alternatives in terms of noise levels.

Table 4.4: Relative alternatives efficiencies in terms of the environmental criteria

Criterion	**Noise (relative)**	**Dust (relative)**	**Emissions (relative)**
Objective Transport system	Minimise	Minimise	Minimise
Rail transport	0.93	0.05	0.00
Belt conveyor transport	0.77	0.80	0.00
Truck transport	1.09	2.00	0.74

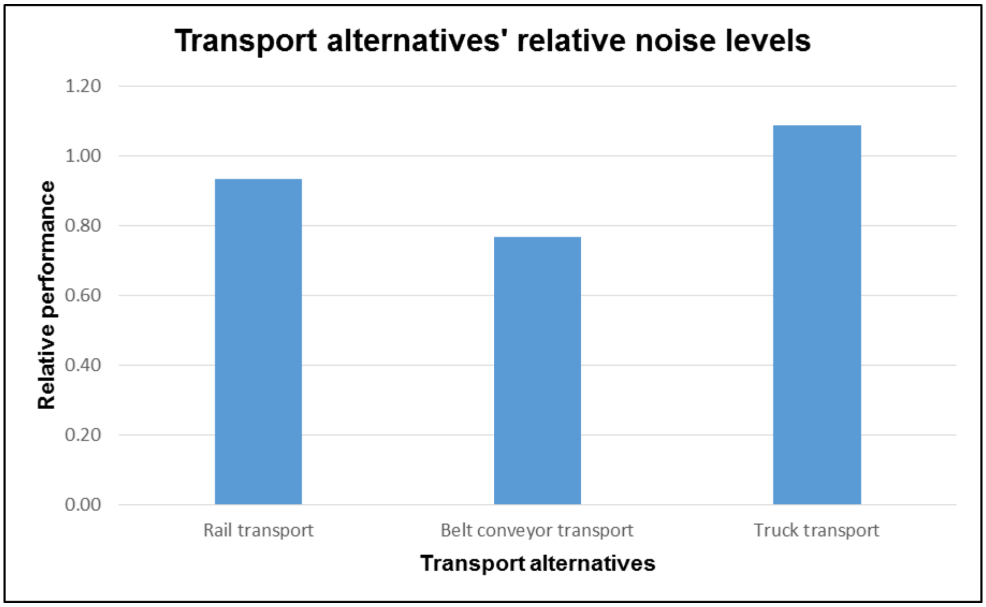


Figure 4.6: Relative noise levels of the transport alternatives

As shown in Figure 4.6, the belt conveyor system emits the least noise into the environment, followed by the rail and the truck transport systems, respectively. If the decision was based on minimising noise levels only, then the belt conveyor system would be the optimum system.

4.3.5 Relative dust levels of the transport alternatives

Figure 4.7 shows the relative performance of each of the three transport alternatives in terms of dust levels.

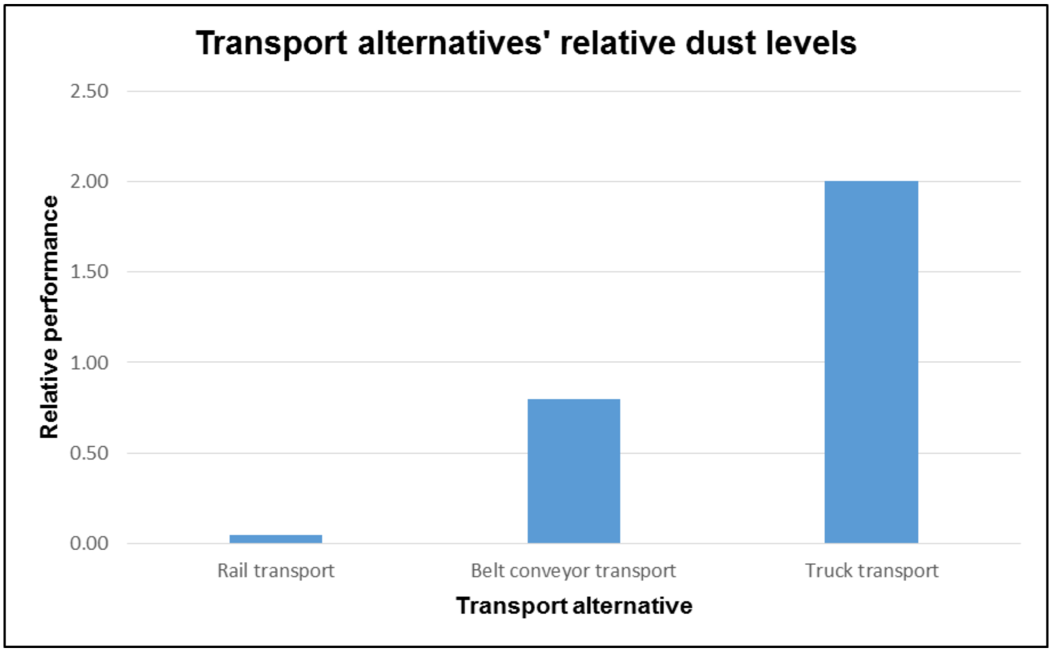


Figure 4.7: Relative dust levels of the transport alternatives

As shown in Figure 4.7, the rail system produces the least dust into the environment, followed by the belt conveyor and the truck transport systems, respectively. If the decision was based on minimising dust levels only, then the rail system would be the optimum system.

4.3.6 Relative gas emissions levels of the transport alternatives

Figure 4.8 shows the relative performance of each alternative in terms of gas emissions levels.

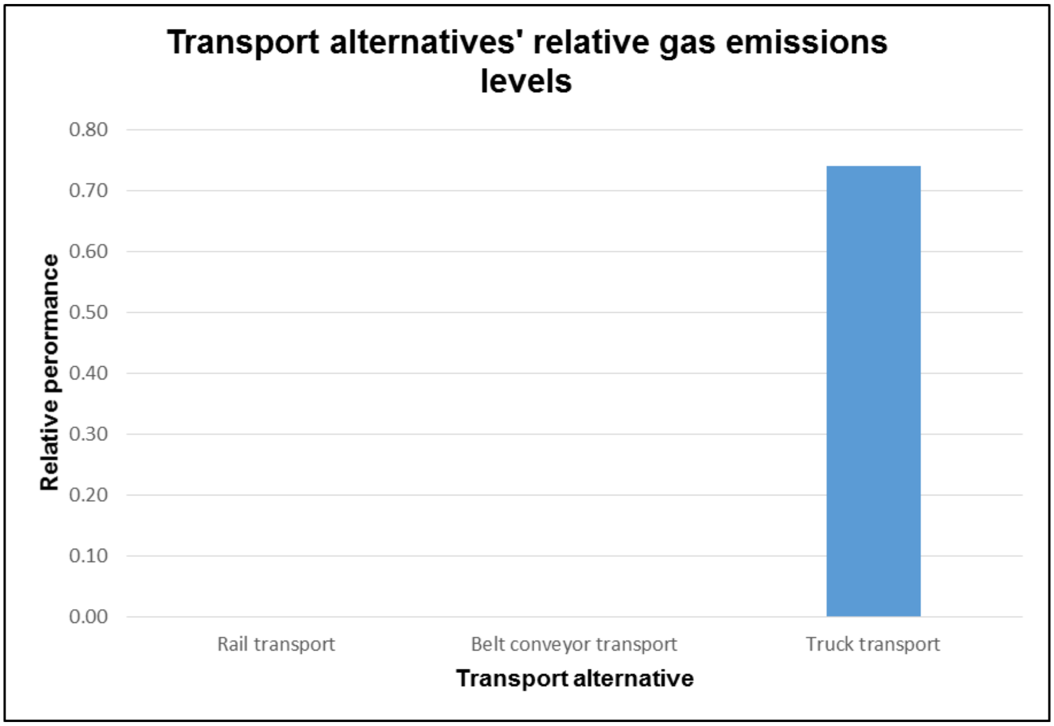


Figure 4.8: Relative gas emissions levels of the transport alternatives

As shown in Figure 4.8, the rail and the belt conveyor systems do not produce gas emissions into the environment while the truck transport system does. If the decision was based on minimising gas emissions only, then both the rail and the belt conveyor systems would be the optimum systems.

4.3.7 Availabilities of the transport alternatives

The three criteria that were selected for technical consideration were availability, safety and productivity. The weighted scores for these criteria for the three transport alternatives are shown in Table 4.5 developed from data in Appendix 8.13 and Appendix 8.14.

Table 4.5: Alternatives efficiencies relative to technical criteria

Criterion	Availability (%)	Safety (rating)	Productivity (tpm)
Objective Transport system	Maximise	Maximise	Maximise
Rail transport	94	57%	90,000
Belt conveyor transport	94	54%	90,000
Truck transport	78	38%	90,000

The availabilities of the systems were extracted from Appendix 8.14 and were budget projections for the financial year 2019 to 2020 budget. These are shown in Figure 4.9.

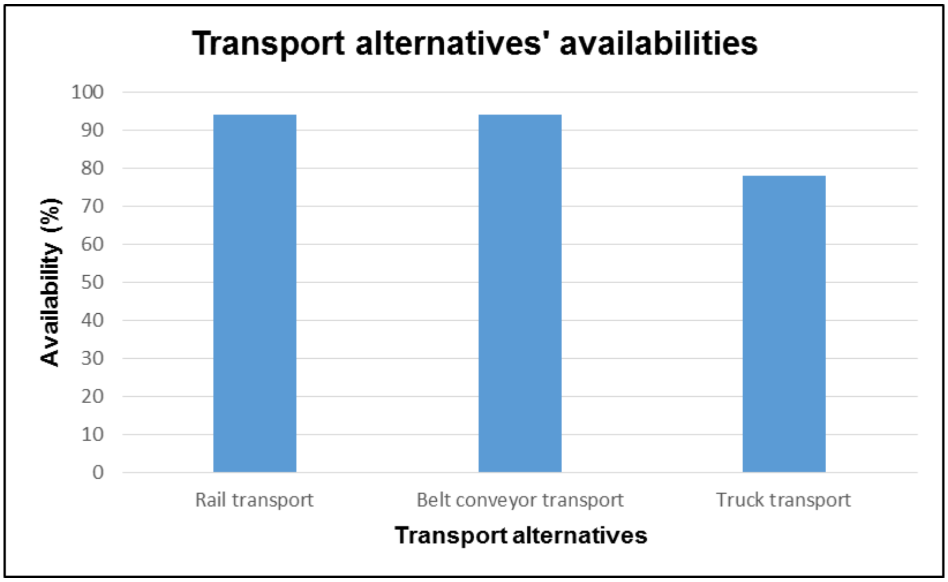


Figure 4.9: Availabilities of the transport alternatives

As shown in Figure 4.9, the rail and belt conveyor systems have equal availabilities, followed by the truck transport system. If the decision was based on maximising availability only, then the rail and belt conveyor systems would be the optimum systems.

4.3.8 Safety ratings of the transport alternatives

The safety criterion was split into five sub-categories namely; operator fatigue, operating at night, unauthorised access risk, injury risk and risk of fire. The experts were asked to assign weights according to the importance of each sub-category on a scale of 1 to 3. The scale of importance was interpreted as follows: a weight of 1 implies low importance, a weight of 2 implies moderate importance and a weight of 3 implies critical importance. The performance of each alternative was also compared against each sub-category on a performance score of 1 to 3. The performance scores were interpreted as follows: a poor performance attracted a score of 1, a moderate performance attracted a score of 2 and an excellent performance attracted a score of 3. The performance scores were then multiplied by the corresponding weighting to obtain weighted scores which were then summed up to obtain the overall relative performance in each category with respect to each alternative. The results of experts' weighted scoring for the safety criterion are shown in Appendix 8.13 and plotted in Figure 4.10.

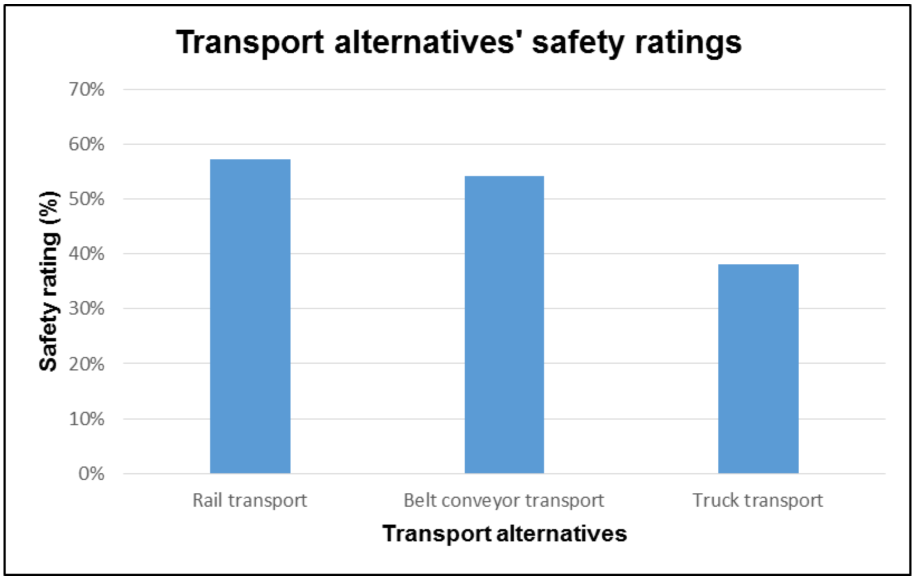


Figure 4.10: Safety ratings of the transport alternatives

As shown in Figure 4.10, the rail system is the safest, followed by the belt conveyor and the truck transport systems, respectively. If the decision was based on maximising safety only, then the rail system would be the optimum system.

4.3.9 Productivities of the transport alternatives

The three transport systems were designed to meet the minimum productivity throughput of 90,000 tpm as shown in Figure 4.11.

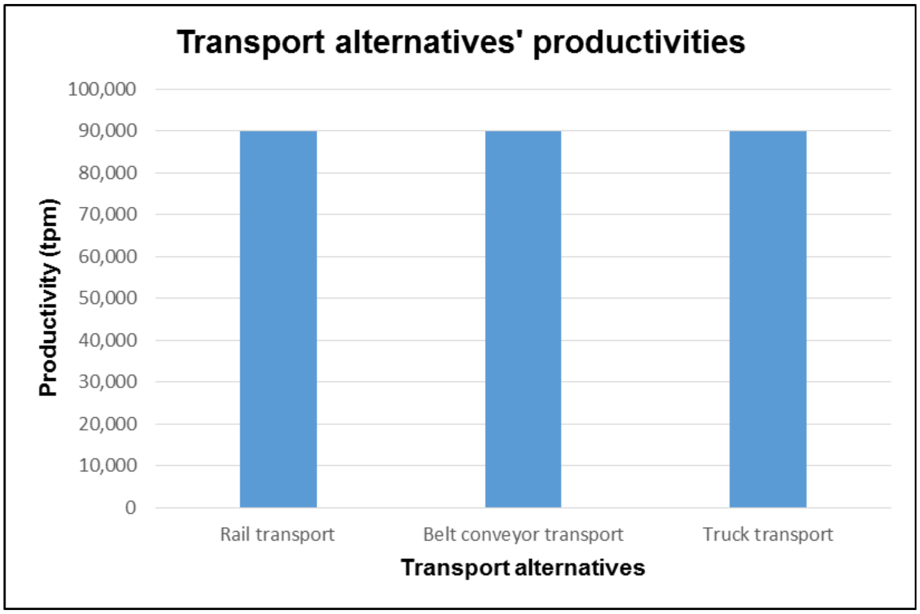


Figure 4.11: Productivities of the transport alternatives

As shown in Figure 4.11, if the decision was based on maximising productivity only, then all the three transport systems would be the optimum.

4.4 Aggregated alternatives efficiencies

The efficiencies of the three alternatives were finally aggregated into a single efficiency matrix. Table 4.6 is a summary of the efficiencies of the three transport alternatives relative to the nine evaluation criteria. The optimal alternative for each objective criterion is circled.

Table 4.6: Aggregated alternatives efficiencies

Criterion	Capital cost ($'000)	Operating cost ($/t)	Energy cost ($/t)	Noise (relative)	Dust (relative)	Emissions (relative)	Availability (%)	Safety (rating)	Productivity (ktpm)
Objective Transport system	minimise	minimise	minimise	minimise	minimise	minimise	maximise	maximise	maximise
Rail system	3,563.69	1.13	0.04	0.93	0.05	0.00	94	57%	90
Belt conveyor system	802.31	0.40	0.05	0.77	0.80	0.00	94	54%	90
Truck system	2,497.68	1.41	0.23	1.09	2.00	0.74	78	38%	90

As shown in Table 4.6, minimisation is the objective for the economic and environmental criteria while maximisation is the objective for the technical criteria. It is not clear which transport system is the best by merely considering the data in Table 4.6. For example, the truck system is a better compared to the rail system in terms of capital cost but the rail system is a better than the truck system in terms of unit operating cost. However, both criteria require minimisation (implying that they are competing), yet the alternative that is more preferred with respect to one minimisation criterion is less preferred with respect to another minimisation criterion (implying that they are conflicting). This leaves the decision maker with no easy choice to make but to resort to a MCDA technique such as AHP to solve this multi-criteria decision problem.

4.5 Chapter summary

The layout design of the three transport systems namely: rail; belt conveyor; and truck systems was considered. The three transport systems were compared with respect to nine evaluation criteria and their efficiencies with respect to these nine criteria were aggregated. The efficiencies of the alternatives coupled with criteria importance were used in the next chapter in the AHP model in order to rank the options and choose the optimal system.

5 SELECTION OF THE OPTIMAL TRANSPORT SYSTEM

5.1 Chapter overview

Following the development of the AHP model in Chapter 3 and analysis of the three transport systems designs and expected efficiencies in Chapter 4, this chapter focuses on the application of the AHP model in order to select the optimal transport system. The rankings of the transport alternatives with respect to the three main categories and the overall AHP ranking are discussed in this chapter. From the ranking, the optimal transport system is presented. To validate the AHP results, a Discounted Cashflow analysis is done and the results are also presented in this chapter.

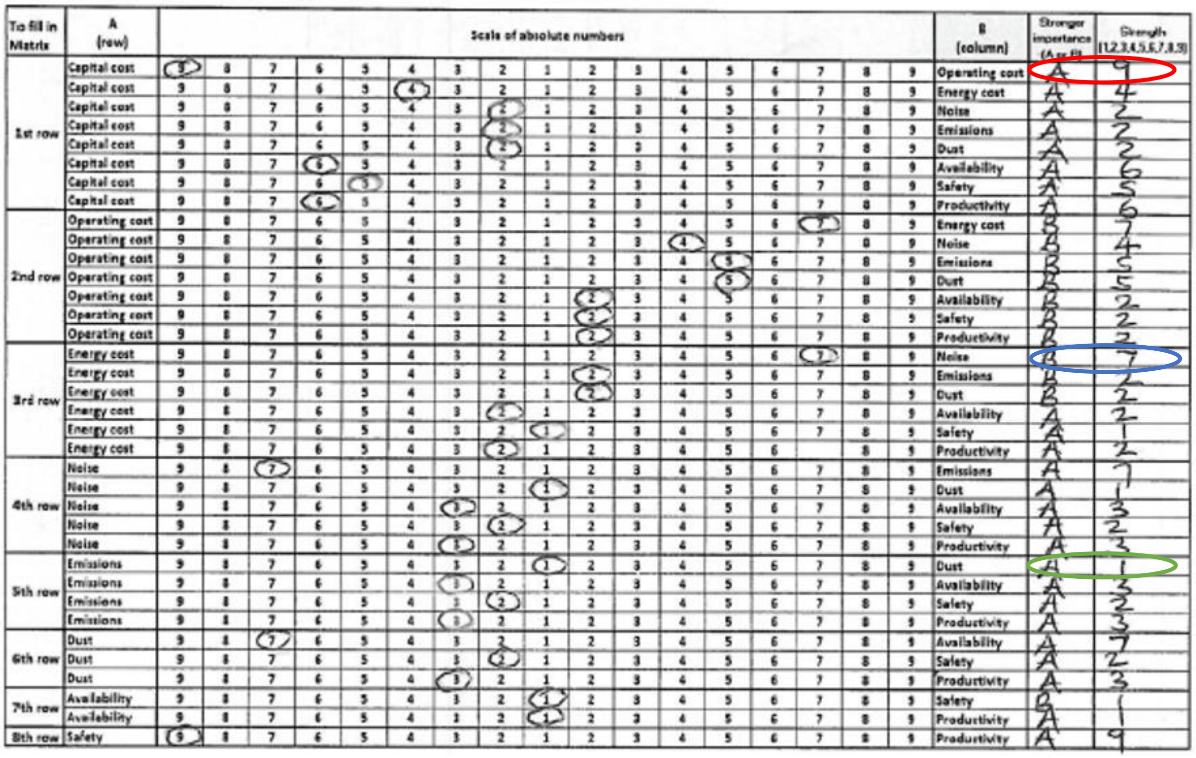
5.2 Step 1 of the AHP model

Appendix 8.15 shows the sample template for the pairwise comparison questionnaire and Appendices 8.16 and 8.17 show results of the criteria pair-wise judgements by the five individual experts. This was done in line with the first step of the AHP model described in Section 3.3. This step involves checking the consistency of the five experts' judgements. However, in this section, only the results of consistency check for Expert 1 are presented in the following sub-sections. This is because the process is repetitive. The computation was then repeated for the other four experts and the consistency check results of the five experts are presented in Table 5.10.

5.2.1 Criteria pair-wise comparison results from Expert 1

Table 5.1 shows the criteria pair-wise comparison results for Expert 1. The same results are shown in Appendix 8.16.

