SELECTION OF AN OPTIMAL LATERAL ORE TRANSPORTATION SYSTEM USING THE ANALYTIC HIERARCHY PROCESS FOR THE BLANKET MINE EXPANSION PROJECT

Sydney Mandidi

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, 2022

DECLARATION

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

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ABSTRACT

Blanket Mine (BM) is undergoing a production ramp-up phase and has recently sunk and commissioned a new Central Shaft up to 34 Level which is 1,010m below surface, enabling it to access deeper parts of the ore body. Previously, the mine`s deepest workings were at 26 Level which is 870m below surface. The ramp-up drive by the mine has witnessed the mine introducing to its underground transport systems, trackless machinery such as Load-Haul-Dump (LHD) equipment, dump trucks and belt conveyor systems in addition to the rail system which has been operational at the mine since the mine started operations. All these underground ore transport systems have been used at BM and have performed at different efficiency levels. However, no systematic approach has been followed on the mine on which transport system was best and decisions were based more on preference or application. As the mine got deeper costs have been generally increasing. To achieve the production ramp up within the targeted costs of between US$700 – US$800 / oz of gold produced, the underground ore transport system has been identified as an area which must be optimised.

Optimisation in mining transport systems requires a system with the lowest impact on the environment that can be operated safely with best performance parameters, and with lowest overall cost. This makes the optimisation problem a multi-criteria one which must be solved using Multi-Criteria Decision Analysis (MCDA) techniques to select the optimal transport system. It was, therefore, the aim of this research study to review and select an optimal underground ore transport system to use for the BM expansion project. The literature review revealed that the Analytic Hierarchical Process (AHP), which is an MCDA technique was the most appropriate technique to use in the selection of optimal transport system(s). The AHP model was used to rank the transportation options based on three main broad criteria which are economic, environmental/safety and technical. The identified criteria were derived from a literature review of similar related studies on transport selection from other mining operations.

The research established that the belt conveyor system is the optimal system followed by the locomotive and lastly, the dump truck system. The approach used for this research can be applied to similar problems that require ranking of competing alternatives. Decision makers and management can adopt a similar approach using pairwise comparison and the AHP model in dealing with challenges associated with decision making in mining operations.

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DEDICATION

To my parents, Patrick and Smangele Mandidi. They are a blessing to me and are my source of courage and inspiration.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytical Network Process
BM	Blanket Mine
CMC	Caledonia Mining Corporation
CI	Consistency Index
CR	Consistency Ratio
dB (A)	A-Weighted Decibel
ELECTRE	Elimination Et Choix Traduisant la Re´alite´
LHD	Load-Haul-Dump
LOM	Life of Mine
MAUT	Multiple Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluation
ROM	Run of Mine
USD	United States Dollar

1 INTRODUCTION

1.1 Overview of Chapter 1

This chapter presents a historical background, information on current operations, existing strategic mine plan and key economic issues for Blanket Mine (BM). The chapter focuses on the need to examine transport options available at the mine. The chapter starts with a background on the mine layout, current production, producing ore bodies and available ore handling systems. It summarises the importance of the mine transport system as one of the major cost drivers which can impact on the mine's economic viability. The chapter gives a brief introduction of the need for a new ore transport system considering options and the basic requirements in the option selection. The discussion leads to the selection of the ore transport system using a multi-criteria decision analysis (MCDA). The research significance and research scope are discussed in this chapter. Finally, a chapter summary and outline of the report are given.

1.2 Background information

BM is a wholly owned subsidiary of Caledonia Mining Corporation (CMC), which is listed on the Toronto Stock Exchange. The mine is a relatively large-scale gold mining operation compared to other gold mines in Zimbabwe. The mine is located on the Gwanda greenstone belt in Zimbabwe and has a current annual production of over 55 000ounces (oz) of gold. The mine has been on a gradual production ramp up with production increasing from 39 000oz of gold in 2001 to a planned target of 80 000oz of gold in 2022, as per the mine's current expansion plan. The mine complex comprises of a conglomerate of several ore bodies that are geographically scattered over a 3km long north-south strike and dipping westwards. The ore bodies are mined as separate sections connected by haulages at a regular vertical spacing of 120m between consecutive haulages. The cross-sectional setup and layout for BM are illustrated in Figure 1.1.