Table 5.1: Criteria pair-wise comparison response by Expert 1



To fill in Matrix	A (row)	Scale of absolute numbers																	B (column)	Stronger importance (A or B)	Strength (1,2,3,4,5,6,7,8,9)
1st row	Capital cost	[✓ 9]	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Operating cost	A	9
	Capital cost	9	8	7	6	5	[✓ 4]	3	2	1	2	3	4	5	6	7	8	9	Energy cost	A	4
	Capital cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Noise	A	2
	Capital cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Emissions	A	2
	Capital cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Dust	A	2
	Capital cost	9	8	7	[✓ 6]	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability	A	6
	Capital cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Safety	A	5
	Capital cost	9	8	7	[✓ 6]	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity	A	6
2nd row	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	[✓ 7]	8	9	Energy cost	B	7
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	[✓ 4]	5	6	7	8	9	Noise	B	4
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Emissions	B	5
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Dust	B	5
	Operating cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Availability	B	2
	Operating cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Safety	B	2
	Operating cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Productivity	B	2
3rd row	Energy cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	[✓ 7]	8	9	Noise	B	7
	Energy cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Emissions	B	2
	Energy cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Dust	B	2
	Energy cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Availability	A	2
	Energy cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	A	1
	Energy cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6		8	9	Productivity	A	2
4th row	Noise	9	8	[✓ 7]	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Emissions	A	7
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Noise	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Availability	A	3
	Noise	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Safety	A	2
	Noise	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Productivity	A	3
5th row	Emissions	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Emissions	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Availability	A	3
	Emissions	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Safety	A	2
	Emissions	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Productivity	A	3
6th row	Dust	9	8	[✓ 7]	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability	A	7
	Dust	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Safety	A	2
	Dust	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Productivity	A	3
7th row	Availability	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	B	1
	Availability	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	A	1
8th row	Safety	[✓ 9]	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity	A	9

Table 5.1 is interpreted as follows; for example, the first last two entries in the first row marked with a red circle imply that Expert 1 considered capital cost to be extremely more important than unit operating cost and made the entry as “A 9” since the score is more on the “A” column than the “B” column. Similarly, the last two entries in the 16th row marked with a blue circle imply that Expert 1 considered noise to be very strongly more important than unit energy cost, hence the entry “B 7. The last two entries in the 27th row marked with a green circle imply that Expert 1 considered gas emissions to be of equal importance as dust cost thereby making the entry as “A 1”. Table 5.2 shows the judgements from Expert 1 that were entered into the upper half of the table.

Table 5.2: Expert 1's upper filled criteria pair-wise comparison matrix

Criteria	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
Capital cost	1.00	9.00	4.00	2.00	2.00	2.00	6.00	5.00	6.00
Unit operating cost		1.00	0.14	0.25	0.20	0.20	0.50	0.50	0.50
Unit energy cost			1.00	0.14	0.50	0.50	2.00	1.00	2.00
Noise				1.00	7.00	1.00	3.00	2.00	3.00
Emissions					1.00	1.00	3.00	2.00	3.00
Dust						1.00	7.00	2.00	3.00
Availability							1.00	1.00	1.00
Safety								1.00	9.00
Productivity									1.00

As shown in Table 5.2, for example; an entry of "9" under the unit operating cost criterion circled in red corresponds to "A 9" in Table 5.1 since capital cost is considered to be extremely more important than unit operating cost. On the other hand, an entry of "0.14" (or $^{1}/_{7}$) under the noise criterion circled in blue corresponds to "B 7" in Table 5.1 since noise is considered to be very strongly more important than unit energy cost. An entry of 1 under the dust criterion circled in green corresponds to "A 1" since gas emissions are considered to be of equal importance as dust. The same process was done for all the other upper half entries highlighted in yellow above the diagonal. The grey diagonal entries were populated with the value of "1" since a criterion is as important as itself as explained in Section 2.8. Table 5.3 shows the complete matrix with the lower half entries below the populated.

Table 5.3: Expert 1's complete criteria pair-wise comparison matrix

Criteria	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
Capital cost	1.00	9.00	4.00	2.00	2.00	2.00	6.00	5.00	6.00
Unit operating cost	0.11	1.00	0.14	0.25	0.20	0.20	0.50	0.50	0.50
Unit energy cost	0.25	7.00	1.00	0.14	0.50	0.50	2.00	1.00	2.00
Noise	0.50	4.00	7.00	1.00	7.00	1.00	3.00	2.00	3.00
Emissions	0.50	5.00	2.00	0.14	1.00	1.00	3.00	2.00	3.00
Dust	0.50	5.00	2.00	1.00	1.00	1.00	7.00	2.00	3.00
Availability	0.17	2.00	0.50	0.33	0.33	0.14	1.00	1.00	1.00
Safety	0.20	2.00	1.00	0.50	0.50	0.50	1.00	1.00	9.00
Productivity	0.17	2.00	0.50	0.33	0.33	0.33	1.00	0.11	1.00

As shown in Table 5.3, the lower half entries of the matrix are populated as reciprocals of the corresponding entries in the upper half. For example, the value of "2" in the entry circled in red in the lower half under the unit operating cost criterion is equivalent to the reciprocal of "0.5" in the corresponding entry circled in green in the upper half under the productivity criterion. As explained in Section 2.8, this means that if productivity is twice as important as unit operating cost, it implies that unit operating cost is half as important as productivity. This procedure was done for all entries in the lower half of the matrix.

5.2.2 Normalisation of Expert 1's results

The matrix in Table 5.3 was then normalised by first summing each matrix column as shown in Table 5.4.

Table 5.4: Column sums for Expert 1's criteria pair-wise comparison matrix

Criteria	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
Capital cost	1.00	9.00	4.00	2.00	2.00	2.00	6.00	5.00	6.00
Unit operating cost	0.11	1.00	0.14	0.25	0.20	0.20	0.50	0.50	0.50
Unit energy cost	0.25	7.00	1.00	0.14	0.50	0.50	2.00	1.00	2.00
Noise	0.50	4.00	7.00	1.00	7.00	1.00	3.00	2.00	3.00
Emissions	0.50	5.00	2.00	0.14	1.00	1.00	3.00	2.00	3.00
Dust	0.50	5.00	2.00	1.00	1.00	1.00	7.00	2.00	3.00
Availability	0.17	2.00	0.50	0.33	0.33	0.14	1.00	1.00	1.00
Safety	0.20	2.00	1.00	0.50	0.50	0.50	1.00	1.00	9.00
Productivity	0.17	2.00	0.50	0.33	0.33	0.33	1.00	0.11	1.00
Sum of columns	***3.394***	***37.000***	***18.143***	***5.702***	***12.867***	***6.676***	***24.500***	***14.611***	***28.500***

Each entry in Table 5.4 was then divided by its corresponding column sum to normalise the matrix. The normalised matrix is shown in Table 5.5.

Table 5.5: Normalised matrix for Expert 1

	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
Capital cost	0.295	0.243	0.220	0.351	0.155	0.300	0.245	0.342	0.211
Unit operating cost	0.033	0.027	0.008	0.044	0.016	0.030	0.020	0.034	0.018
Unit energy cost	0.074	0.189	0.055	0.025	0.039	0.075	0.082	0.068	0.070
Noise	0.147	0.108	0.386	0.175	0.544	0.150	0.122	0.137	0.105
Emissions	0.147	0.135	0.110	0.025	0.078	0.150	0.122	0.137	0.105
Dust	0.147	0.135	0.110	0.175	0.078	0.150	0.286	0.137	0.105
Availability	0.049	0.054	0.028	0.058	0.026	0.021	0.041	0.068	0.035
Safety	0.059	0.054	0.055	0.088	0.039	0.075	0.041	0.068	0.316
Productivity	0.049	0.054	0.028	0.058	0.026	0.050	0.041	0.008	0.035
Sum of columns	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

5.2.3 Computation of eigenvector for Expert 1

The average of the elements of each normalised row was then computed to derive the eigenvector as shown in Table 5.6.

Table 5.6: Eigenvector for Expert 1

Criteria	Criteria weights / eigenvector w
Capital cost	0.262
Unit operating cost	0.025
Unit energy cost	0.075
Noise	0.208
Emissions	0.112
Dust	0.147
Availability	0.042
Safety	0.088
Productivity	0.039

For example, 0.262 circled in red is the arithmetic average of elements in the capital cost row in Table 5.5. As shown in Table 5.6, the eigenvector elements give the aggregated weight for each criterion which is an indication of the relative importance of that criterion. As shown in Table 5.6, capital cost was considered to be the most important criterion by Expert 1 with a weight of 0.262 followed by noise with a weight of 0.208, and so on.

5.2.4 Computation of weight sums vector for Expert 1

The weight sums vector, $\boldsymbol{w_s}$, was then computed using Equation 4 (Section 2.8). The $\boldsymbol{w_s}$ results are shown in Table 5.7.

Table 5.7: Computation of Expert 1 weight sums vector, $\boldsymbol{w_s}$

										Criteria weights / eigenvector	Weight sums vector
Criteria	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity	w	$w_s = W.w$
Capital cost	1.00	9.00	4.00	2.00	2.00	2.00	6.00	5.00	6.00	0.262	2.655
Unit operating cost	0.11	1.00	0.14	0.25	0.20	0.20	0.50	0.50	0.50	0.025	0.254
Unit energy cost	0.25	7.00	1.00	0.14	0.50	0.50	2.00	1.00	2.00	0.075	0.729
Noise	0.50	4.00	7.00	1.00	7.00	1.00	3.00	2.00	3.00	0.208	2.320
Emissions	0.50	5.00	2.00	0.14	1.00	1.00	3.00	2.00	3.00	0.112	1.118
Dust	0.50	5.00	2.00	1.00	1.00	1.00	7.00	2.00	3.00	0.147	1.465
Availability	0.17	2.00	0.50	0.33	0.33	0.14	1.00	1.00	1.00	0.042	0.429
Safety	0.20	2.00	1.00	0.50	0.50	0.50	1.00	1.00	9.00	0.088	0.892
Productivity	0.17	2.00	0.50	0.33	0.33	0.33	1.00	0.11	1.00	0.039	0.379

The weight sums vector, $\boldsymbol{w_s}$, in Table 5.7 is a matrix multiplication of the criteria pair-wise comparison matrix shown in Table 5.2, $\boldsymbol{W}$, and the eigenvector, $\boldsymbol{w}$. For example, the value circled in a red circle of 2.655 was obtained by multiplying each element in the capital cost row by a corresponding element by position in the eigenvector column and summing the products as follows:

$$(1x0.262) + (9x0.025) +\ldots+ (6x0.039) = 2.655$$

The other remaining weight sums vector elements were calculated in the same way.

5.2.5 *Calculation of consistency vector and eigenvalue for Expert 1*

After calculating $\boldsymbol{w_s}$, the consistency vector, {cons.}, was computed using Equation 4 while the eigenvalue, λ_{max}, was calculated as the arithmetic average of the elements of the consistency vector, {cons.}. The results are shown in Table 5.8.

Table 5.8: Consistency vector and eigenvalue for Expert 1

Criteria	Criteria weights / eigenvector	Weight sums vector	Consistency vector	eigenvalue
	w	$w_s = W.w$	$w_s.1/w$	λ_{max}
Capital cost	0.262	2.655	10.119	10.098
Unit operating cost	0.025	0.254	9.974	
Unit energy cost	0.075	0.729	9.688	
Noise	0.208	2.320	11.136	
Emissions	0.112	1.118	9.961	
Dust	0.147	1.465	9.966	
Availability	0.042	0.429	10.149	
Safety	0.088	0.892	10.098	
Productivity	0.039	0.379	9.787	

The consistency vector, {cons.}, in Table 5.8 is a dot product of $\boldsymbol{w_s}$ and $1/\boldsymbol{w}$. For example, the consistency vector element of 10.119 circled in the table for capex is given by:

$$\text{Consistency vector element} = 2.655x1/0.262 = 10.119$$

The average of the elements of the consistency vector gave the eigenvalue, λ_{max} = 10.098. Since $\lambda_{max} > 9$ where 9 is the number of criteria, it implies that the judgements for Expert 1 were inconsistent. As explained in Section 2.8, perfectly consistent judgements result in λ_{max} = number of criteria (= 9 in this case). There was therefore need to check for the degree of inconsistency of Expert 1.

5.2.6 Computation of consistency ratio for Expert 1

Table 5.9 shows the results of the computation of the consistency ratio (CR) for Expert 1.

Table 5.9: Estimation of consistency of judgements for Expert 1

Parameter	Formula	Value	Decision
λ_{max}	Average of consistency vector elements	10.098	Matrix is inconsistent
n	Order of matrix	9	
CI	Equation 5: (λ_{max}-n)/(n-1)	0.137	
RI	From Saaty's CIr values for matrices (Table 2.2)	1.45	
CR	Equation 6: CI/RI	0.095	Accept

The Consistency Index, CI, in Table 5.9 was first calculated using Equation 5 as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} = \frac{10.098-9}{9-1} = \frac{1.098}{8} = 0.13725$$

A Random Index, RI, was read from Table 2.2 for n = 9, since there are nine criteria under consideration. RI = 1.45 from Table 2.2. The CR was then calculated using Equation 6 as follows:

$$CR = \frac{CI}{RI} = \frac{0.13725}{1.45} = \ 0.095 = 9.5\%$$

Since CR<10%, it means that the aggregate judgements from Expert 1 are reliable enough to proceed with the AHP as explained in Section 2.8.

The steps in sub-section 5.2.1 to 5.2.6 were repeated for Expert 2, Expert 3, Expert 4 and Expert 5. Table 5.10 shows the summary of the experts' eigenvalues, CI, RI, CR and the final decision of whether the levels of inconsistencies were acceptable enough to proceed with the AHP process.

Table 5.10: Results of the five experts' criteria pair-wise comparisons

Expert	λ_{max}	Consistency	n	CI	RI	CR	Decision
1	10.10	Matrix is inconsistent	9	0.137	1.45	9.5%	Accept
2	9.94	Matrix is inconsistent	9	0.118	1.45	8.1%	Accept
3	9.01	Matrix is inconsistent	9	0.001	1.45	0.1%	Accept
4	9.63	Matrix is inconsistent	9	0.079	1.45	5.5%	Accept
5	9.90	Matrix is inconsistent	9	0.112	1.45	7.7%	Accept

As shown in Table 5.10, all the consistency ratios of the five individual experts' criteria pair-wise comparisons are less than 10% (Expert 1 CR = 9.5%; Expert 2 CR = 8.1%; Expert 3 CR = 0.1%; Expert 4 CR = 5.5%; and Expert 5 CR = 7.7%). This means that the individual judgements could be trusted to proceed with the AHP modelling process.

5.3 Aggregation of the pair-wise judgements of the five experts

Since the judgements from the five experts are acceptable as shown in Table 5.10, the individual criteria pair-wise comparison matrices from the five experts shown in Appendix 8.17 were then aggregated into a single composite matrix, ***W***. The aggregated matrix is shown in Table 5.11. The matrix was obtained by taking the geometric mean of all corresponding cell entries across the individual expert pair-wise comparison matrices displayed in Appendix 8.17.

Table 5.11: Aggregated criteria pair-wise comparison matrix

Criteria	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
Capital cost	1.00	4.17	3.44	3.63	3.63	4.52	3.06	3.39	2.05
Unit operating cost	0.24	1.00	1.05	1.17	0.85	1.31	0.69	1.09	0.46
Unit energy cost	0.29	0.95	1.00	0.82	1.43	0.99	0.94	0.94	0.63
Noise	0.28	0.86	1.22	1.00	1.48	1.38	0.84	0.86	0.56
Emissions	0.28	1.17	0.70	0.68	1.00	1.25	0.84	0.86	0.74
Dust	0.22	0.76	1.01	0.72	0.80	1.00	0.80	0.69	0.45
Availability	0.33	1.44	1.06	1.18	1.18	1.25	1.00	1.15	0.67
Safety	0.29	0.92	1.06	1.16	1.16	1.45	0.87	1.00	1.12
Productivity	0.49	2.16	1.58	1.77	1.34	2.21	1.50	0.89	1.00

Table 5.11 is interpreted as follows: for example, the entry circled in red with the value of "1" means that the capex criterion is as important as itself and the entry circled in green with a value of "4.17" means that capital cost is 4.17 times more important than unit operating cost. The responses of the five experts, Expert 1 to Expert 5, have the values of 9, 5, 1, 7 and 4, respectively, when they weighed capex against unit operating cost. These scores are circled in red in Appendix 8.17 for the five experts. The geometric means of these individual scores is calculated as illustrated below for unit operating cost:

$$\text{Geometric mean} = \sqrt[5]{(9x5x1x7x4)} = \sqrt[5]{1260} = 4.17$$

5.4 Aggregated results' eigenvector, weight sums vector and consistency check

The steps in sub-section 5.2.1 to 5.2.6 (for the individual experts' matrices) were repeated for the aggregated matrix. The results of the eigenvector, weight sums vector, consistency vector and eigenvalue for the aggregated matrix are shown in Table 5.12.

Table 5.12: Consistency vector and eigenvalue for the aggregated matrix

Criteria	Criteria weights / eigenvector	Weight sums vector	Consistency vector	eigenvalue
	w	$w_s = W.w$	$w_s.1/w$	λ_{max}
Capital cost	0.292	2.663	9.110	9.103
Unit operating cost	0.078	0.715	9.114	
Unit energy cost	0.082	0.747	9.090	
Noise	0.085	0.772	9.088	
Emissions	0.077	0.705	9.108	
Dust	0.066	0.597	9.092	
Availability	0.094	0.859	9.115	
Safety	0.094	0.852	9.099	
Productivity	0.131	1.197	9.115	

As shown in Table 5.12, the eigenvalue, $\lambda_{max} > 9$ where 9 is the number of criteria implying that the aggregated judgements were inconsistent. As explained in Section 2.8, perfectly consistent judgements result in λ_{max} = number of criteria (= 9 in this case). There was therefore need to check for the degree of inconsistency for the aggregated judgements of the five experts. Table 5.13 shows the computation of the consistency ratio for the aggregated matrix.

Table 5.13: Estimation of consistency of judgements

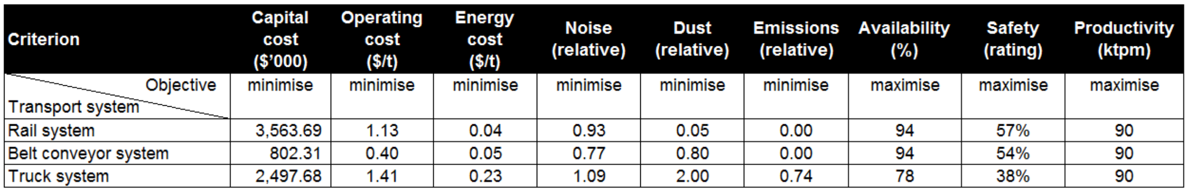
Parameter	Formula	Value	Decision
λ_{max}	Average of consistency vector elements	9.103	Matrix is inconsistent
n	Order of matrix	9	
CI	Equation 5: $(\lambda_{max}-n)/(n-1)$	0.013	
RI	From Saaty's CIr values for matrices (Table 2.2)	1.45	
CR	Equation 6: CI/RI	0.009	Accept

Since the CR in Table 5.13 is less than 10%, it means that the aggregated judgements are reliable enough to proceed with the AHP since the inconsistency of the experts after aggregation was below the threshold of 10% as explained in Section 2.8.

5.5 Final AHP priority score

The data applicable to the efficiency scores of the three alternative system was discussed in Chapter 4. Table 5.14 is a summary of the efficiency scores for the three transport alternatives under analysis. This table is a duplicate of Table 4.6.

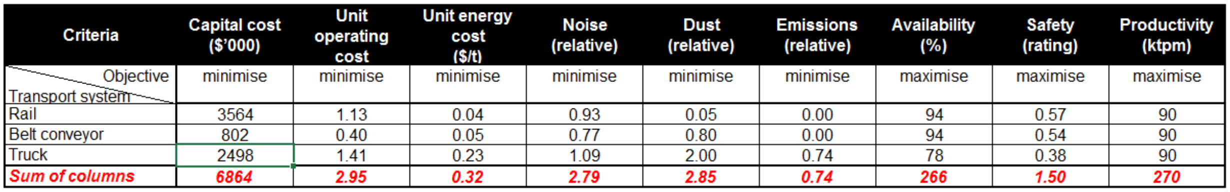
Table 5.14: Aggregated alternatives' efficiency scores



Criterion	Capital cost ($'000)	Operating cost ($/t)	Energy cost ($/t)	Noise (relative)	Dust (relative)	Emissions (relative)	Availability (%)	Safety (rating)	Productivity (ktpm)
Objective Transport system	minimise	minimise	minimise	minimise	minimise	minimise	maximise	maximise	maximise
Rail system	3,563.69	1.13	0.04	0.93	0.05	0.00	94	57%	90
Belt conveyor system	802.31	0.40	0.05	0.77	0.80	0.00	94	54%	90
Truck system	2,497.68	1.41	0.23	1.09	2.00	0.74	78	38%	90

As shown in Table 5.14, the criteria required either minimisation or maximisation. The efficiency scores were normalised since they have different units of measurement. To normalise the aggregated alternatives efficiency scores, the sum of each column of the aggregated alternatives efficiency scores was computed. The column sums for each criterion are shown in Table 5.15.

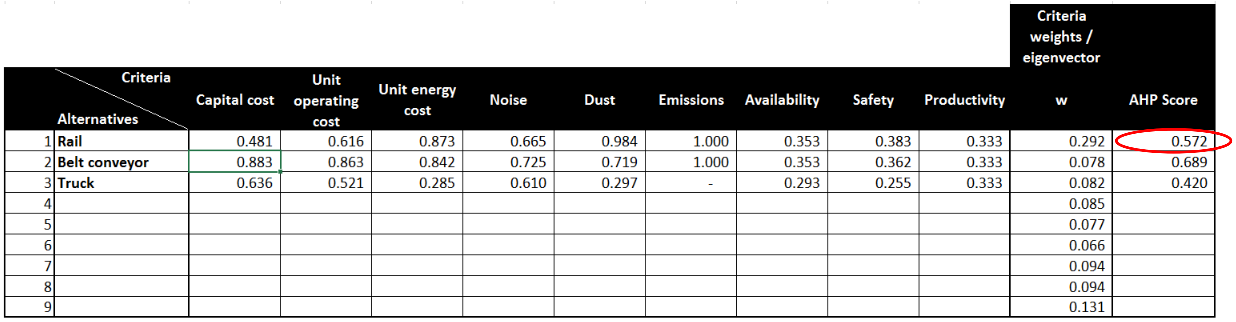
Table 5.15: Column sums of the aggregated alternatives' efficiency scores



Criteria	Capital cost ($'000)	Unit operating cost	Unit energy cost ($/t)	Noise (relative)	Dust (relative)	Emissions (relative)	Availability (%)	Safety (rating)	Productivity (ktpm)
Objective Transport system	minimise	minimise	minimise	minimise	minimise	minimise	maximise	maximise	maximise
Rail	3564	1.13	0.04	0.93	0.05	0.00	94	0.57	90
Belt conveyor	802	0.40	0.05	0.77	0.80	0.00	94	0.54	90
Truck	2498	1.41	0.23	1.09	2.00	0.74	78	0.38	90
Sum of columns	***6864***	***2.95***	***0.32***	***2.79***	***2.85***	***0.74***	***266***	***1.50***	***270***

Each entry in Table 5.15 was then divided by its corresponding column sum to normalise the matrix in the case of maximisation criteria. As for the minimisation criteria, the difference between one a particular entry was divided by its corresponding sum. Table 5.16 shows the normalised efficiency scores, the eigenvector and the AHP priority scores.

Table 5.16: Normalised efficiency scores, eigenvector and AHP priority scores



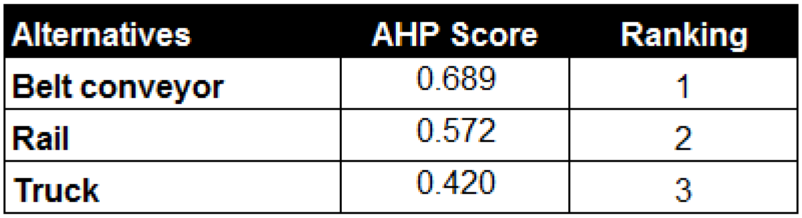
	Criteria Alternatives	Capital cost	Unit operating cost	Unit energy cost	Noise	Dust	Emissions	Availability	Safety	Productivity	Criteria weights / eigenvector w	AHP Score
1	**Rail**	0.481	0.616	0.873	0.665	0.984	1.000	0.353	0.383	0.333	0.292	0.572
2	**Belt conveyor**	0.883	0.863	0.842	0.725	0.719	1.000	0.353	0.362	0.333	0.078	0.689
3	**Truck**	0.636	0.521	0.285	0.610	0.297	-	0.293	0.255	0.333	0.082	0.420
4											0.085	
5											0.077	
6											0.066	
7											0.094	
8											0.094	
9											0.131	

In Table 5.16, the AHP scores were calculated by multiplying the normalised efficiency scores matrix by the eigenvector shown in Table 5.12. The AHP priority scores give the ranking of the transport alternatives. For example, the AHP score value of 0.572 for the rail system circled in red circle calculated as follows:

$$(0.481 \text{x} 0.292)+(0.616 \text{x} 0.078)+\ldots+0.333 \text{x} 0.131) = 0.584$$

The same calculation was done for the belt and truck systems. The results of the final ranking of the alternatives are shown in Table 5.17.

Table 5.17: The transport alternatives ranked according to AHP priority scores



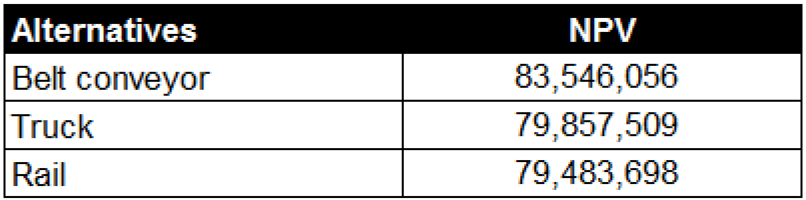
Alternatives	AHP Score	Ranking
Belt conveyor	0.689	1
Rail	0.572	2
Truck	0.420	3

Table 5.17 shows that the belt conveyor system is the optimal transportation system with a priority score of 0.689 followed by the rail system with a priority score of 0.572 and lastly the truck system with a priority score of 0.420. To validate the results of the AHP analysis, a Discounted Cashflow (DCF) analysis was done.

5.6 Net Present Value analysis

An analysis of the Net Present Value (NPV) of the operation with respect to each of the three transport alternatives was done to check if the decision based on NPV would be consistent with AHP. A 5-year period from April 2019 to March 2024 was considered as this is the life of the operation up to 39/0 lift according to the scope of this study. Table 5.18 is a summary of the NPVs of the operation when each transport alternative is in use. A 10% discount rate was used because it was BNC's prevailing cost of capital at the time of computation (Fincent Advisory, 2019). The detailed DCFs for the rail, belt conveyor and truck systems are shown in Appendices 8.18, 8.19 and 8.20, respectively.

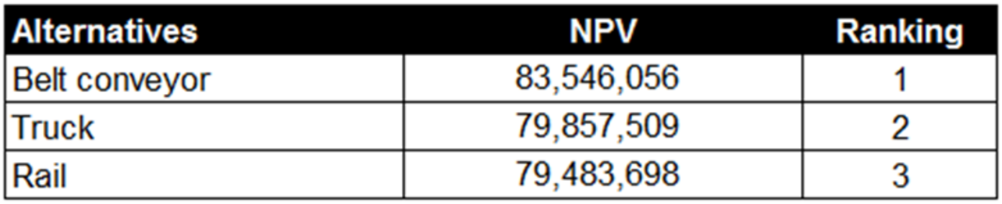
Table 5.18: NPVs of the three transport alternatives



Alternatives	NPV
Belt conveyor	83,546,056
Truck	79,857,509
Rail	79,483,698

Table 5.18, shows that the belt conveyor system has the highest NPV of US$83.5m, followed by the truck system and lastly the rail system. Table 5.19 shows the ranking of the three transport systems based on NPV.

Table 5.19: Alternatives ranked according to NPV



Alternatives	NPV	Ranking
Belt conveyor	83,546,056	1
Truck	79,857,509	2
Rail	79,483,698	3

As shown in Table 5.19, the belt conveyor system ranked first followed by the truck and rail system respectively. The ranking of the belt conveyor system as the first alternative is consistent with the AHP ranking whilst there is a reversal in rank for the truck and rail systems compared to the AHP ranking. The rail alternative ranks last due to its high initial capital cost of US$3,563,690 relative to the truck system with a capital cost of US$2,497,675 giving a 43.7% difference. However, the two systems have a NPV difference of US$373,811 translating to a 0.47% difference which reflects on the competitiveness of the rail system when a DCF analysis is performed despite its high initial capital cost. The difference in the ranking of the three alternatives between the AHP and NPV analysis results does not affect the selection of the belt conveyor system as the optimal alternative since both methods rank the belt conveyor system as the first alternative. In addition, the AHP considers factors beyond the financial metrics criteria such as technical and environmental criteria in making a decision. This implies that if one is to consider the rankings of the two techniques, the AHP order would still be upheld given that the difference in NPVs between the rail and the truck systems whose ranks reversed after the DCF analysis was performed is negligible.

5.7 Chapter summary

The use of AHP as a tool for selecting an optimal transport system has been demonstrated. The findings of the AHP analysis have shown that the belt conveyor transportation system is the optimal system over the rail and truck transportation systems respectively. This was confirmed by the DCF analysis.

6 CONCLUSION AND RECOMMENDATIONS

6.1 Chapter overview

Trojan mine has in the past used rail haulage as a means of horizontal transportation of rock (ore and waste) from chutes to main passes. However, given the increasing depth, decreasing Mineral Reserve grade with depth and a relatively lower nickel price, there has arisen a need to evaluate other transportation systems in order to identify an optimal one. The other forms of transportation that have been compared are truck and belt conveyor transportation systems.

The comparison of the alternatives was done using the AHP which is based on matrix and vector algebra. Criteria pair-wise responses were obtained from five experts whose responses were individually checked for consistency and aggregated into a single matrix of criteria weights. The efficiencies of the transport alternatives with respect to each criterion were also determined and these were aggregated together with the ultimate criteria weights in order to obtain the final AHP scoring on the basis that the higher the AHP score, the more preferred the alternative. This chapter concludes the study and provides recommendations for possible future work.

6.2 Conclusion

Through a literature review on underground mine design in general and ore transportation systems in particular as well as the common practice at Trojan mine, it was noted that the three possible alternatives that can be used at the mine are rail, belt conveyor and truck transport systems. These transport alternatives were evaluated against three broad categories namely; economic, environmental and technical. These were further spilt into nine criteria namely; capital cost, unit operating cost, unit energy cost, gas emissions, noise, dust, availability, safety and productivity. The economic category was deemed to be the most important set of factors affecting the selection of a transportation system. With capital having the highest importance overall of 29.2%, it played a significant role in skewing the decision point towards the least capital intensive system namely the belt conveyor system. From the AHP analysis, the belt conveyor system was found to be the most optimal alternative, followed by the rail and truck transport alternatives, respectively.

To validate the AHP findings, a DCF analysis was done on the three transport systems. The results of the DCF analysis were consistent with those of AHP. It therefore concluded that the belt conveyor is the optimal transportation system to use along Trojan mine's 37/0L, 39/0L and subsequently lower haulages.

6.3 Recommendations

From the conclusion above, it is recommended that the mine should use the belt conveyor system for all future haulages. The application of the belt conveyor system will help to create value for the operation due to its lower capital and operating costs. However, even though the methodology applied in this study within the limits of the research proposal was a success, it was not exhaustive. A further opportunity for further research would be the extension of the criteria pair-wise comparisons to the senior BNC executives as they are the key decision makers in the company. This will ensure that a robust decision is made.

6.4 Research limitations

More criteria could have been considered under each of the three broad categories namely; economic, environmental and technical. However, as the number of criteria to be considered goes up, the number of pair-wise comparisons to be done also increases thereby clouding judgement and making it difficult to reach consistency. To improve consistency and understanding when the criteria are many, there is need to break down the criteria into clusters in order to limit the number of criteria per hierarchy level thereby improving understanding and consistency.

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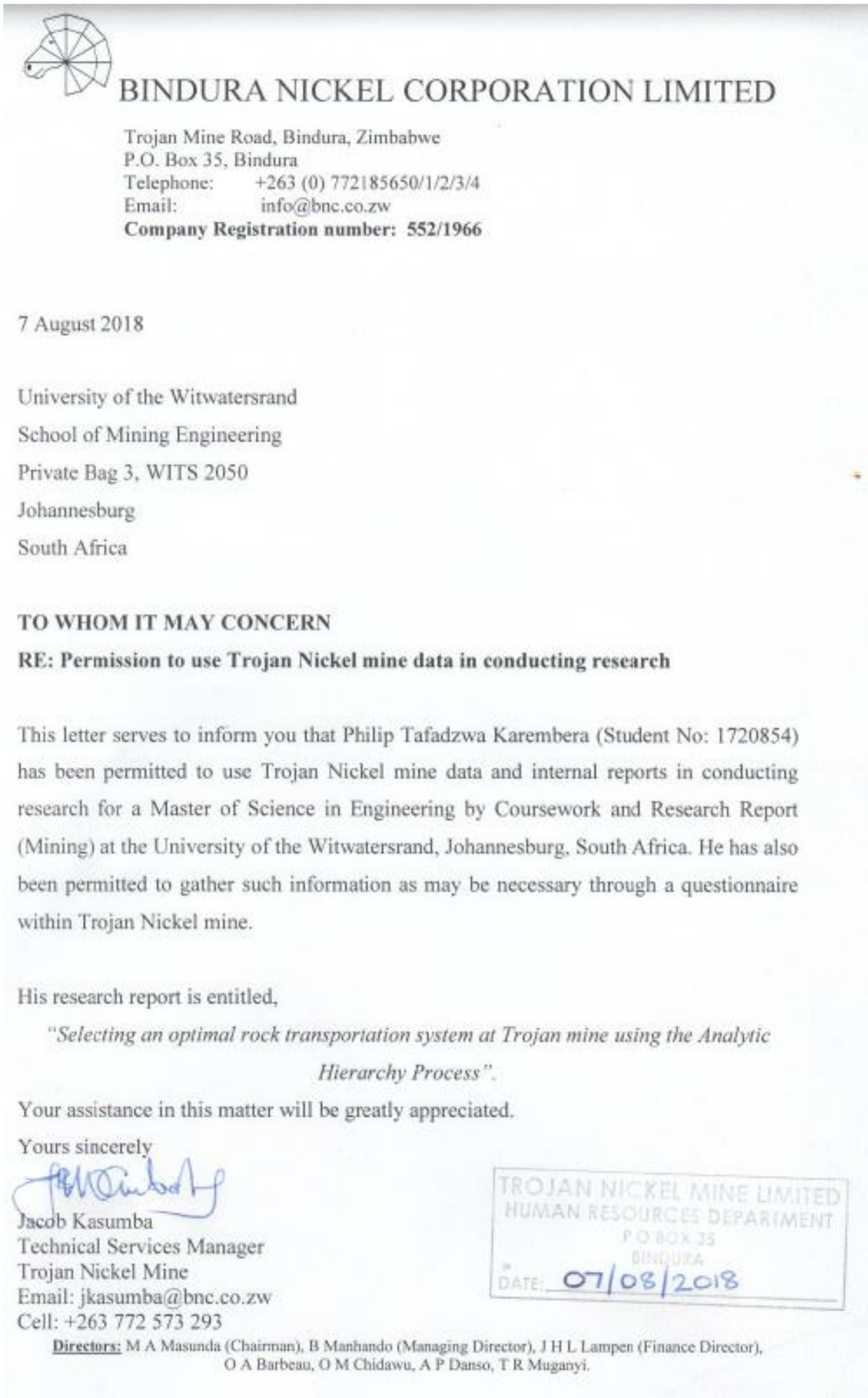
8 APPENDICES

Appendix 8.1: Permission letter from Bindura Nickel Corporation



BINDURA NICKEL CORPORATION LIMITED

Trojan Mine Road, Bindura, Zimbabwe
P.O. Box 35, Bindura
Telephone: +263 (0) 772185650/1/2/3/4
Email: info@bnc.co.zw
Company Registration number: 552/1966

7 August 2018

University of the Witwatersrand
School of Mining Engineering
Private Bag 3, WITS 2050
Johannesburg
South Africa

TO WHOM IT MAY CONCERN

RE: Permission to use Trojan Nickel mine data in conducting research

This letter serves to inform you that Philip Tafadzwa Karembera (Student No: 1720854) has been permitted to use Trojan Nickel mine data and internal reports in conducting research for a Master of Science in Engineering by Coursework and Research Report (Mining) at the University of the Witwatersrand, Johannesburg, South Africa. He has also been permitted to gather such information as may be necessary through a questionnaire within Trojan Nickel mine.

His research report is entitled,

"Selecting an optimal rock transportation system at Trojan mine using the Analytic Hierarchy Process".

Your assistance in this matter will be greatly appreciated.

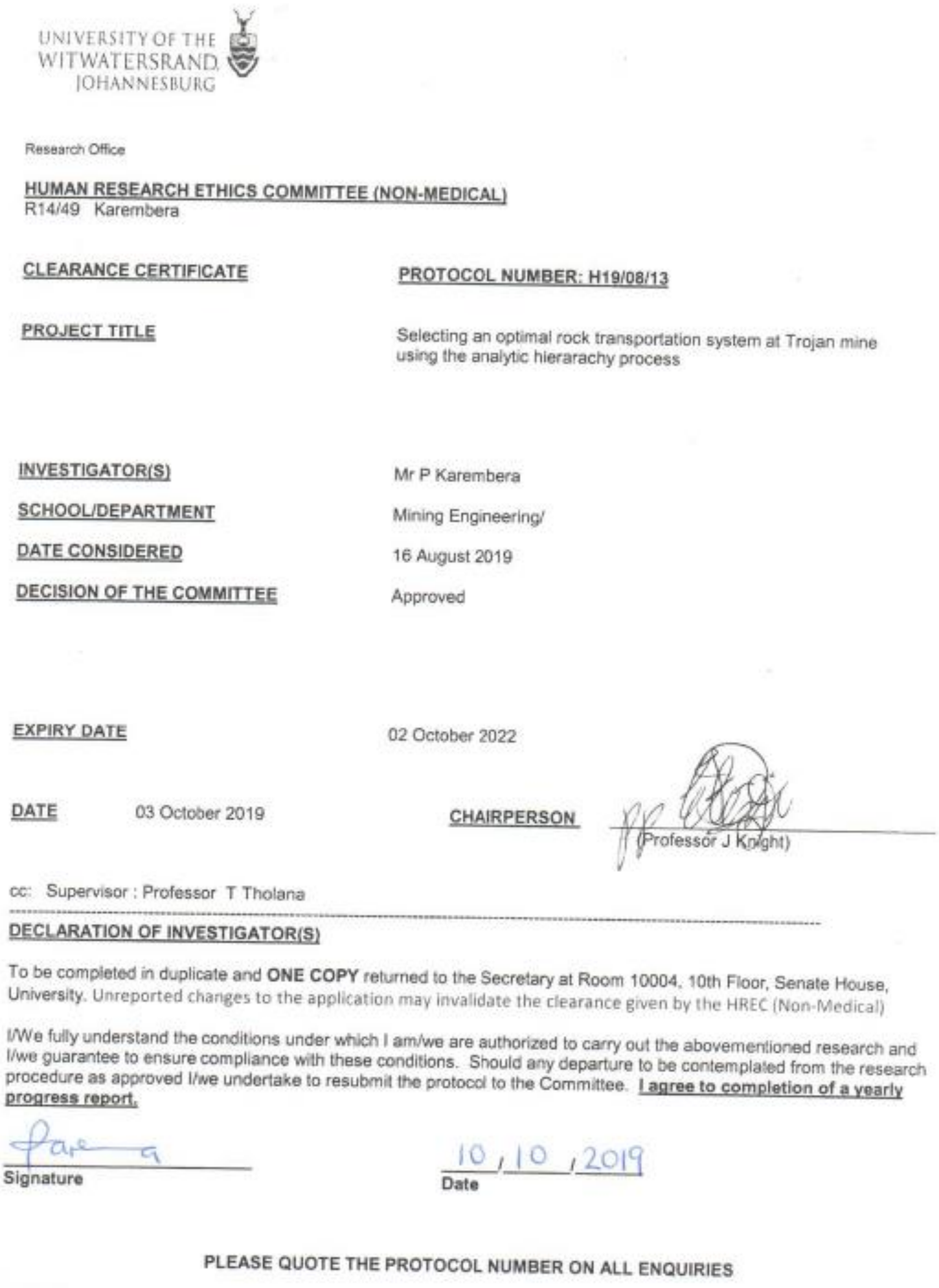
Yours sincerely

Jacob Kasumba
Technical Services Manager
Trojan Nickel Mine
Email: jkasumba@bnc.co.zw
Cell: +263 772 573 293

TROJAN NICKEL MINE LIMITED
HUMAN RESOURCES DEPARTMENT
P O BOX 35
BINDURA
DATE: 07/08/2018

Directors: M A Masunda (Chairman), B Manhando (Managing Director), J H L Lampen (Finance Director), O A Barbeau, O M Chidawu, A P Danso, T R Muganyi.

Appendix 8.2: Ethics clearance certificate



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

Research Office

HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)
R14/49 Karembera

CLEARANCE CERTIFICATE	**PROTOCOL NUMBER: H19/08/13**
PROJECT TITLE	Selecting an optimal rock transportation system at Trojan mine using the analytic hierarachy process
INVESTIGATOR(S)	Mr P Karembera
SCHOOL/DEPARTMENT	Mining Engineering/
DATE CONSIDERED	16 August 2019
DECISION OF THE COMMITTEE	Approved
EXPIRY DATE	02 October 2022

DATE 03 October 2019 **CHAIRPERSON** (Professor J Knight)

cc: Supervisor : Professor T Tholana

DECLARATION OF INVESTIGATOR(S)

To be completed in duplicate and **ONE COPY** returned to the Secretary at Room 10004, 10th Floor, Senate House, University. Unreported changes to the application may invalidate the clearance given by the HREC (Non-Medical)

I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee. **I agree to completion of a yearly progress report.**

Signature

10/10/2019
Date

PLEASE QUOTE THE PROTOCOL NUMBER ON ALL ENQUIRIES

Appendix 8.3: Participant Information Sheet

UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

Good day

My name is Philip Tafadzwa Karembera and I am a Masters student in the School of Mining Engineering at the University of the Witwatersrand in Johannesburg. As part of my studies, I have to undertake a research project entitled "Selecting an optimal rock transportation system at Trojan mine using the Analytic Hierarchy Process". The aim of this research project is to find out which transport system is the most optimal among a set of alternatives which will be evaluated against a set of economic, environmental and technical criteria using the Analytic Hierarchy Process (AHP).

As part of this project, I would like to invite you to take part in answering a questionnaire which will be used to collect research data. This activity will require you to provide responses through ranking criteria by scoring for importance, assigning criteria pair-wise judgements with respect to the selection goal as well as alternatives pair-wise judgements with respect to each criterion. A workshop will be conducted at Trojan mine to demonstrate how the pair-wise judgements will be assigned and how inconsistences in the responses will be checked. This workshop may take approximately 30 minutes. After the workshop, you will be issued with the questionnaire so that you can give your responses as with regards to pair-wise judgements as guided by the questionnaire. The response process will take approximately 30 minutes and may require to be repeated if inconsistencies indicated by a consistency ratio of more than 10% are detected since the AHP process requires inconsistencies in responses on pair-wise judgements to be within 10%. There will be a total of five participants, of which you are part.

You will not receive any direct benefits from participating in this research. There are no disadvantages or penalties for not participating and you may also withdraw at any time. Given that I am going to carry out a workshop on how to assign the pair-wise judgements, anonymity among the five selected participants may not be guaranteed since all the five participants will be available during the workshop. In addition, by virtue of your role at Trojan mine, you may become identifiable in my final research report. Confidentiality will be guaranteed since the individual participants will be assigned pseudo codenames, Expert 1 to Expert 5, whose identity will be known only by the researcher and the particular participant and will not be shared with any other participant or individual. In addition, the individual responses will be directly collected from the participants by the researcher and at no point will the responses of one participant be shared with another participant or any other person whatsoever. All the responses will be aggregated into a single matrix by the researcher and will be held securely and not disclosed to anyone.

If you have any questions at any time during the research process or afterwards about this research, feel free to contact me or my supervisor on the details listed below. If you wish to receive a summary of this report or require any further information, please feel free to get in contact. If you have any concerns or complaints regarding the ethical procedures of this study, you are welcome to contact the University Human Research Ethics Committee (Non-Medical), telephone +27 11 717 1408 or email Shaun.Schoeman@wits.ac.za

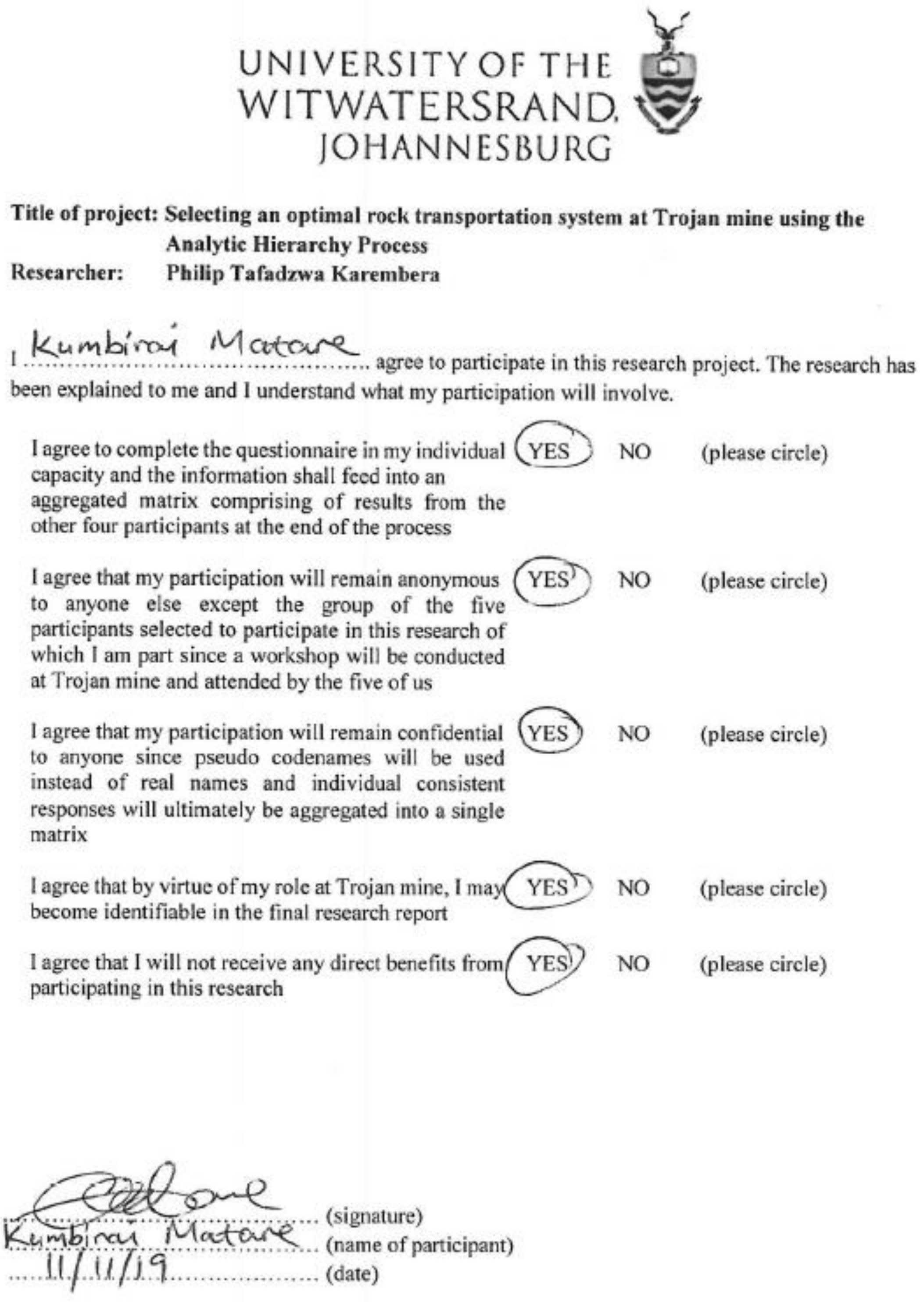
Yours sincerely,

Philip Tafadzwa Karembera

Researcher: Philip Tafadzwa Karembera, 1720854@students.wits.ac.za, +263 773 802 276.
Supervisor: Tinashe Tholana, Tinashe.Tholana@wits.ac.za, +27 11 717 7427.

Appendix 8.4: Consent forms for the five experts

Expert 1's consent form



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

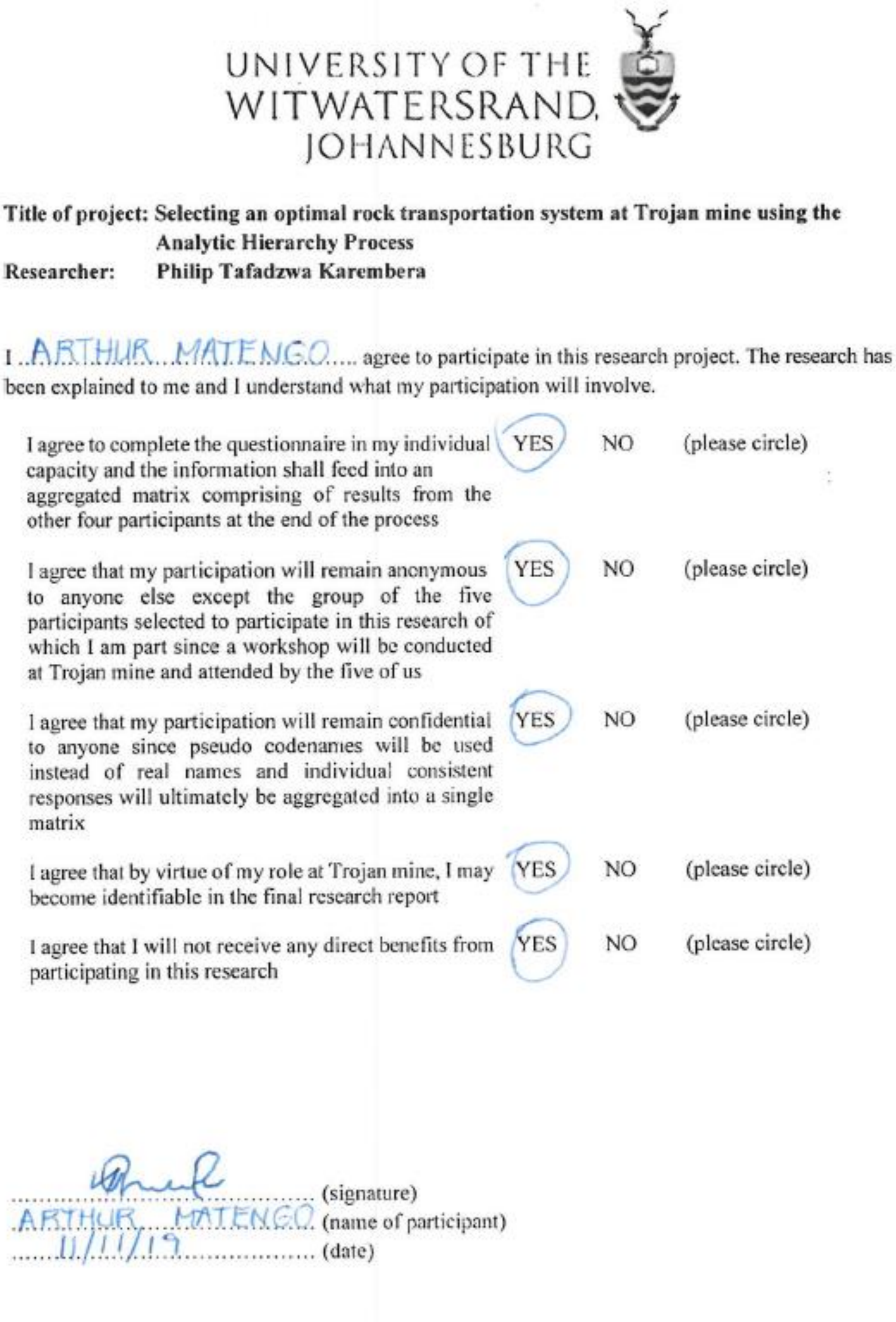
Title of project: **Selecting an optimal rock transportation system at Trojan mine using the Analytic Hierarchy Process**
Researcher: **Philip Tafadzwa Karembera**

I Kumbirai Matare agree to participate in this research project. The research has been explained to me and I understand what my participation will involve.

I agree to complete the questionnaire in my individual capacity and the information shall feed into an aggregated matrix comprising of results from the other four participants at the end of the process	[✓ YES]	NO	(please circle)
I agree that my participation will remain anonymous to anyone else except the group of the five participants selected to participate in this research of which I am part since a workshop will be conducted at Trojan mine and attended by the five of us	[✓ YES]	NO	(please circle)
I agree that my participation will remain confidential to anyone since pseudo codenames will be used instead of real names and individual consistent responses will ultimately be aggregated into a single matrix	[✓ YES]	NO	(please circle)
I agree that by virtue of my role at Trojan mine, I may become identifiable in the final research report	[✓ YES]	NO	(please circle)
I agree that I will not receive any direct benefits from participating in this research	[✓ YES]	NO	(please circle)

.... (signature)
Kumbirai Matare (name of participant)
11/11/19 (date)

Expert 2’s consent form



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

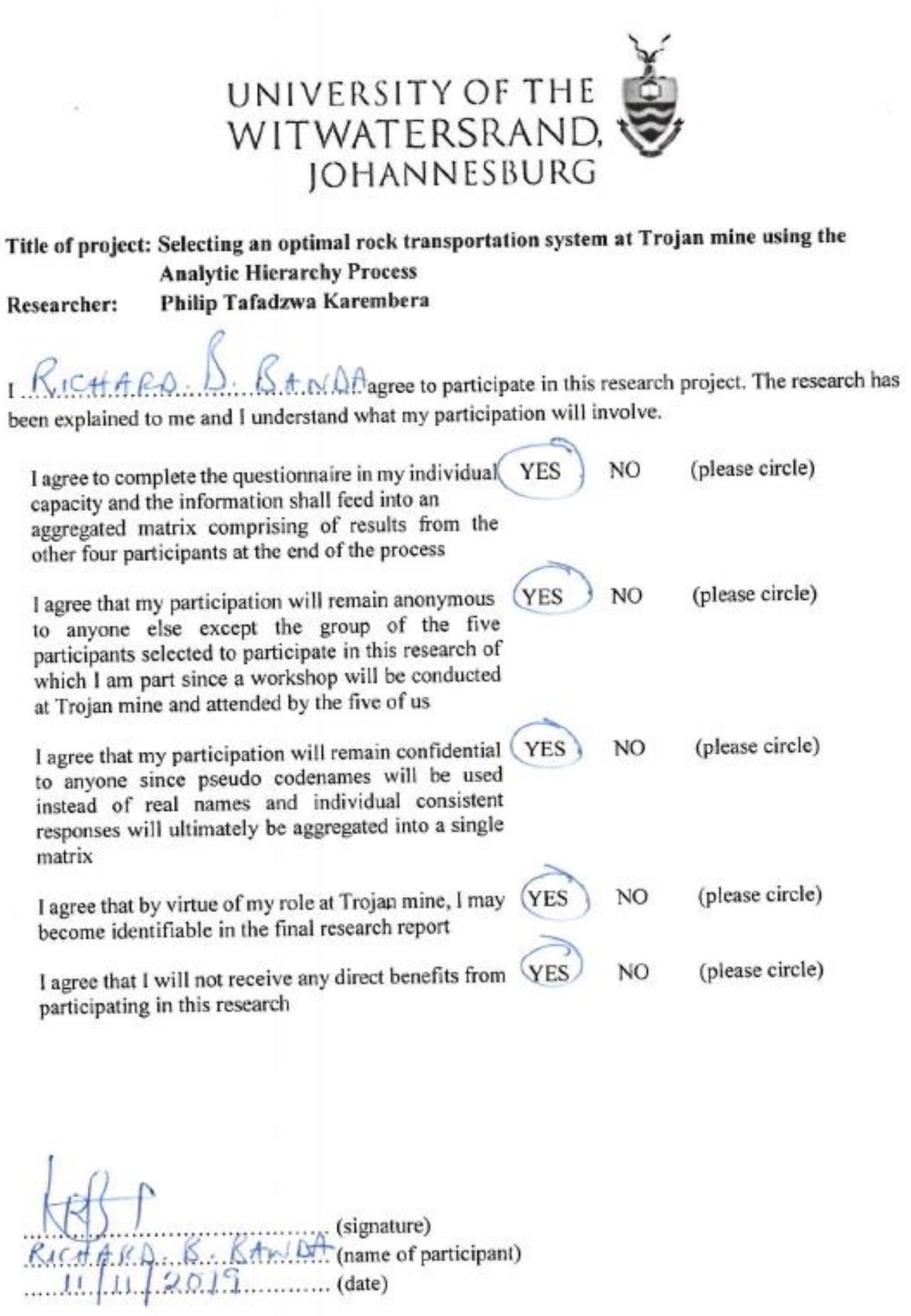
Title of project: **Selecting an optimal rock transportation system at Trojan mine using the Analytic Hierarchy Process**
Researcher: **Philip Tafadzwa Karembera**

I ..ARTHUR...MATENGO..... agree to participate in this research project. The research has been explained to me and I understand what my participation will involve.

I agree to complete the questionnaire in my individual capacity and the information shall feed into an aggregated matrix comprising of results from the other four participants at the end of the process	[✓ YES]	NO	(please circle)
I agree that my participation will remain anonymous to anyone else except the group of the five participants selected to participate in this research of which I am part since a workshop will be conducted at Trojan mine and attended by the five of us	[✓ YES]	NO	(please circle)
I agree that my participation will remain confidential to anyone since pseudo codenames will be used instead of real names and individual consistent responses will ultimately be aggregated into a single matrix	[✓ YES]	NO	(please circle)
I agree that by virtue of my role at Trojan mine, I may become identifiable in the final research report	[✓ YES]	NO	(please circle)
I agree that I will not receive any direct benefits from participating in this research	[✓ YES]	NO	(please circle)

.... (signature)
.ARTHUR....MATENGO. (name of participant)
.......11/11/19.................. (date)

Expert 3’s consent form



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

Title of project: **Selecting an optimal rock transportation system at Trojan mine using the Analytic Hierarchy Process**

Researcher: **Philip Tafadzwa Karembera**

I RICHARD. B. BANDA agree to participate in this research project. The research has been explained to me and I understand what my participation will involve.

I agree to complete the questionnaire in my individual capacity and the information shall feed into an aggregated matrix comprising of results from the other four participants at the end of the process [✓ YES] NO (please circle)

I agree that my participation will remain anonymous to anyone else except the group of the five participants selected to participate in this research of which I am part since a workshop will be conducted at Trojan mine and attended by the five of us [✓ YES] NO (please circle)

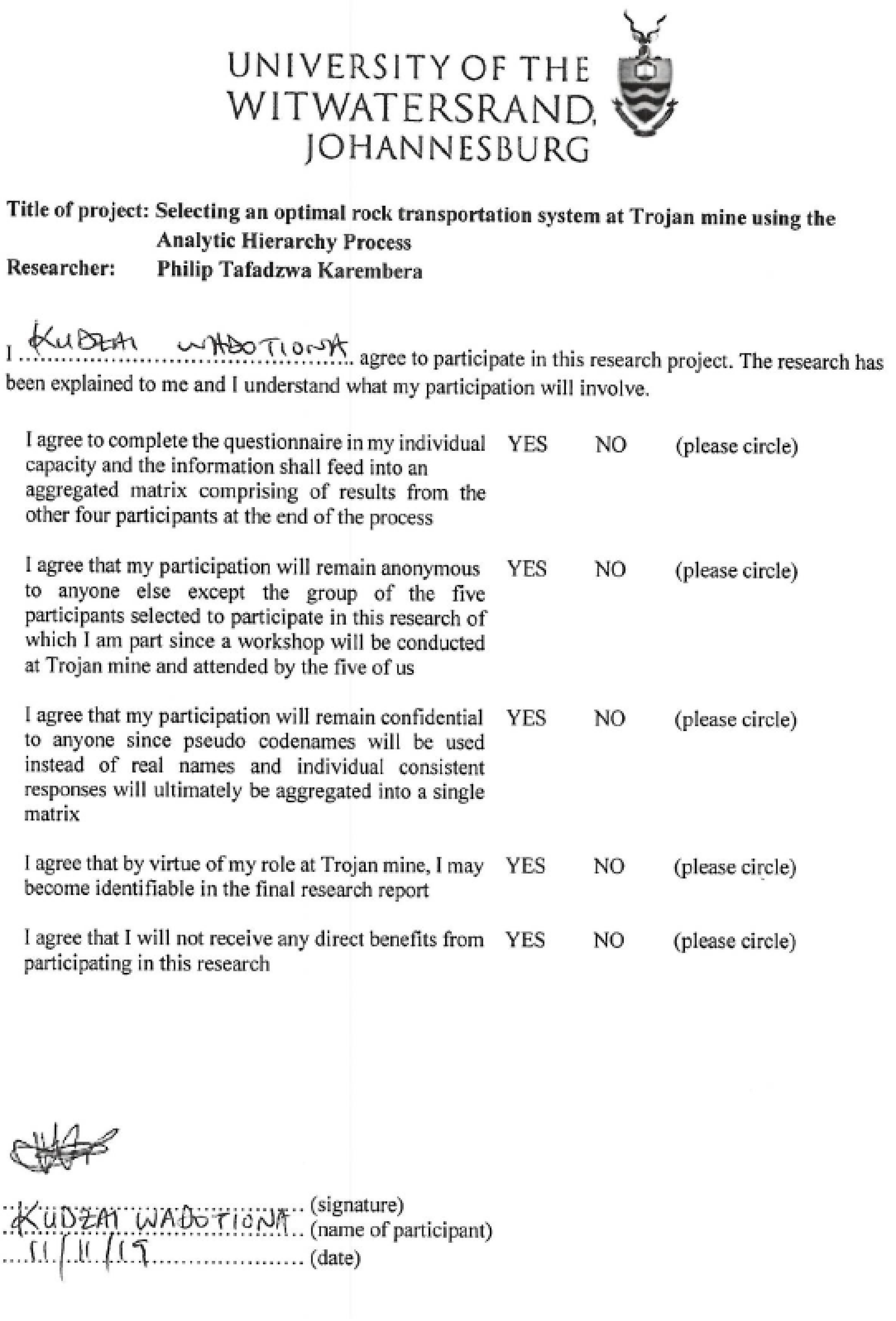
I agree that my participation will remain confidential to anyone since pseudo codenames will be used instead of real names and individual consistent responses will ultimately be aggregated into a single matrix [✓ YES] NO (please circle)

I agree that by virtue of my role at Trojan mine, I may become identifiable in the final research report [✓ YES] NO (please circle)

I agree that I will not receive any direct benefits from participating in this research [✓ YES] NO (please circle)

……………………………………. (signature)
RICHARD. B. BANDA (name of participant)
11/11/2019 (date)

Expert 4's consent form



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

Title of project: **Selecting an optimal rock transportation system at Trojan mine using the Analytic Hierarchy Process**
Researcher: **Philip Tafadzwa Karembera**

I Kudzai Wadotiona agree to participate in this research project. The research has been explained to me and I understand what my participation will involve.

I agree to complete the questionnaire in my individual capacity and the information shall feed into an aggregated matrix comprising of results from the other four participants at the end of the process YES NO (please circle)

I agree that my participation will remain anonymous to anyone else except the group of the five participants selected to participate in this research of which I am part since a workshop will be conducted at Trojan mine and attended by the five of us YES NO (please circle)

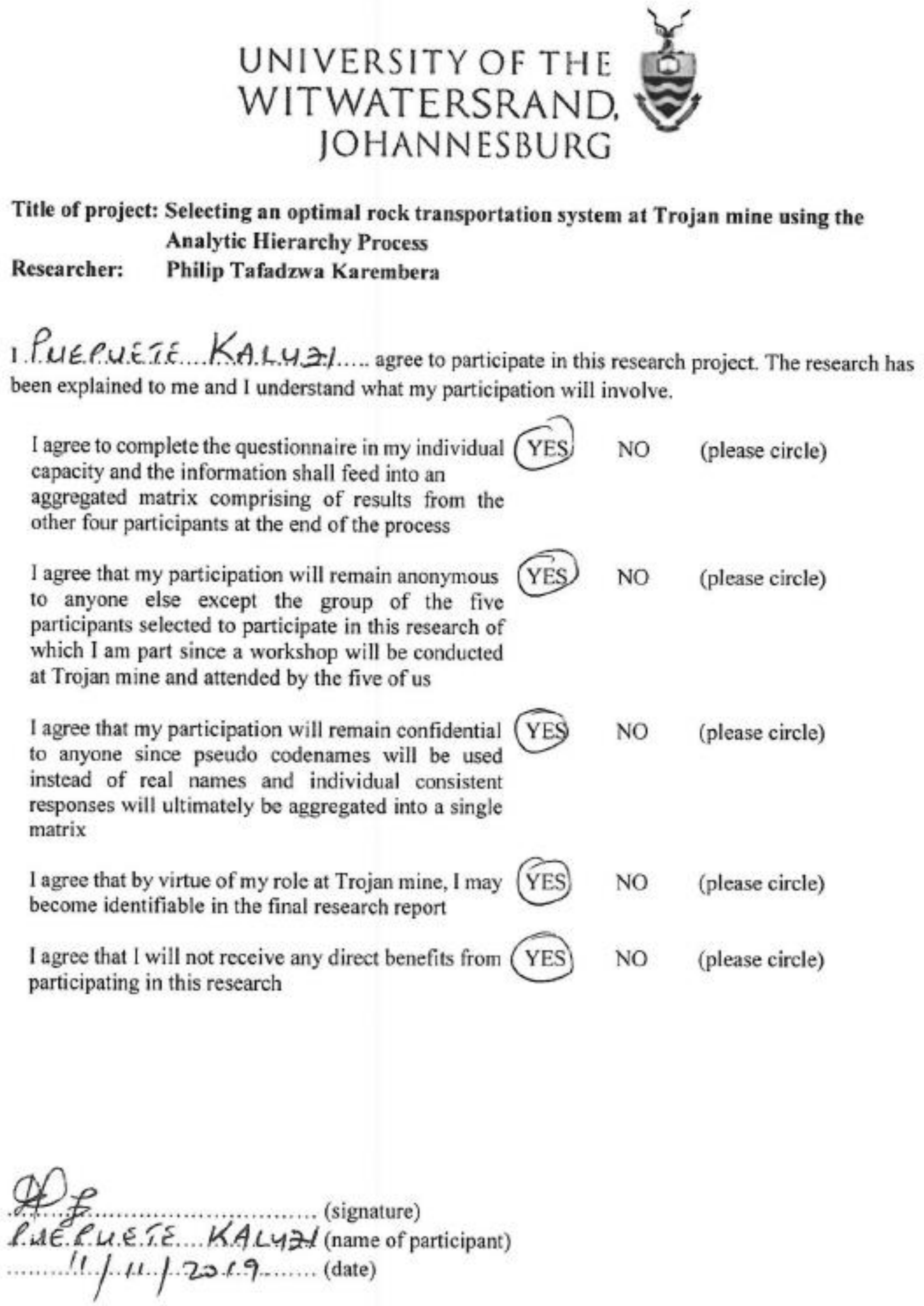
I agree that my participation will remain confidential to anyone since pseudo codenames will be used instead of real names and individual consistent responses will ultimately be aggregated into a single matrix YES NO (please circle)

I agree that by virtue of my role at Trojan mine, I may become identifiable in the final research report YES NO (please circle)

I agree that I will not receive any direct benefits from participating in this research YES NO (please circle)

.... (signature)
KUDZAI WADOTIONA (name of participant)
11/11/19 (date)

Expert 5's consent form



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

Title of project: **Selecting an optimal rock transportation system at Trojan mine using the Analytic Hierarchy Process**
Researcher: **Philip Tafadzwa Karembera**

I PUEPUETE KALUZI agree to participate in this research project. The research has been explained to me and I understand what my participation will involve.

I agree to complete the questionnaire in my individual capacity and the information shall feed into an aggregated matrix comprising of results from the other four participants at the end of the process	[✓ YES]	NO	(please circle)
I agree that my participation will remain anonymous to anyone else except the group of the five participants selected to participate in this research of which I am part since a workshop will be conducted at Trojan mine and attended by the five of us	[✓ YES]	NO	(please circle)
I agree that my participation will remain confidential to anyone since pseudo codenames will be used instead of real names and individual consistent responses will ultimately be aggregated into a single matrix	[✓ YES]	NO	(please circle)
I agree that by virtue of my role at Trojan mine, I may become identifiable in the final research report	[✓ YES]	NO	(please circle)
I agree that I will not receive any direct benefits from participating in this research	[✓ YES]	NO	(please circle)

.... (signature)
PUEPUETE KALUZI (name of participant)
11/11/2019 (date)

Appendix 8.5: Selection of evaluation criteria - Questionnaire (sample)

UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

Questionnaire 1 – Selection of evaluation criteria

This questionnaire is part of a research to aid in gathering information in selecting an optimal rock transportation system at Trojan mine’s 37/0L and 39/0L haulages from chutes to the main passes. The methodology used is the Analytic Hierarchy Process (AHP) and is based on the assignment of pair-wise judgements to compare available alternatives based on selected evaluation criteria. Three alternatives have been considered namely: rail (trolley locomotive); belt conveyor; and truck haulage. The evaluation criteria are to be selected as follows:

1. Choose the underground transportation system you have had experience with by checking the box next to the system

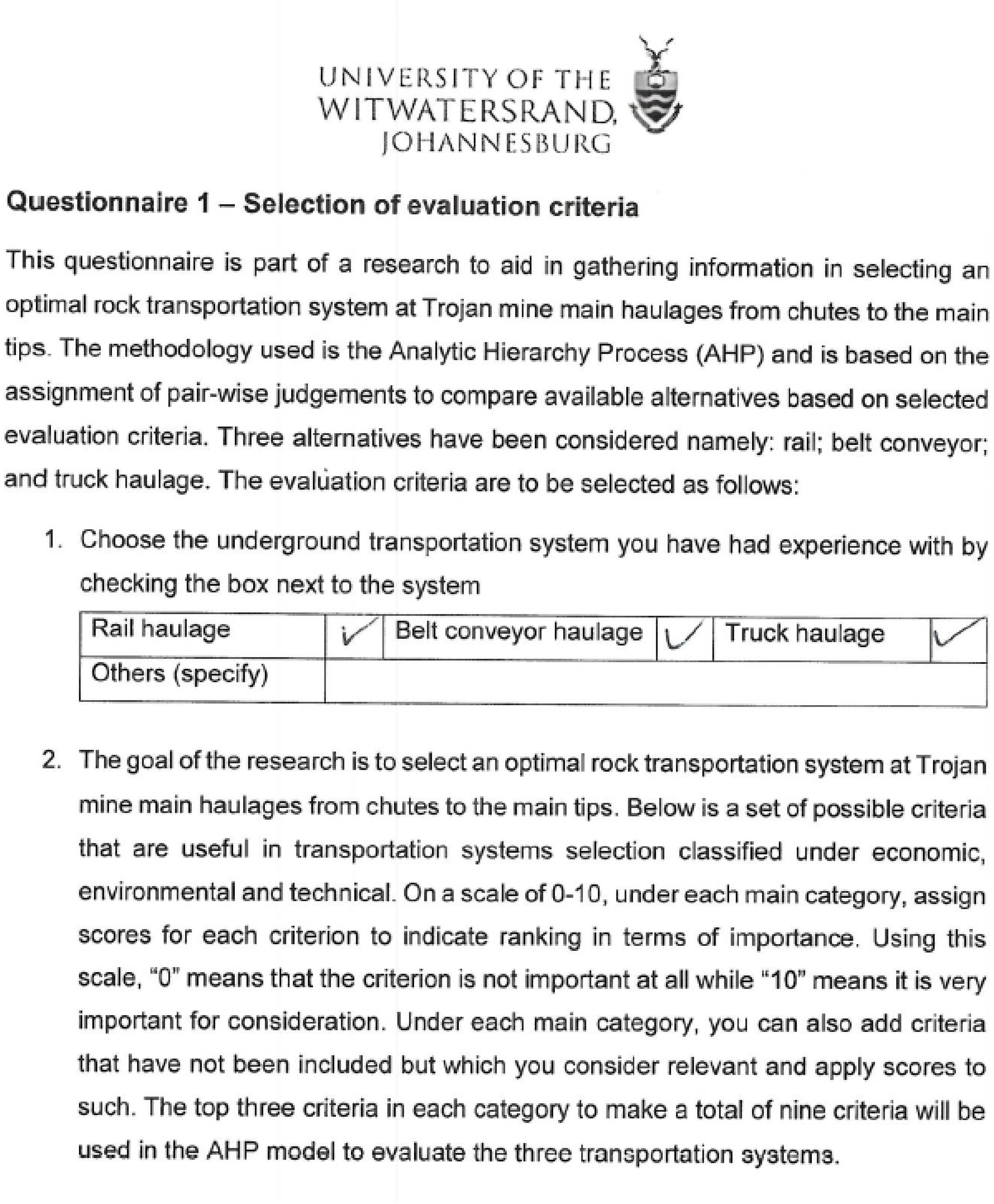
Rail haulage		Belt conveyor haulage		Truck haulage	
Others (specify)					

2. The goal of the research is to select an optimal rock transportation system at Trojan mine’s 37/0L and 39/0L haulages from chutes to the main passes. Below is a set of possible criteria that are useful in transportation systems selection classified under economic, environmental and technical. On a scale of 0-10, under each main category, assign scores for each criterion to indicate ranking in terms of importance. Using this scale, “0” means that the criterion is not important at all while “10” means it is very important for consideration. Under each main category, you can also add criteria that have not been included but which you consider relevant and apply scores to such. The top three criteria in each category to make a total of nine criteria will be used in the AHP model to evaluate the three transportation systems.

Category	**Criteria**	**Importance score (Scale: 0-10)**
Economic	Capital cost Unit operating cost Labour cost Maintenance cost Unit energy cost **Other criteria:**	
Environmental	Aesthetics Gas emissions Noise Dust Heat **Other criteria:**	
Technical	Productivity Safety Availability Ease of configuration Degree of automation General supervision required Maintainability Power source (diesel, electric) Auxiliary machine required Logistic support or management Drive system (hydraulic, electric, mechanical) Administration Operator capability Site or deposit parameters **Other criteria:**	

Appendix 8.6: Selection of evaluation criteria by the five experts (completed questionnaires)

Expert 1's response



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Questionnaire 1 – Selection of evaluation criteria

This questionnaire is part of a research to aid in gathering information in selecting an optimal rock transportation system at Trojan mine main haulages from chutes to the main tips. The methodology used is the Analytic Hierarchy Process (AHP) and is based on the assignment of pair-wise judgements to compare available alternatives based on selected evaluation criteria. Three alternatives have been considered namely: rail; belt conveyor; and truck haulage. The evaluation criteria are to be selected as follows:

1. Choose the underground transportation system you have had experience with by checking the box next to the system

Rail haulage	✓	Belt conveyor haulage	✓	Truck haulage	✓
Others (specify)					

2. The goal of the research is to select an optimal rock transportation system at Trojan mine main haulages from chutes to the main tips. Below is a set of possible criteria that are useful in transportation systems selection classified under economic, environmental and technical. On a scale of 0-10, under each main category, assign scores for each criterion to indicate ranking in terms of importance. Using this scale, "0" means that the criterion is not important at all while "10" means it is very important for consideration. Under each main category, you can also add criteria that have not been included but which you consider relevant and apply scores to such. The top three criteria in each category to make a total of nine criteria will be used in the AHP model to evaluate the three transportation systems.

Category	**Criteria**	**Importance score (Scale: 0-10)**
Economic	Capital cost Operating cost Labour cost Maintenance cost Energy cost **Others** None	9 7 4 5 5 —
Environmental	Aesthetics Emissions Noise Dust Heat **Others** None	3 5 5 5 5 —
Technical	Productivity Safety Availability Ease of configuration Degree of automation General supervision required Maintainability Power source (diesel, electric) Auxiliary machine required Logistic support or management Drive system (hydraulic, electric, mechanical) Administration Operator capability Site or deposit parameters **Others** None	8 7 8 7 7 7 5 5 0 4 8 2 3 0 —

Expert 2's response

UNIVERSITY OF THE
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JOHANNESBURG

Questionnaire 1 – Selection of evaluation criteria

This questionnaire is part of a research to aid in gathering information in selecting an optimal rock transportation system at Trojan mine main haulages from chutes to the main tips. The methodology used is the Analytic Hierarchy Process (AHP) and is based on the assignment of pair-wise judgements to compare available alternatives based on selected evaluation criteria. Three alternatives have been considered namely: rail; belt conveyor; and truck haulage. The evaluation criteria are to be selected as follows:

1. Choose the underground transportation system you have had experience with by checking the box next to the system

Rail haulage	✓	Belt conveyor haulage	✓	Truck haulage	✓
Others (specify)					

2. The goal of the research is to select an optimal rock transportation system at Trojan mine main haulages from chutes to the main tips. Below is a set of possible criteria that are useful in transportation systems selection classified under economic, environmental and technical. On a scale of 0-10, under each main category, assign scores for each criterion to indicate ranking in terms of importance. Using this scale, "0" means that the criterion is not important at all while "10" means it is very important for consideration. Under each main category, you can also add criteria that have not been included but which you consider relevant and apply scores to such. The top three criteria in each category to make a total of nine criteria will be used in the AHP model to evaluate the three transportation systems.

Category	Criteria	Importance score (Scale: 0-10)
Economic	Capital cost	8
	Operating cost	6
	Labour cost	7
	Maintenance cost	5
	Energy cost	7
	Others None	–
Environmental	Aesthetics	7
	Emissions	8
	Noise	6
	Dust	6
	Heat	6
	Others None	–
Technical	Productivity	8
	Safety	9
	Availability	8
	Ease of configuration	5
	Degree of automation	5
	General supervision required	7
	Maintainability	7
	Power source (diesel, electric)	5
	Auxiliary machine required	2
	Logistic support or management	5
	Drive system (hydraulic, electric, mechanical)	5
	Administration	5
	Operator capability	5
	Site or deposit parameters	5
	Others None	–

Expert 3’s response

UNIVERSITY OF THE
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JOHANNESBURG

Questionnaire 1 – Selection of evaluation criteria

This questionnaire is part of a research to aid in gathering information in selecting an optimal rock transportation system at Trojan mine main haulages from chutes to the main tips. The methodology used is the Analytic Hierarchy Process (AHP) and is based on the assignment of pair-wise judgements to compare available alternatives based on selected evaluation criteria. Three alternatives have been considered namely: rail; belt conveyor; and truck haulage. The evaluation criteria are to be selected as follows:

1. Choose the underground transportation system you have had experience with by checking the box next to the system

Rail haulage	✓	Belt conveyor haulage	✓	Truck haulage	✓
Others (specify)					

2. The goal of the research is to select an optimal rock transportation system at Trojan mine main haulages from chutes to the main tips. Below is a set of possible criteria that are useful in transportation systems selection classified under economic, environmental and technical. On a scale of 0-10, under each main category, assign scores for each criterion to indicate ranking in terms of importance. Using this scale, “0” means that the criterion is not important at all while “10” means it is very important for consideration. Under each main category, you can also add criteria that have not been included but which you consider relevant and apply scores to such. The top three criteria in each category to make a total of nine criteria will be used in the AHP model to evaluate the three transportation systems.

Category	**Criteria**	**Importance score (Scale: 0-10)**
Economic	Capital cost	10
	Operating cost	10
	Labour cost	2
	Maintenance cost	10
	Energy cost	6
	Others None	—
Environmental	Aesthetics	0
	Emissions	10
	Noise	8
	Dust	8
	Heat	6
	Others None	—
Technical	Productivity	2
	Safety	8
	Availability	8
	Ease of configuration	5
	Degree of automation	5
	General supervision required	5
	Maintainability	6
	Power source (diesel, electric)	6
	Auxiliary machine required	4
	Logistic support or management	4
	Drive system (hydraulic, electric, mechanical)	8
	Administration	4
	Operator capability	6
	Site or deposit parameters	2
	Others None	—

Expert 4's response

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JOHANNESBURG

Questionnaire 1 – Selection of evaluation criteria

This questionnaire is part of a research to aid in gathering information in selecting an optimal rock transportation system at Trojan mine main haulages from chutes to the main tips. The methodology used is the Analytic Hierarchy Process (AHP) and is based on the assignment of pair-wise judgements to compare available alternatives based on selected evaluation criteria. Three alternatives have been considered namely: rail; belt conveyor; and truck haulage. The evaluation criteria are to be selected as follows:

1. Choose the underground transportation system you have had experience with by checking the box next to the system

Rail haulage	✓	Belt conveyor haulage	✓	Truck haulage	✓
Others (specify)					

2. The goal of the research is to select an optimal rock transportation system at Trojan mine main haulages from chutes to the main tips. Below is a set of possible criteria that are useful in transportation systems selection classified under economic, environmental and technical. On a scale of 0-10, under each main category, assign scores for each criterion to indicate ranking in terms of importance. Using this scale, "0" means that the criterion is not important at all while "10" means it is very important for consideration. Under each main category, you can also add criteria that have not been included but which you consider relevant and apply scores to such. The top three criteria in each category to make a total of nine criteria will be used in the AHP model to evaluate the three transportation systems.

Category	**Criteria**	**Importance score (Scale: 0-10)**
Economic	Capital cost	10
	Operating cost	9
	Labour cost	8
	Maintenance cost	9
	Energy cost	10
	Others	-
	None	
Environmental	Aesthetics	6
	Emissions	9
	Noise	8
	Dust	8
	Heat	9
	Others	
	None	-
Technical	Productivity	10
	Safety	10
	Availability	10
	Ease of configuration	7
	Degree of automation	6
	General supervision required	9
	Maintainability	7
	Power source (diesel, electric)	6
	Auxiliary machine required	4
	Logistic support or management	6
	Drive system (hydraulic, electric, mechanical)	7
	Administration	6
	Operator capability	9
	Site or deposit parameters	8
	Others	
	None	-

Expert 5's response

UNIVERSITY OF THE
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JOHANNESBURG

Questionnaire 1 – Selection of evaluation criteria

This questionnaire is part of a research to aid in gathering information in selecting an optimal rock transportation system at Trojan mine main haulages from chutes to the main tips. The methodology used is the Analytic Hierarchy Process (AHP) and is based on the assignment of pair-wise judgements to compare available alternatives based on selected evaluation criteria. Three alternatives have been considered namely: rail; belt conveyor; and truck haulage. The evaluation criteria are to be selected as follows:

1. Choose the underground transportation system you have had experience with by checking the box next to the system

Rail haulage	✓	Belt conveyor haulage	✓	Truck haulage	✓
Others (specify)					

2. The goal of the research is to select an optimal rock transportation system at Trojan mine main haulages from chutes to the main tips. Below is a set of possible criteria that are useful in transportation systems selection classified under economic, environmental and technical. On a scale of 0-10, under each main category, assign scores for each criterion to indicate ranking in terms of importance. Using this scale, "0" means that the criterion is not important at all while "10" means it is very important for consideration. Under each main category, you can also add criteria that have not been included but which you consider relevant and apply scores to such. The top three criteria in each category to make a total of nine criteria will be used in the AHP model to evaluate the three transportation systems.

Category	**Criteria**	**Importance score (Scale: 0-10)**
Economic	Capital cost	10
	Operating cost	10
	Labour cost	10
	Maintenance cost	8
	Energy cost	10
	Others NONE	—
Environmental	Aesthetics	6
	Emissions	4
	Noise	5
	Dust	5
	Heat	5
	Others NONE	—
Technical	Productivity	10
	Safety	10
	Availability	10
	Ease of configuration	8
	Degree of automation	8
	General supervision required	4
	Maintainability	7
	Power source (diesel, electric)	8
	Auxiliary machine required	4
	Logistic support or management	4
	Drive system (hydraulic, electric, mechanical)	8
	Administration	4
	Operator capability	6
	Site or deposit parameters	8
	Others NONE	—

Appendix 8.7: Results of evaluation criteria selection by experts

		Importance score (Scale: 0-10)					Mean score	Ranking
Category	**Criteria**	**E1**	**E2**	**E3**	**E4**	**E5**		
Economic	Capital cost	9	8	10	10	10	9.40	1
	Unit operating cost	7	6	10	9	10	8.40	2
	Labour cost	4	7	2	8	10	6.20	5
	Maintenance cost	5	5	10	9	8	7.40	4
	Unit energy cost	5	7	6	10	10	7.60	3
	Others							
Environmental	Aesthetics	3	4	0	6	6	3.80	4
	Emissions	5	8	10	9	4	7.20	1
	Noise	5	6	8	8	5	6.40	2
	Dust	5	6	8	8	5	6.40	2
	Heat	5	6	6	9	5	6.20	3
	Others							
Technical	Productivity	8	8	2	10	10	7.60	2
	Safety	7	9	8	10	10	8.80	1
	Availability	8	8	8	10	10	8.80	1
	Ease of configuration	7	5	5	7	8	6.40	4
	Degree of automation	7	5	5	6	8	6.20	5
	General supervision required	7	7	5	5	4	5.60	8
	Maintainability	5	7	6	7	7	6.40	4
	Power source (diesel, electric)	5	5	6	6	8	6.00	6
	Auxiliary machine required	0	2	4	4	4	2.80	12
	Logistic support or management	4	5	4	6	4	4.60	9
	Drive system (hydraulic, electric, mechanical)	8	5	8	7	8	7.20	3
	Administration	2	5	4	6	4	4.20	10
	Operator capability	3	5	6	9	6	5.80	7
	Site or deposit parameters	0	5	2	8	0	3.00	11
	Others							

Appendix 8.8: Belt conveyor system’s capital cost estimation

(Source: New Enterprise Trading, 2019a)

16E Haulage (A)

Component	UOM	Quantity	Unit cost (US$)	Total cost (US$)	Ordering Specifications
Electric motor	ea	1	5,470.53	5,470.53	100hp 550V 4 pole induction motor
Electric motor to gearbox coupling	ea	1	109.41	109.41	Fenaflex F110 Type F Tyre Coupling
Gearbox	ea	1	31,236.44	31,236.44	17 ER - U Ratio 50:1 David Brown Gearbox
Gearbox to head pulley coupling	ea	1	2,228.10	2,228.10	David Brown MD 6 Cone Ring Coupling
Belt	m	962	94.11	90,533.82	1050mm 630/5 Grade M Fireproof conveyor belt
Stringers and support brackets	lengths (6m)	73	67.12	4,899.76	127 x 64mm S355 JR Channel
Carrying idler frames & idlers	ea	281	39.30	11,043.30	Continental BB 30020-5-42 carrying idler/frame set
Return Idler frames & idlers	ea	140	40.46	5,664.40	Continental BB 30100-5-42 return idler/frame set
Head pulley	ea	1	528.47	528.47	500mm x 1200mm conveyor pulley with herringbone lagging and 80mm shaft size
Tail pulley	ea	1	564.07	564.07	500mm x 1200mm conveyor pulley with herringbone lagging and 80mm shaft size
Transfer chutes	ea	5	162.68	813.40	5 x 8mm M/S plates
Sub-total				**153,091.70**	

East Haulage (B)

Component	UOM	Quantity	Unit cost (US$)	Total cost (US$)	Ordering Specifications
Electric motor	ea	1	1,965.71	1,965.71	50hp 550V 4 pole induction motor
Electric motor to gearbox coupling	ea	1	69.34	69.34	Fenaflex F90 Type F Tyre Coupling
Gearbox	ea	1	13,508.76	13,508.76	14 ER - U Ratio 50:1 David Brown Gearbox
Gearbox to head pulley coupling	ea	1	2,228.10	2,228.10	David Brown MD 6 Cone Ring Coupling
Belt	m	412	94.11	38,773.32	1050mm 630/5 Grade M Fireproof conveyor belt
Stringers and support brackets	lengths (6m)	27	67.12	1,812.24	127 x 64mm S355 JR Channel
Carrying idler frames & idlers	ea	97	39.30	3,812.10	Continental BB 30020-5-42 carrying idler/frame set
Return Idler frames & idlers	ea	49	40.46	1,982.54	Continental BB 30100-5-42 return idler/frame set
Head pulley	ea	1	528.47	528.47	500mm x 1200mm conveyor pulley with herringbone lagging and 80mm shaft size
Tail pulley	ea	1	564.07	564.07	500mm x 1200mm conveyor pulley with herringbone lagging and 80mm shaft size
Transfer chutes	ea	5	162.68	813.40	5 x 8mm M/S plates
Sub-total				**66,058.05**	

22E Haulage (C)

Component	UOM	Quantity	Unit cost (US$)	Total cost (US$)	Ordering Specifications
Electric motor	ea	1	1,192.32	1,192.32	30hp 550V 4 pole induction motor
Electric motor to gearbox coupling	ea	1	40.89	40.89	Fenaflex F70 Type F Tyre Coupling
Gearbox	ea	1	13,508.76	13,508.76	12 ER - U Ratio 50:1 David Brown Gearbox
Gearbox to head pulley coupling	ea	1	1,118.07	1,118.07	David Brown MD 4 Cone Ring Coupling
Belt	m	194	94.11	18,257.34	1050mm 630/5 Grade M Fireproof conveyor belt
Stringers and support brackets	lengths (6m)	9	67.12	604.08	127 x 64mm S355 JR Channel
Carrying idler frames & idlers	ea	25	39.30	982.50	Continental BB 30020-5-42 carrying idler/frame set
Return Idler frames & idlers	ea	12	40.46	485.52	Continental BB 30100-5-42 return idler/frame set
Head pulley	ea	1	528.47	528.47	500mm x 1200mm conveyor pulley with herringbone lagging and 80mm shaft size
Tail pulley	ea	1	564.07	564.07	500mm x 1200mm conveyor pulley with herringbone lagging and 80mm shaft size
Transfer chutes	ea	2	162.68	325.36	5 x 8mm M/S plates
Sub-total				**37,607.38**	

West Haulage (D)

Component	UOM	Quantity	Unit cost (US$)	Total cost (US$)	Ordering Specifications
Electric motor	ea	1	1,965.71	1,965.71	50hp 550V 4 pole induction motor
Electric motor to gearbox coupling	ea	1	69.34	69.34	Fenaflex F90 Type F Tyre Coupling
Gearbox	ea	1	13,508.76	13,508.76	14 ER - U Ratio 50:1 David Brown Gearbox
Gearbox to head pulley coupling	ea	1	2,228.10	2,228.10	David Brown MD 6 Cone Ring Coupling
Belt	m	370	94.11	34,820.70	1050mm 630/5 Grade M Fireproof conveyor belt
Stringers and support brackets	lengths (6m)	24	67.12	1,610.88	127 x 64mm S355 JR Channel
Carrying idler frames & idlers	ea	83	39.30	3,261.90	Continental BB 30020-5-42 carrying idler/frame set
Return Idler frames & idlers	ea	42	40.46	1,699.32	Continental BB 30100-5-42 return idler/frame set
Head pulley	ea	1	528.47	528.47	500mm x 1200mm conveyor pulley with herringbone lagging and 80mm shaft size
Tail pulley	ea	1	564.07	564.07	500mm x 1200mm conveyor pulley with herringbone lagging and 80mm shaft size
Transfer chutes	ea	5	162.68	813.40	5 x 8mm M/S plates
Sub-total				**61,070.65**	

2W Haulage (E)

Component	UOM	Quantity	Unit cost (US$)	Total cost (US$)	Ordering Specifications
Electric motor	ea	1	1,965.71	1,965.71	50hp 550V 4 pole induction motor
Electric motor to gearbox coupling	ea	1	69.34	69.34	Fenaflex F90 Type F Tyre Coupling
Gearbox	ea	1	13,508.76	13,508.76	14 ER - U Ratio 50:1 David Brown Gearbox
Gearbox to head pulley coupling	ea	1	2,228.10	2,228.10	David Brown MD 6 Cone Ring Coupling
Belt	m	500	94.11	47,055.00	1050mm 630/5 Grade M Fireproof conveyor belt
Stringers and support brackets	lengths (6m)	35	67.12	2,349.20	127 x 64mm S355 JR Channel
Carrying idler frames & idlers	ea	127	39.30	4,991.10	Continental BB 30020-5-42 carrying idler/frame set
Return Idler frames & idlers	ea	63	22.06	1,389.78	Continental BB 30100-5-42 return idler/frame set
Head pulley	ea	1	528.47	528.47	500mm x 1200mm conveyor pulley with herringbone lagging and 80mm shaft size
Tail pulley	ea	1	564.07	564.07	500mm x 1200mm conveyor pulley with herringbone lagging and 80mm shaft size
Transfer chutes plates	ea	5	162.68	813.40	5 x 8mm M/S plates
Sub-total				**75,462.93**	
Total cost				**393,290.71**	
Tools and accessories				7,865.81	
Total cost				**401,156.52**	
Number of operating levels				2.00	
Grand total cost				**802,313.05**	

Assumptions;

1. Carrying idler frame spacing is 1.5m
2. 3 idler frames are used
3. Return idler frame spacing is 3m.
4. Continental Belt Conveyor Idlers Series 30000 accessories are used for both carrying and return frames and rollers
5. 4 pole electric motors (1440 rpm) are used
6. David Brown ER Series gearboxes with 50:1 gear ratio are used
7. Fenaflex Tyre Couplings are used for the electric motor to gearbox drive
8. David Brown Cone Ring (MD) Couplings are used for the gearbox to head pulley drive
9. All head and tail pulleys have a 500mm diameter and 1200mm width

Justification of belt conveyor system assumptions

1. A carrying idler frame spacing of 1.5 m was selected on the basis of economy. This was as a result of calculation after taking into account the maximum permissible sag allowed on the conveyor belt which should be less than 3% (Conveyor Equipment Manufacturers Association, 2002).
2. The 3 idler spacing is the most common and cheap idler set available on the mine. It was also selected on the basis that it also reduces replacement cost of worn out idler rolls.
3. The return idler frame spacing can be 2 - 3 times the carrying idler frame spacing (Conveyor Equipment Manufacturers Association, 2002). The chosen multiplier of 2 was used to arrive at a spacing of 3 m.
4. The Continental belt conveyor idlers series 30000 was chosen mainly because of the duty cycle and the ore characteristics of the conveyor. Frasers (2020) noted that the Series 30000 belt conveyor idlers are recommended for heavy material.
5. The 4 pole (1440) rpm electric motor was selected on the basis of availability and economy. It is cheaper when compared to other pole configurations.
6. The David Brown gear box ER series was chosen based on better duty and torque output with respect to other brands and gearbox configurations.
7. Fenaflex tyre couplings were selected as they are the cheapest and most flexible couplings which are widely used at Trojan mine on most equipment.
8. The David Brown cone ring (MD) couplings come with an optional cone ring coupling for the conveyors. This is a flexible, robust and cost effective coupling for torque transmission for a belt conveyor.
9. The pulley face width of 1,200 mm is standard for a 1,050 mm conveyor belt.

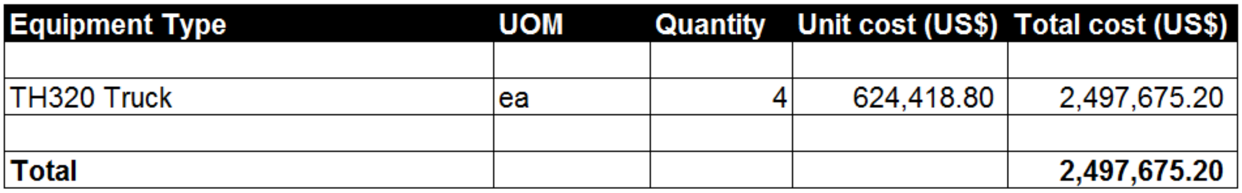
Appendix 8.9: Rail system's capital cost estimation

(Source: New Enterprise Trading, 2019b)

Item	UOM	Quantity	Unit cost (US$)	Total cost (US$)	Comments
Rails 45 lb/m	ea	204	280.25	57,233.28	n rails
45 lb fish plates	pair	202	14.83	2,998.96	(n-2) joints = (n-2) pairs of fish plates
45 lb fish plates bolts and nuts	ea	404	0.86	347.82	4 bolts & nuts/pair
45 lb right rail turn out switches	ea	3	3,092.21	9,276.63	as per layout
45 lb left rail turn out switches	ea	3	3,092.21	9,276.63	as per layout
45 lb Rail tongs	ea	2	65.94	131.88	2 pairs per year
45 lb Jim crows	ea	2	559.72	1,119.44	2 per year
Wooden sleepers	ea	1,021	73.84	75,398.84	as per rail requirements
Corch screws (for 45 lb/m rails)	ea	4,084	1.83	7,474.53	as per wooden sleeper requirements
Chutes					
Complete chute	ea	8	15,000.00	120,000.00	For 8 ore and waste passes
				283,258.01	
Rolling stock					
10T Goodman Locomotive on 24" (615mm)	ea	4	263,761.21	1,055,044.84	
5t Granby cars	ea	26	5,486.24	142,642.24	
Sub-total				**1,764,203.11**	
Tools and accessories				17,642.03	
Total				**1,781,845.14**	
Number of operating levels				2.00	
Grand total				**3,563,690.28**	

Appendix 8.10: Truck system's capital cost

(Source: Sandvik Mining and Construction, 2019)



Equipment Type	UOM	Quantity	Unit cost (US$)	Total cost (US$)
TH320 Truck	ea	4	624,418.80	2,497,675.20
Total				**2,497,675.20**

Appendix 8.11: Alternative systems unit operating and energy cost

(Source: Trojan Nickel Mine, 2019a)

Rail transport system	**FY18-19 Actual efficiencies summary**
Trammed ore and waste material (t)	308,629
Rails & fittings cost - Hoisting (US$)	2,311.52
Rails & fittings cost - Production (US$)	3,755.80
Electrical locomotives (US$)	225,301.12
Rails & locos energy cost (US$)	12,583.94
Rails & locos labour cost (US$)	105,548.74
Rails & locos total operating cost (US$)	349,501.12
Rail transport operating unit cost (US$/t)	**1.13**
Rail transport energy unit cost (US$/t)	**0.04**
Belt conveyor transport system	**FY18-19 Actual efficiencies summary**
Hoisted ore and waste material (t)	444,240
Belt conveyors componet replacement cost (US$)	91,145.50
Belt conveyors energy cost (US$)	22,546.91
Belt conveyors labour cost (US$)	66,043.69
Belt conveyors total operating cost (US$)	179,736.10
Belt conveyor transport operating unit cost (US$/t)	**0.40**
Belt conveyor transport energy unit cost (US$/t)	**0.05**
Truck transport system	**Expected efficiencies summary**
Truck annual productivity (t)	230,400
Truck transport energy cost (US$)	52,913
Truck transport operating cost (excluding energy cost) (US$)	272,175
Truck transport total operating cost (US$)	325,087.01
Truck transport operating unit cost (US$/t)	**1.41**
Truck transport energy unit cost (US$/t)	**0.23**

Appendix 8.12: Environmental efficiencies of the transport systems

(Source: Trojan Nickel Mine, 2019b)

Transport alternative	Criteria	Units	Threshold	Actual average readings	Relative weighting (with respect to threshold)
Rail	Noise	dB(A)	90	84	0.93
	Dust	mg/m^3	5	0.23	0.05
	Emissions - Nitrous fumes (NxOy)	ppm	5	0	0.00
	- Carbon monoxide (CO)	ppm	100	0	
Belt	Noise	dB(A)	90	69	0.77
	Dust	mg/m^3	5	4	0.80
	Emissions - Nitrous fumes (NxOy)	ppm	5	0	0.00
	- Carbon monoxide (CO)	ppm	100	0	
Truck	Noise	dB(A)	90	98	1.09
	Dust	mg/m^3	5	10	2.00
	Emissions - Nitrous fumes (NxOy)	ppm	5	3	0.74
	- Carbon monoxide (CO)	ppm	100	88	

Appendix 8.13: Individual and aggregated scores for the safety criterion

Expert 1

Transport system		Rail	Belt conveyor	Truck	Rail	Belt conveyor	Truck
Aspects	**Weighting**	**Performance score**	**Performance score**	**Performance score**	**Weighted score**	**Weighted score**	**Weighted score**
Operator fatigue	3	1	3	1	3	9	3
Operating at night	1	3	3	3	3	3	3
Unauthorised access risk	1	3	3	1	3	3	1
Risk of injury	2	2	3	2	4	6	4
Risk of fire	2	3	2	1	6	4	2
Sub-total					**19**	**25**	**13**

Expert 2

Transport system		Rail	Belt conveyor	Truck	Rail	Belt conveyor	Truck
Aspects	**Weighting**	**Performance score**	**Performance score**	**Performance score**	**Weighted score**	**Weighted score**	**Weighted score**
Operator fatigue	3	2	3	1	6	9	3
Operating at night	1	3	3	3	3	3	3
Unauthorised access risk	2	2	3	1	4	6	2
Risk of injury	3	2	3	1	6	9	3
Risk of fire	3	2	3	1	6	9	3
Sub-total					**25**	**36**	**14**

Expert 3

Transport system		Rail	Belt conveyor	Truck	Rail	Belt conveyor	Truck
Aspects	**Weighting**	**Performance score**	**Performance score**	**Performance score**	**Weighted score**	**Weighted score**	**Weighted score**
Operator fatigue	3	1	2	1	3	6	3
Operating at night	1	2	2	1	2	2	1
Unauthorised access risk	3	1	1	2	3	3	6
Risk of injury	3	1	2	1	3	6	3
Risk of fire	3	2	2	1	6	6	3
Sub-total					**17**	**23**	**16**

Expert 4

Transport system		Rail	Belt conveyor	Truck	Rail	Belt conveyor	Truck
Aspects	**Weighting**	**Performance score**	**Performance score**	**Performance score**	**Weighted score**	**Weighted score**	**Weighted score**
Operator fatigue	3	3	2	3	9	6	9
Operating at night	2	3	1	2	6	2	4
Unauthorised access risk	1	2	2	2	2	2	2
Risk of injury	3	3	1	1	9	3	3
Risk of fire	3	3	1	1	9	3	3
Sub-total					**35**	**16**	**21**

Expert 5

Transport system		Rail	Belt conveyor	Truck	Rail	Belt conveyor	Truck
Aspects	**Weighting**	**Performance score**	**Performance score**	**Performance score**	**Weighted score**	**Weighted score**	**Weighted score**
Operator fatigue	3	2	1	1	6	3	3
Operating at night	1	3	3	3	3	3	3
Unauthorised access risk	2	3	2	2	6	4	4
Risk of injury	3	3	2	3	9	6	9
Risk of fire	3	3	2	1	9	6	3
Sub-total					**33**	**22**	**22**

Appendix 8.14: Alternatives expected technical efficiencies

Aggregated alternatives weighted scores relative to the safety criterion

Expert Transport system	E1	E2	E3	E4	E5	Safety rating
Rail system	19	25	17	35	33	**57%**
Belt conveyor ststem	25	36	23	16	22	**54%**
Truck system	13	14	16	21	22	**38%**

Alternatives expected productivity

Criterion Transport system	Productivity (tpm)
Rail system	90,000
Belt conveyor ststem	90,000
Truck system	90,000

Alternatives expected efficiencies with respect to the availability criterion

(Source: Trojan Nickel Mine, 2019c)

Transport system	Expected availability (%)
Rail system	**94**
Belt conveyor system	**94**
Truck system	**78**

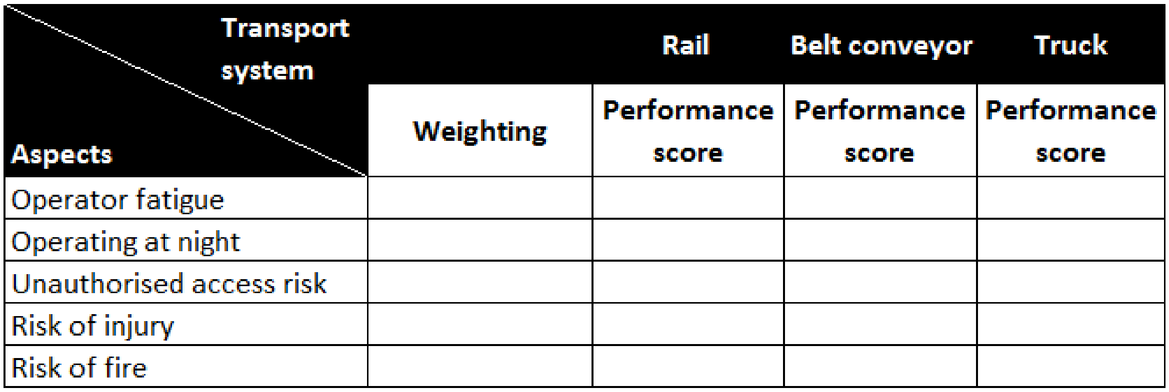
Appendix 8.15: Pair-wise comparisons (sample)

Questionnaire 2 – Pair-wise comparison template

The nine criteria that were eventually selected and their objectives are explained as shown in the following table:

Criteria	**Objectives**
Capital cost	System requiring minimum procurement capital is desired
Unit operating cost	System with minimum unit operating cost (maintenance, repairs etc.) is desired
Unit energy cost	System with minimum unit energy cost is desired
Noise	System with minimum unpleasant sound emitted to the underground environment is desired
Gas emissions	System with minimum gas emissions generated is desired
Dust	System with minimum dust generation into the general body of air is desired
Availability	System with maximum availability and higher efficiency is required
Safety	System that ensures maximum safety during operation is desired
Productivity	System with the maximum productivity is desired

The safety criterion was further split into five sub-categories namely: operator fatigue; operating at night; unauthorised access risk; risk of injury; and risk of fire. You are required to assign weights according to the importance of each sub-category on a scale of 1 to 3 in the format outlined in the table below.



Transport system Aspects		Rail	Belt conveyor	Truck
	Weighting	Performance score	Performance score	Performance score
Operator fatigue				
Operating at night				
Unauthorised access risk				
Risk of injury				
Risk of fire				

The scale of importance can be interpreted as follows: a weight of 1 implies low importance; a weight of 2 implies moderate importance; and a weight of 3 implies critical importance. The performance of each alternative is also compared against each sub-category on a performance score of 1 to 3. The performance scores can be interpreted as follows: a poor performance attracts a score of 1; a moderate performance attracts a score of 2; and an excellent performance attracts a score of 3. The performance scores are then multiplied by the corresponding weighting to obtain weighted scores which are then summed up to obtain the overall relative performance in each category with respect to each alternative.

The table below shows the scale used for assigning the pair-wise judgements:

The fundamental scale for pair-wise comparison*		
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one activity over another
5	Strong importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation

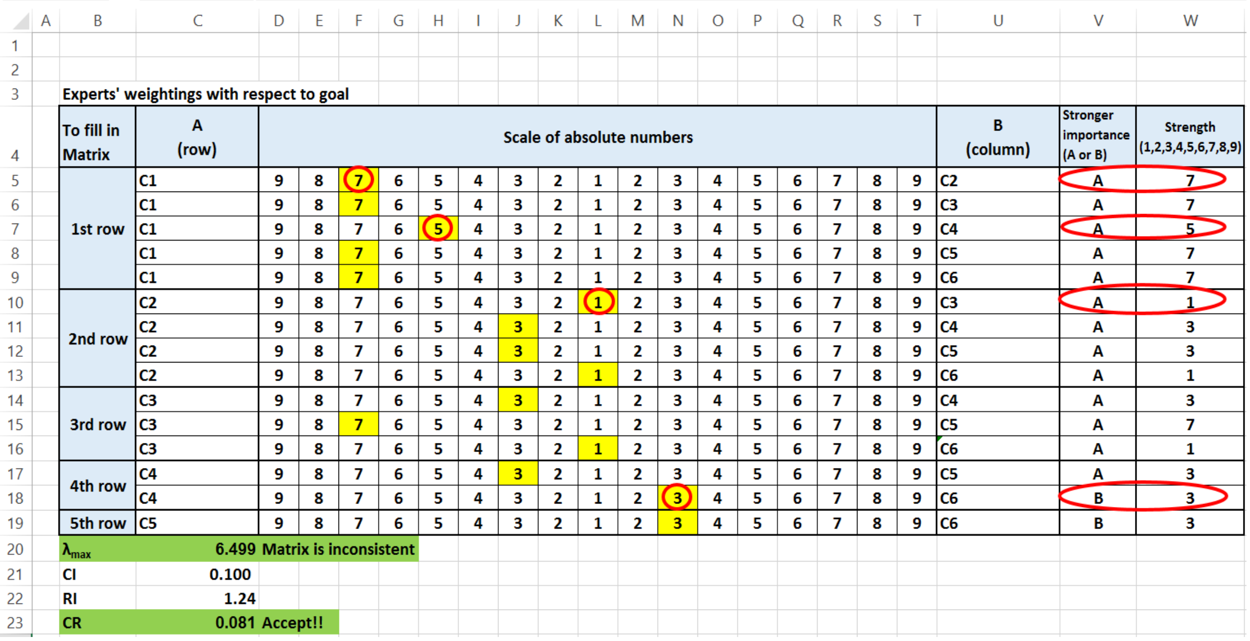
*Mid-values 2, 4, 6 and 8 can also be assumed where necessary.

Consider a hypothetical problem with the goal of selecting an optimal rock transportation system at Trojan mine main haulages from chutes to the main passes involving the following set of variables:

- Three alternatives A1, A2 and A3;
- Six criteria C1, C2, C3, C4, C5 and C6; and
- Five decision makers (DMs) or experts.

The following is an example of how a DM can assign the criteria pair-wise comparisons and the interpretation thereof with respect to the goal:

Expert’s criteria pair-wise comparison for the six criteria with respect to the goal



Experts' weightings with respect to goal

To fill in Matrix	A (row)	Scale of absolute numbers																	B (column)	Stronger importance (A or B)	Strength (1,2,3,4,5,6,7,8,9)
1st row	C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C2	A	7
	C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C3	A	7
	C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4	A	5
	C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5	A	7
	C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C6	A	7
2nd row	C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C3	A	1
	C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4	A	3
	C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5	A	3
	C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C6	A	1
3rd row	C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4	A	3
	C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5	A	7
	C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C6	A	1
4th row	C4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5	A	3
	C4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C6	B	3
5th row	C5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C6	B	3

λ_{max}	6.499	Matrix is inconsistent
CI	0.100	
RI	1.24	
CR	0.081	Accept!!

With reference to the scale for assigning pair-wise judgements, the shaded cells show the scores of the team of experts and the encircled scores can be interpreted as follows:

- The entry marked “7” in cell F5 means C1 is very strongly more important than C2 and will be summarised in columns V and W as “A 7”;
- The entry marked “5” in cell H7 means C1 is strongly more important than C4 and will be summarised in columns V and W as “A 5”;
- The entry marked “1” in cell L10 means C2 is as equally important as C3 and will be summarised in columns V and W as “A 1”; and

- The entry marked “3” in cell N18 means C6 is moderately more important than C4 and will be summarised in columns V and W as “B 3”.

At the end of the process, the most important criterion (with the highest weight) all the way down to the least important criterion (with the lowest weight) with respect to the selection goal will be identified.

Criteria pair-wise comparison for the six criteria with respect to the goal

Below is the fundamental scale for pair-wise comparison

The fundamental scale for pair-wise comparison		
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one activity over another
5	Strong importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation

*Mid-values 2, 4, 6 and 8 can also be assumed where necessary

You are required to make your criteria pair-wise comparisons with respect to the goal as explained in the hypothetical case.

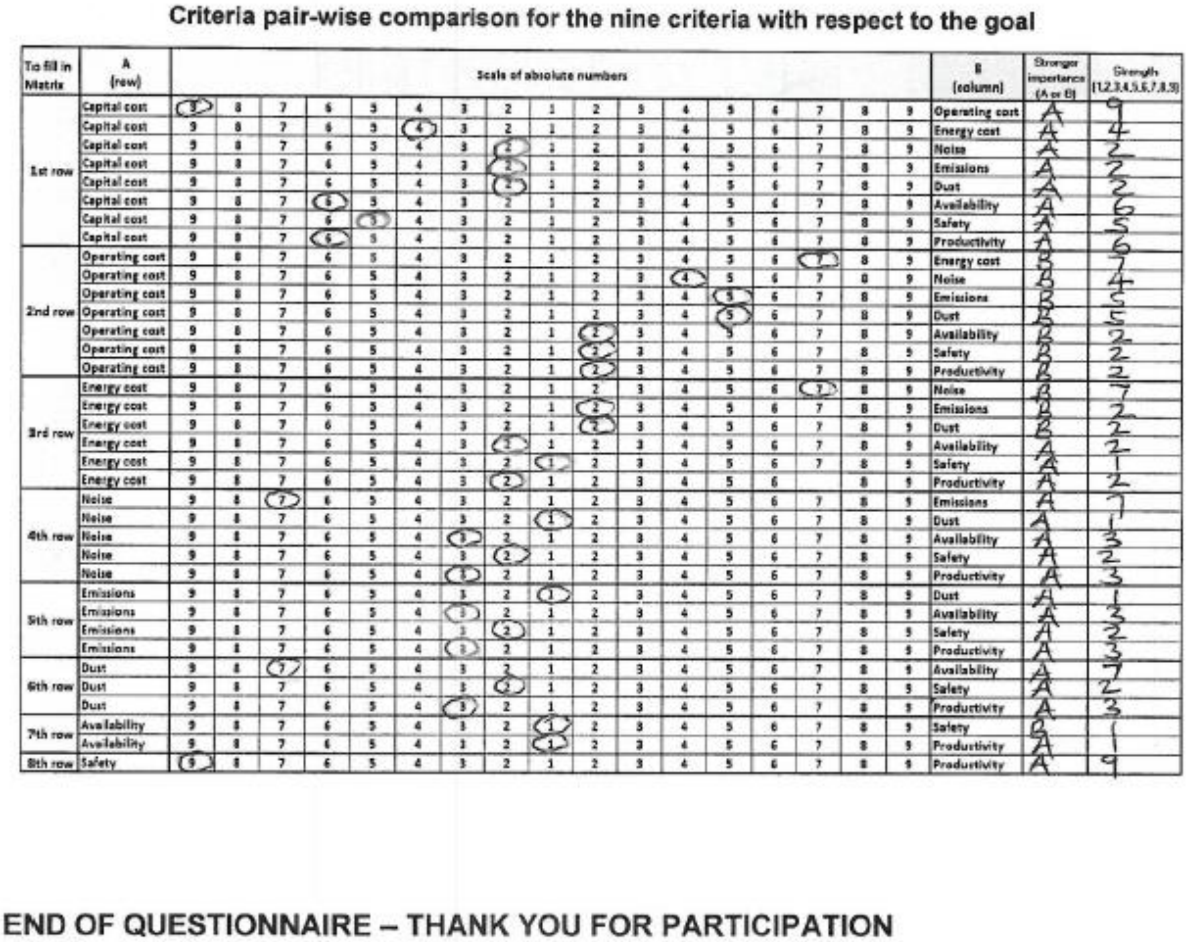
Criteria pair-wise comparison for the nine criteria with respect to the goal

To fill in Matrix	A (row)	Scale of absolute numbers																	B (column)	Stronger importance (A or B)	Strength (1,2,3,4,5,6,7,8,9)
1st row	Capital cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Unit operating cost		
	Capital cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Unit energy cost		
	Capital cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Noise		
	Capital cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Emissions		
	Capital cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Dust		
	Capital cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability		
	Capital cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety		
	Capital cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity		
2nd row	Unit operating cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Unit energy cost		
	Unit operating cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Noise		
	Unit operating cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Emissions		
	Unit operating cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Dust		
	Unit operating cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability		
	Unit operating cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety		
	Unit operating cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity		
3rd row	Unit energy cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Noise		
	Unit energy cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Emissions		
	Unit energy cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Dust		
	Unit energy cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability		
	Unit energy cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety		
	Unit energy cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6		8	9	Productivity		
4th row	Noise	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Emissions		
	Noise	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Dust		
	Noise	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability		
	Noise	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety		
	Noise	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity		
5th row	Emissions	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Dust		
	Emissions	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability		
	Emissions	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety		
	Emissions	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity		
6th row	Dust	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability		
	Dust	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety		
	Dust	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity		
7th row	Availability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety		
	Availability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity		
8th row	Safety	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity		

END OF QUESTIONNAIRE – THANK YOU FOR PARTICIPATION

Appendix 8.16: Pair-wise comparisons (actual)

Expert 1's Pair-wise comparison results

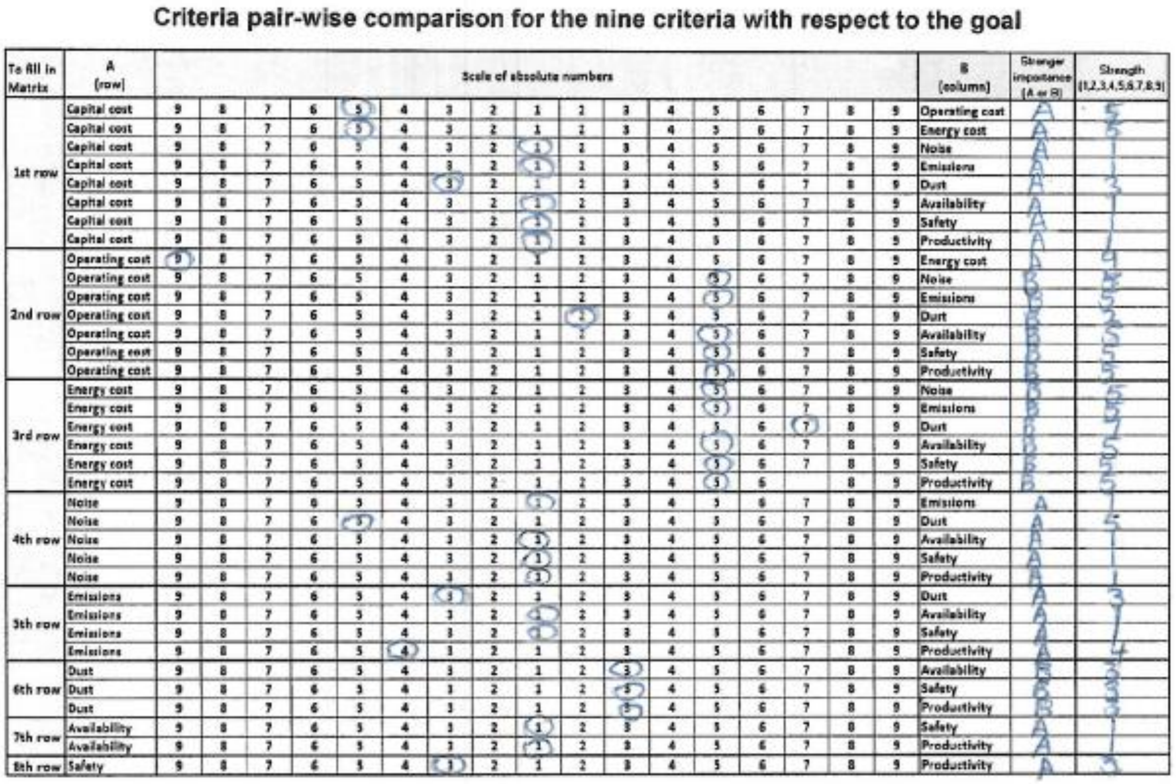


Criteria pair-wise comparison for the nine criteria with respect to the goal

To fill in Matrix	A (row)	Scale of absolute numbers																	B (column)	Stronger importance (A or B)	Strength (1,2,3,4,5,6,7,8,9)
1st row	Capital cost	[✓ 9]	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Operating cost	A	9
	Capital cost	9	8	7	6	5	[✓ 4]	3	2	1	2	3	4	5	6	7	8	9	Energy cost	A	4
	Capital cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Noise	A	2
	Capital cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Emissions	A	2
	Capital cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Dust	A	2
	Capital cost	9	8	7	[✓ 6]	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability	A	6
	Capital cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Safety	A	5
	Capital cost	9	8	7	[✓ 6]	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity	A	6
2nd row	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	[✓ 7]	8	9	Energy cost	B	7
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	[✓ 4]	5	6	7	8	9	Noise	B	4
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Emissions	B	5
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Dust	B	5
	Operating cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Availability	B	2
	Operating cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Safety	B	2
	Operating cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Productivity	B	2
3rd row	Energy cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	[✓ 7]	8	9	Noise	B	7
	Energy cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Emissions	B	2
	Energy cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Dust	B	2
	Energy cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Availability	A	2
	Energy cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	A	1
	Energy cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6		8	9	Productivity	A	2
4th row	Noise	9	8	[✓ 7]	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Emissions	A	7
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Noise	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Availability	A	3
	Noise	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Safety	A	2
	Noise	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Productivity	A	3
5th row	Emissions	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Emissions	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Availability	A	3
	Emissions	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Safety	A	2
	Emissions	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Productivity	A	3
6th row	Dust	9	8	[✓ 7]	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability	A	7
	Dust	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Safety	A	2
	Dust	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Productivity	A	3
7th row	Availability	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	B	1
	Availability	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	A	1
8th row	Safety	[✓ 9]	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity	A	9

END OF QUESTIONNAIRE – THANK YOU FOR PARTICIPATION

Expert 2’s Pair-wise comparison results



Criteria pair-wise comparison for the nine criteria with respect to the goal

To fill in Matrix	A (row)	Scale of absolute numbers																	B (column)	Stronger importance (A or B)	Strength (1,2,3,4,5,6,7,8,9)
1st row	Capital cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Operating cost	A	5
	Capital cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Energy cost	A	5
	Capital cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Noise	A	1
	Capital cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Emissions	A	1
	Capital cost	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Dust	A	3
	Capital cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Capital cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	A	1
	Capital cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	A	1
2nd row	Operating cost	[✓ 9]	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Energy cost	A	9
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Noise	B	5
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Emissions	B	5
	Operating cost	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Dust	B	2
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Availability	B	5
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Safety	B	5
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Productivity	B	5
3rd row	Energy cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Noise	B	5
	Energy cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Emissions	B	5
	Energy cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	[✓ 7]	8	9	Dust	B	7
	Energy cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Availability	B	5
	Energy cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Safety	B	5
	Energy cost	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6		8	9	Productivity	B	5
4th row	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Emissions	A	1
	Noise	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Dust	A	5
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	A	1
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	A	1
5th row	Emissions	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Dust	A	3
	Emissions	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Emissions	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	A	1
	Emissions	9	8	7	6	5	[✓ 4]	3	2	1	2	3	4	5	6	7	8	9	Productivity	A	4
6th row	Dust	9	8	7	6	5	4	3	2	1	2	[✓ 3]	4	5	6	7	8	9	Availability	B	3
	Dust	9	8	7	6	5	4	3	2	1	2	[✓ 3]	4	5	6	7	8	9	Safety	B	3
	Dust	9	8	7	6	5	4	3	2	1	2	[✓ 3]	4	5	6	7	8	9	Productivity	B	3
7th row	Availability	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	A	1
	Availability	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	A	1
8th row	Safety	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Productivity	A	3

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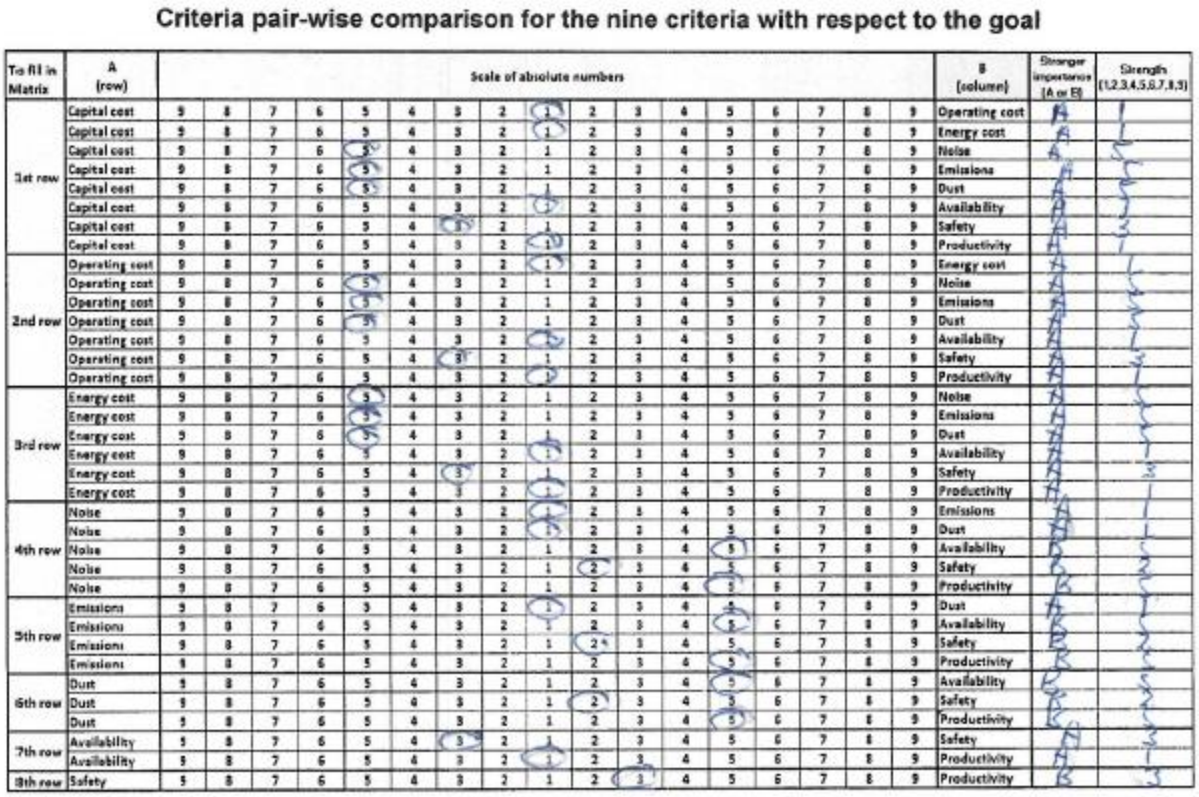
Expert 3's Pair-wise comparison results



Criteria pair-wise comparison for the nine criteria with respect to the goal

To fill in Matrix	A (row)	Scale of absolute numbers																	B (column)	Stronger importance (A or B)	Strength (1,2,3,4,5,6,7,8,9)
1st row	Capital cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Operating cost	A	1
	Capital cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Energy cost	A	1
	Capital cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Noise	A	5
	Capital cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Emissions	A	5
	Capital cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Dust	A	5
	Capital cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Capital cost	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Safety	A	3
	Capital cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	A	1
2nd row	Operating cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Energy cost	A	1
	Operating cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Noise	A	5
	Operating cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Emissions	A	5
	Operating cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Dust	A	5
	Operating cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Operating cost	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Safety	A	3
	Operating cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	A	1
3rd row	Energy cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Noise	A	5
	Energy cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Emissions	A	5
	Energy cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Dust	A	5
	Energy cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Energy cost	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Safety	A	3
	Energy cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6		8	9	Productivity	A	1
4th row	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Emissions	A	1
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Noise	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Availability	B	5
	Noise	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Safety	B	2
	Noise	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Productivity	B	5
5th row	Emissions	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Emissions	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Availability	B	5
	Emissions	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Safety	B	2
	Emissions	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Productivity	B	5
6th row	Dust	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Availability	B	5
	Dust	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Safety	B	2
	Dust	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Productivity	B	5
7th row	Availability	9	8	7	6	5	4	[✓ 3]	2	1	2	3	4	5	6	7	8	9	Safety	A	3
	Availability	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	A	1
8th row	Safety	9	8	7	6	5	4	3	2	1	2	[✓ 3]	4	5	6	7	8	9	Productivity	B	3

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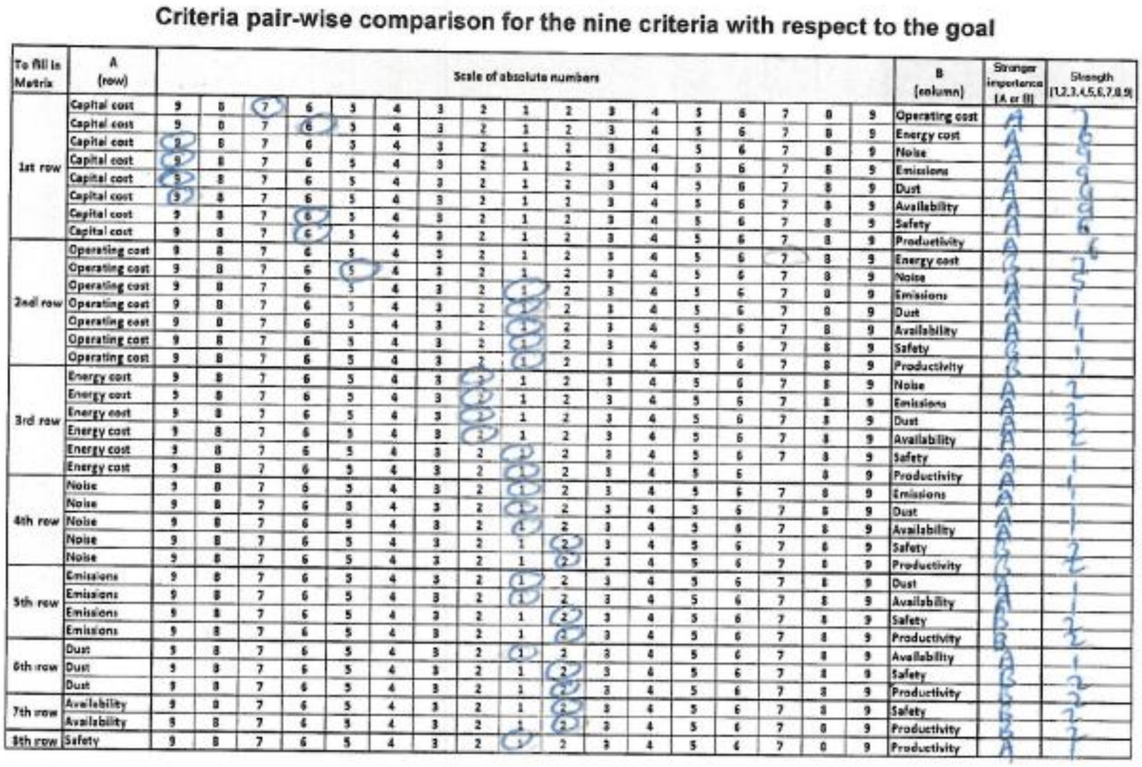
Expert 4’s Pair-wise comparison results



Criteria pair-wise comparison for the nine criteria with respect to the goal

To fill in Matrix	A (row)	Scale of absolute numbers																	B (column)	Stronger importance (A or B)	Strength (1,2,3,4,5,6,7,8,9)
1st row	Capital cost	9	8	[✓ 7]	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Operating cost	A	7
	Capital cost	9	8	7	[✓ 6]	5	4	3	2	1	2	3	4	5	6	7	8	9	Energy cost	A	6
	Capital cost	[✓ 9]	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Noise	A	9
	Capital cost	[✓ 9]	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Emissions	A	9
	Capital cost	[✓ 9]	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Dust	A	9
	Capital cost	[✓ 9]	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Availability	A	9
	Capital cost	9	8	7	[✓ 6]	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety	A	6
	Capital cost	9	8	7	[✓ 6]	5	4	3	2	1	2	3	4	5	6	7	8	9	Productivity	A	6
2nd row	Operating cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	[✓ 7]	8	9	Energy cost	B	7
	Operating cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Noise	A	5
	Operating cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Emissions	A	1
	Operating cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Operating cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Operating cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	B	1
	Operating cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	B	1
3rd row	Energy cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Noise	A	2
	Energy cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Emissions	A	2
	Energy cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Dust	A	2
	Energy cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Availability	A	2
	Energy cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	A	1
	Energy cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6		8	9	Productivity	A	1
4th row	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Emissions	A	1
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Noise	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Safety	B	2
	Noise	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Productivity	B	2
5th row	Emissions	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Emissions	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Emissions	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Safety	B	2
	Emissions	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Productivity	B	2
6th row	Dust	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Dust	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Safety	B	2
	Dust	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Productivity	B	2
7th row	Availability	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Safety	B	2
	Availability	9	8	7	6	5	4	3	2	1	[✓ 2]	3	4	5	6	7	8	9	Productivity	B	2
8th row	Safety	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	A	1

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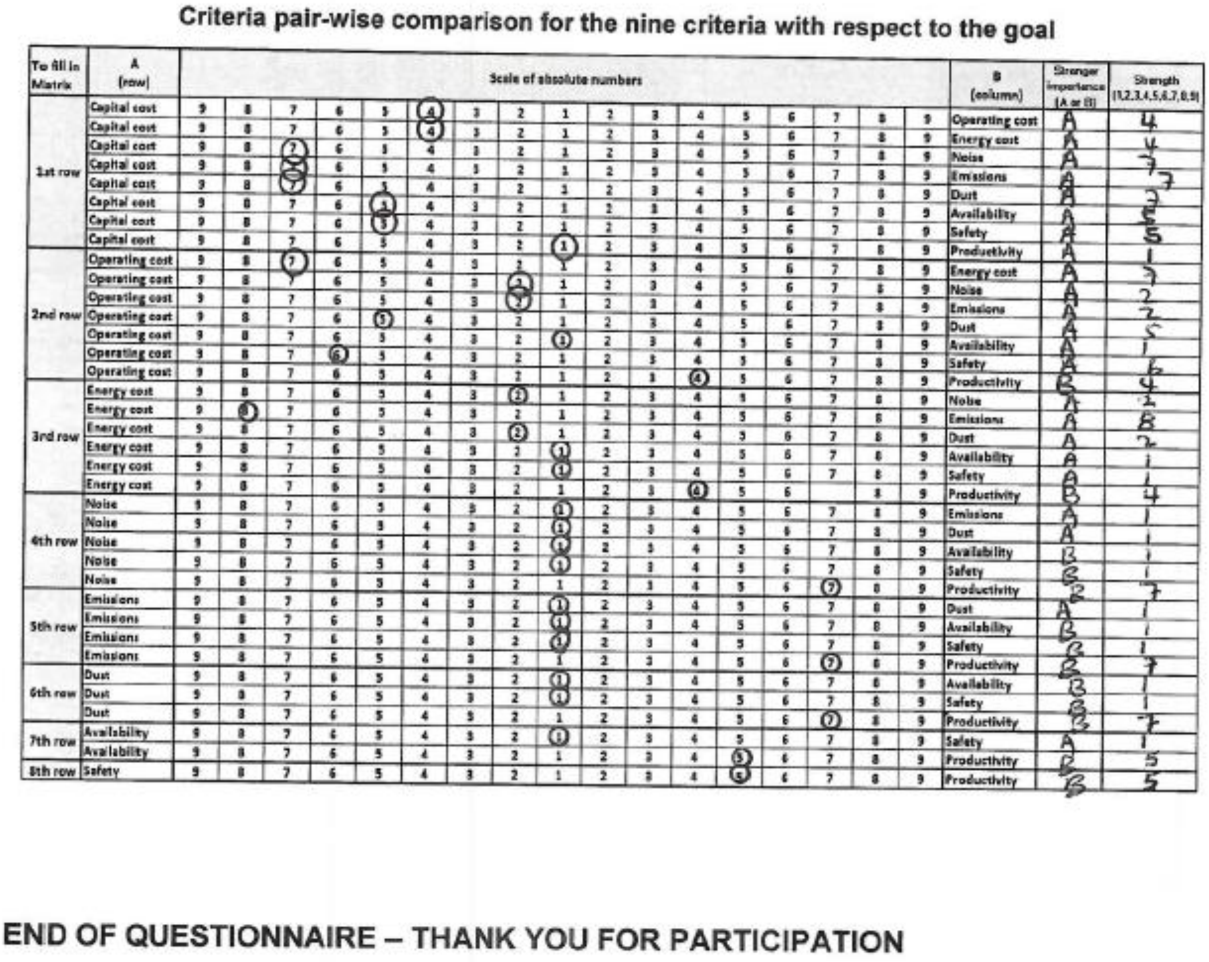
Expert 5's Pair-wise comparison results



Criteria pair-wise comparison for the nine criteria with respect to the goal

To fill in Matrix	A (row)	Scale of absolute numbers																	B (column)	Stronger importance (A or B)	Strength (1,2,3,4,5,6,7,8,9)
1st row	Capital cost	9	8	7	6	5	[✓ 4]	3	2	1	2	3	4	5	6	7	8	9	Operating cost	A	4
	Capital cost	9	8	7	6	5	[✓ 4]	3	2	1	2	3	4	5	6	7	8	9	Energy cost	A	4
	Capital cost	9	8	[✓ 7]	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Noise	A	7
	Capital cost	9	8	[✓ 7]	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Emissions	A	7
	Capital cost	9	8	[✓ 7]	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Dust	A	7
	Capital cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Availability	A	5
	Capital cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Safety	A	5
	Capital cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Productivity	A	1
2nd row	Operating cost	9	8	[✓ 7]	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Energy cost	A	7
	Operating cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Noise	A	2
	Operating cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Emissions	A	2
	Operating cost	9	8	7	6	[✓ 5]	4	3	2	1	2	3	4	5	6	7	8	9	Dust	A	5
	Operating cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Operating cost	9	8	7	[✓ 6]	5	4	3	2	1	2	3	4	5	6	7	8	9	Safety	A	6
	Operating cost	9	8	7	6	5	4	3	2	1	2	3	[✓ 4]	5	6	7	8	9	Productivity	B	4
3rd row	Energy cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Noise	A	2
	Energy cost	9	[✓ 8]	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Emissions	A	8
	Energy cost	9	8	7	6	5	4	3	[✓ 2]	1	2	3	4	5	6	7	8	9	Dust	A	2
	Energy cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	A	1
	Energy cost	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	A	1
	Energy cost	9	8	7	6	5	4	3	2	1	2	3	[✓ 4]	5	6		8	9	Productivity	B	4
4th row	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Emissions	A	1
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	B	1
	Noise	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	B	1
	Noise	9	8	7	6	5	4	3	2	1	2	3	4	5	6	[✓ 7]	8	9	Productivity	B	7
5th row	Emissions	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Dust	A	1
	Emissions	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	B	1
	Emissions	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	B	1
	Emissions	9	8	7	6	5	4	3	2	1	2	3	4	5	6	[✓ 7]	8	9	Productivity	B	7
6th row	Dust	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Availability	B	1
	Dust	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	B	1
	Dust	9	8	7	6	5	4	3	2	1	2	3	4	5	6	[✓ 7]	8	9	Productivity	B	7
7th row	Availability	9	8	7	6	5	4	3	2	[✓ 1]	2	3	4	5	6	7	8	9	Safety	A	1
	Availability	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Productivity	B	5
8th row	Safety	9	8	7	6	5	4	3	2	1	2	3	4	[✓ 5]	6	7	8	9	Productivity	B	5

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Appendix 8.17: Individual criteria pair-wise comparison and aggregation

Expert 1 CR 0.095 Accept

		1	2	3	4	5	5	6	8	9
	0	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
1	**Capital cost**	1.00	9.00	4.00	2.00	2.00	2.00	6.00	5.00	6.00
2	**Unit operating cost**	0.11	1.00	0.14	0.25	0.20	0.20	0.50	0.50	0.50
3	**Unit energy cost**	0.25	7.00	1.00	0.14	0.50	0.50	2.00	1.00	2.00
4	**Noise**	0.50	4.00	7.00	1.00	7.00	1.00	3.00	2.00	3.00
5	**Emissions**	0.50	5.00	2.00	0.14	1.00	1.00	3.00	2.00	3.00
6	**Dust**	0.50	5.00	2.00	1.00	1.00	1.00	7.00	2.00	3.00
7	**Availability**	0.17	2.00	0.50	0.33	0.33	0.14	1.00	1.00	1.00
8	**Safety**	0.20	2.00	1.00	0.50	0.50	0.50	1.00	1.00	9.00
9	**Productivity**	0.17	2.00	0.50	0.33	0.33	0.33	1.00	0.11	1.00

Expert 2 CR 0.081 Accept

		1	2	3	4	5	6	7	8	9
	Criteria	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
1	**Capital cost**	1.00	5.00	5.00	1.00	1.00	3.00	1.00	1.00	1.00
2	**Unit operating cost**	0.20	1.00	9.00	0.20	0.20	0.60	0.20	0.20	0.20
3	**Unit energy cost**	0.20	0.11	1.00	0.20	0.20	0.14	0.20	0.20	0.20
4	**Noise**	1.00	5.00	5.00	1.00	1.00	5.00	1.00	1.00	1.00
5	**Emissions**	1.00	5.00	5.00	1.00	1.00	3.00	1.00	1.00	4.00
6	**Dust**	0.33	1.67	7.00	0.20	0.33	1.00	0.33	0.33	0.33
7	**Availability**	1.00	5.00	5.00	1.00	1.00	3.00	1.00	1.00	1.00
8	**Safety**	1.00	5.00	5.00	1.00	1.00	3.00	1.00	1.00	3.00
9	**Productivity**	1.00	5.00	5.00	1.00	0.25	3.00	1.00	0.33	1.00

Expert 3 CR 0.001 Accept

		1	2	3	4	5	6	7	8	9
	Criteria	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
1	**Capital cost**	1.00	1.00	1.00	5.00	5.00	5.00	1.00	3.00	1.00
2	**Unit operating cost**	1.00	1.00	1.00	5.00	5.00	5.00	1.00	3.00	1.00
3	**Unit energy cost**	1.00	1.00	1.00	5.00	5.00	5.00	1.00	3.00	1.00
4	**Noise**	0.20	0.20	0.20	1.00	1.00	1.00	0.20	0.50	0.20
5	**Emissions**	0.20	0.20	0.20	1.00	1.00	1.00	0.20	0.50	0.20
6	**Dust**	0.20	0.20	0.20	1.00	1.00	1.00	0.20	0.50	0.20
7	**Availability**	1.00	1.00	1.00	5.00	5.00	5.00	1.00	3.00	1.00
8	**Safety**	0.33	0.33	0.33	2.00	2.00	2.00	0.33	1.00	0.33
9	**Productivity**	1.00	1.00	1.00	5.00	5.00	5.00	1.00	3.00	1.00

Expert 4 CR 0.055 Accept

		1	2	3	4	5	6	7	8	9
	Criteria	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
1	**Capital cost**	1.00	7.00	6.00	9.00	9.00	9.00	9.00	6.00	6.00
2	**Unit operating cost**	0.14	1.00	0.14	5.00	1.29	1.29	1.29	0.86	0.86
3	**Unit energy cost**	0.17	7.00	1.00	1.50	1.50	1.50	1.50	1.00	1.00
4	**Noise**	0.11	0.20	0.67	1.00	1.00	1.00	1.00	0.67	0.67
5	**Emissions**	0.11	0.78	0.67	1.00	1.00	1.00	1.00	0.67	0.67
6	**Dust**	0.11	0.78	0.67	1.00	1.00	1.00	1.00	0.67	0.67
7	**Availability**	0.11	0.78	0.67	1.00	1.00	1.00	1.00	0.67	0.67
8	**Safety**	0.17	1.17	1.00	1.50	1.50	1.50	1.50	1.00	1.00
9	**Productivity**	0.17	1.17	1.00	1.50	1.50	1.50	1.50	1.00	1.00

Expert 5 CR 0.077 Accept

		1	2	3	4	5	6	7	8	9
	Criteria	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
1	**Capital cost**	1.00	4.00	4.00	7.00	7.00	7.00	5.00	5.00	1.00
2	**Unit operating cost**	0.25	1.00	7.00	1.75	1.75	5.00	1.25	6.00	0.25
3	**Unit energy cost**	0.25	0.14	1.00	1.75	8.00	1.75	1.25	1.25	0.25
4	**Noise**	0.14	0.57	0.57	1.00	1.00	1.00	0.71	0.71	0.14
5	**Emissions**	0.14	0.57	0.13	1.00	1.00	1.00	0.71	0.71	0.14
6	**Dust**	0.14	0.20	0.57	1.00	1.00	1.00	0.71	0.71	0.14
7	**Availability**	0.20	0.80	0.80	1.40	1.40	1.40	1.00	1.00	0.20
8	**Safety**	0.20	0.17	0.80	1.40	1.40	1.40	1.00	1.00	0.20
9	**Productivity**	1.00	4.00	4.00	7.00	7.00	7.00	5.00	5.00	1.00

Aggregated matrix (geometric mean)

CR 0.009 Accept

		1	2	3	4	5	6	7	8	9
	Criteria	Capital cost	Unit operating cost	Unit energy cost	Noise	Emissions	Dust	Availability	Safety	Productivity
1	**Capital cost**	1.00	4.17	3.44	3.63	3.63	4.52	3.06	3.39	2.05
2	**Unit operating cost**	0.24	1.00	1.05	1.17	0.85	1.31	0.69	1.09	0.46
3	**Unit energy cost**	0.29	0.95	1.00	0.82	1.43	0.99	0.94	0.94	0.63
4	**Noise**	0.28	0.86	1.22	1.00	1.48	1.38	0.84	0.86	0.56
5	**Emissions**	0.28	1.17	0.70	0.68	1.00	1.25	0.84	0.86	0.74
6	**Dust**	0.22	0.76	1.01	0.72	0.80	1.00	0.80	0.69	0.45
7	**Availability**	0.33	1.44	1.06	1.18	1.18	1.25	1.00	1.15	0.67
8	**Safety**	0.29	0.92	1.06	1.16	1.16	1.45	0.87	1.00	1.12
9	**Productivity**	0.49	2.16	1.58	1.77	1.34	2.21	1.50	0.89	1.00

Appendix 8.18: NPV of the rail transport system

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Mined		505,600	505,600	575,800	790,002	787,502
Milled		505,600	505,600	575,800	790,002	787,502
Grade		1.69	1.78	1.22	0.67	0.60
% Recovery		86.1	86.6	83.5	72.0	69.1
Nickel in conc		7,345	7,775	5,876	3,798	3,282
FINANCIALS						
LME Ni Price		16,625	16,625	16,625	25,000	28,000
Realised Nickel Price		10,806	10,806	10,806	16,250	18,200
Metal (NiT)		7,345	7,775	5,876	3,798	3,282
DMT Concentrate		61,207	64,795	48,965	31,652	27,350
WMT Concentrate		66,529	70,429	53,223	34,405	29,728
Lots		63	67	50	33	28
Gross Revenue (Nickel)		78,115,174	82,694,537	62,491,948	61,073,263	59,171,042
Gross Revenue (By-Products)		3,788,586	4,010,685	3,030,859	2,962,053	2,869,796
Selling Expenses		(9,148,768)	(9,685,098)	(7,318,992)	(5,354,471)	(4,819,525)
Net Revenue		**72,754,992**	**77,020,124**	**58,203,815**	**58,680,846**	**57,221,313**
Mining Costs		(18,960,475)	(18,960,468)	(21,593,044)	(29,625,822)	(29,532,068)
Processing Costs		(9,257,633)	(9,257,630)	(10,543,010)	(14,465,091)	(14,419,315)
G&A		(5,576,304)	(5,576,304)	(5,576,304)	(5,576,304)	(5,576,304)
Shangani C&M		(243,678)	(243,678)	(243,678)	(243,678)	(243,678)
Management Fees		(1,638,075)	(1,734,104)	(1,310,456)	(1,280,706)	(1,240,817)
EBITDA		**37,078,827**	**41,247,940**	**18,937,323**	**7,489,245**	**6,209,131**

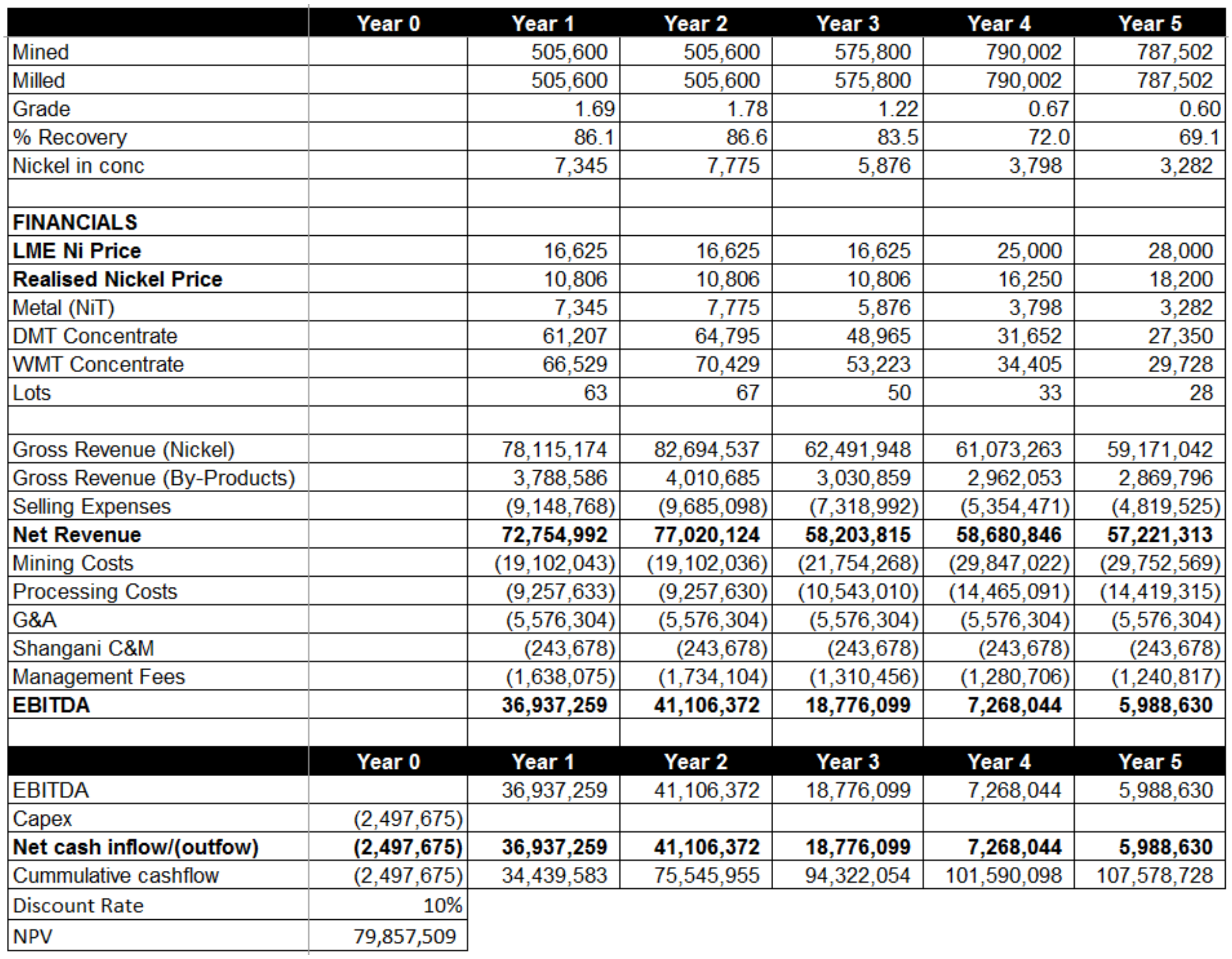
	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
EBITDA		37,078,827	41,247,940	18,937,323	7,489,245	6,209,131
Capex	(3,563,690)					
Net cash inflow/(outfow)	**(3,563,690)**	**37,078,827**	**41,247,940**	**18,937,323**	**7,489,245**	**6,209,131**
Cummulative cashflow	(3,563,690)	33,515,136	74,763,076	93,700,399	101,189,643	107,398,774
Discount Rate	10%					
NPV	79,483,698					

Appendix 8.19: NPV of the belt conveyor transport system

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Mined		505,600	505,600	575,800	790,002	787,502
Milled		505,600	505,600	575,800	790,002	787,502
Grade		1.69	1.78	1.22	0.67	0.60
% Recovery		86.1	86.6	83.5	72.0	69.1
Nickel in conc		7,345	7,775	5,876	3,798	3,282
FINANCIALS						
LME Ni Price		16,625	16,625	16,625	25,000	28,000
Realised Nickel Price		10,806	10,806	10,806	16,250	18,200
Metal (NiT)		7,345	7,775	5,876	3,798	3,282
DMT Concentrate		61,207	64,795	48,965	31,652	27,350
WMT Concentrate		66,529	70,429	53,223	34,405	29,728
Lots		63	67	50	33	28
Gross Revenue (Nickel)		78,115,174	82,694,537	62,491,948	61,073,263	59,171,042
Gross Revenue (By-Products)		3,788,586	4,010,685	3,030,859	2,962,053	2,869,796
Selling Expenses		(9,148,768)	(9,685,098)	(7,318,992)	(5,354,471)	(4,819,525)
Net Revenue		**72,754,992**	**77,020,124**	**58,203,815**	**58,680,846**	**57,221,313**
Mining Costs		(18,591,387)	(18,591,380)	(21,172,710)	(29,049,120)	(28,957,192)
Processing Costs		(9,257,633)	(9,257,630)	(10,543,010)	(14,465,091)	(14,419,315)
G&A		(5,576,304)	(5,576,304)	(5,576,304)	(5,576,304)	(5,576,304)
Shangani C&M		(243,678)	(243,678)	(243,678)	(243,678)	(243,678)
Management Fees		(1,638,075)	(1,734,104)	(1,310,456)	(1,280,706)	(1,240,817)
EBITDA		**37,447,915**	**41,617,028**	**19,357,657**	**8,065,946**	**6,784,007**

Parameter	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
EBITDA		37,447,915	41,617,028	19,357,657	8,065,946	6,784,007
Capex	(802,313)					
Net cash inflow/(outfow)	**(802,313)**	**37,447,915**	**41,617,028**	**19,357,657**	**8,065,946**	**6,784,007**
Cummulative cashflow	(802,313)	36,645,602	78,262,629	97,620,286	105,686,232	112,470,240
Discount Rate	10%					
NPV	83,546,056					

Appendix 8.20: NPV of the truck transport system



	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Mined		505,600	505,600	575,800	790,002	787,502
Milled		505,600	505,600	575,800	790,002	787,502
Grade		1.69	1.78	1.22	0.67	0.60
% Recovery		86.1	86.6	83.5	72.0	69.1
Nickel in conc		7,345	7,775	5,876	3,798	3,282
FINANCIALS						
LME Ni Price		16,625	16,625	16,625	25,000	28,000
Realised Nickel Price		10,806	10,806	10,806	16,250	18,200
Metal (NiT)		7,345	7,775	5,876	3,798	3,282
DMT Concentrate		61,207	64,795	48,965	31,652	27,350
WMT Concentrate		66,529	70,429	53,223	34,405	29,728
Lots		63	67	50	33	28
Gross Revenue (Nickel)		78,115,174	82,694,537	62,491,948	61,073,263	59,171,042
Gross Revenue (By-Products)		3,788,586	4,010,685	3,030,859	2,962,053	2,869,796
Selling Expenses		(9,148,768)	(9,685,098)	(7,318,992)	(5,354,471)	(4,819,525)
Net Revenue		**72,754,992**	**77,020,124**	**58,203,815**	**58,680,846**	**57,221,313**
Mining Costs		(19,102,043)	(19,102,036)	(21,754,268)	(29,847,022)	(29,752,569)
Processing Costs		(9,257,633)	(9,257,630)	(10,543,010)	(14,465,091)	(14,419,315)
G&A		(5,576,304)	(5,576,304)	(5,576,304)	(5,576,304)	(5,576,304)
Shangani C&M		(243,678)	(243,678)	(243,678)	(243,678)	(243,678)
Management Fees		(1,638,075)	(1,734,104)	(1,310,456)	(1,280,706)	(1,240,817)
EBITDA		**36,937,259**	**41,106,372**	**18,776,099**	**7,268,044**	**5,988,630**

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
EBITDA		36,937,259	41,106,372	18,776,099	7,268,044	5,988,630
Capex	(2,497,675)					
Net cash inflow/(outfow)	**(2,497,675)**	**36,937,259**	**41,106,372**	**18,776,099**	**7,268,044**	**5,988,630**
Cummulative cashflow	(2,497,675)	34,439,583	75,545,955	94,322,054	101,590,098	107,578,728
Discount Rate	10%					
NPV	79,857,509					