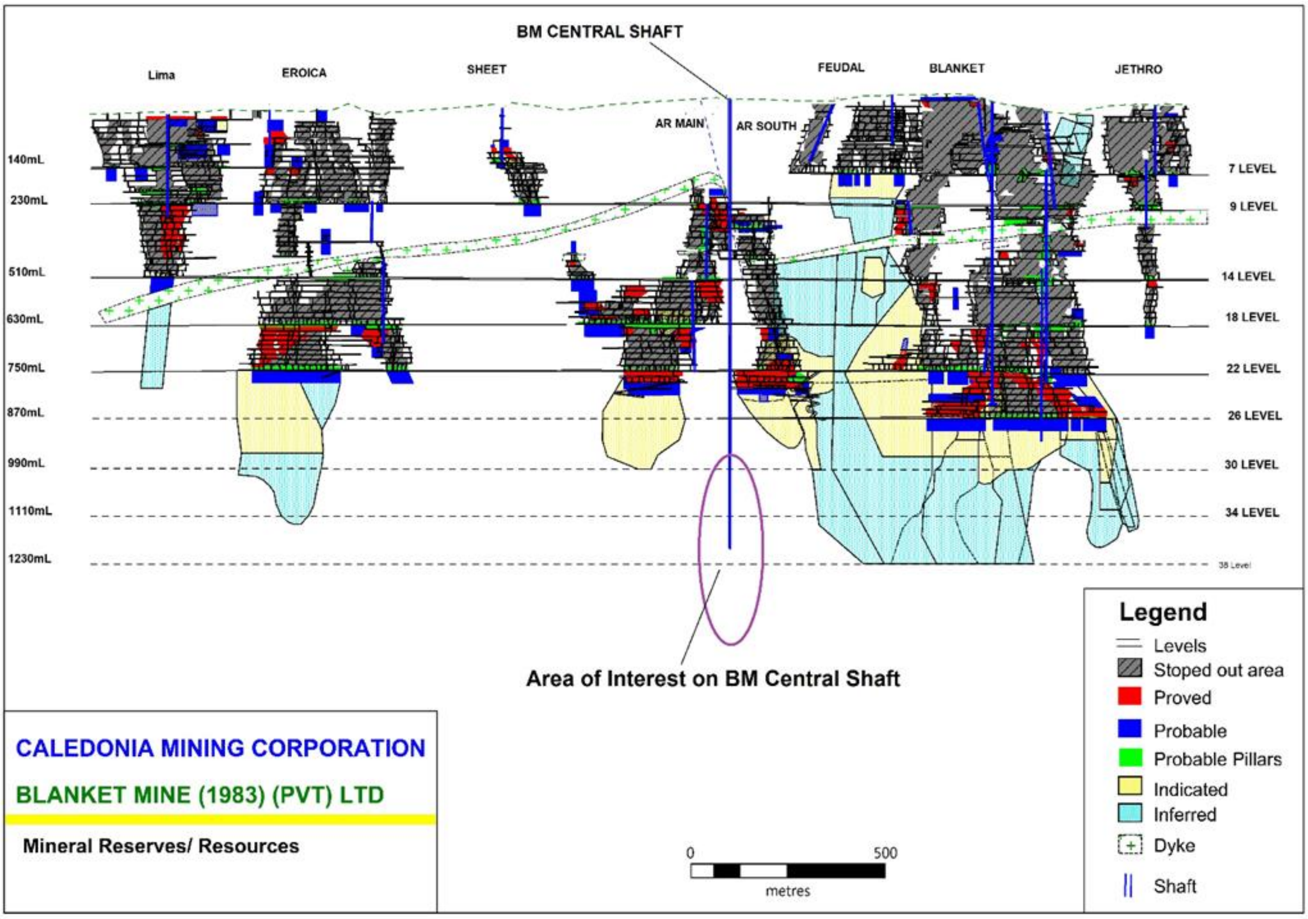

Figure 1.1: Cross-sectional layout for BM

(Source: Caledonia Mining Corporation, 2019)

The current run-of-mine (ROM) ore production target is over 500 000 tonnes per annum (tpa) or about 1 800 tonnes per day (tpd). The average ROM grade is about 3.7g/t. The mine has hoisting and main tramming haulages at 22 Level (750m), 14 Level (510m) and 8 Level (320m). The deepest workings are at 26 Level on one section (Blanket 2 ore body), whilst the rest of the ore bodies are at 22 Level. Ore that is mined at 26 Level is hoisted by a sub-vertical shaft to 22 Level where it is trammed to the main grizzly for eventual hoisting to surface. The hoisting of ore and waste is done through the No.4 Shaft which has a hoisting capacity of 2 200tpd (Caledonia Mining Corporation, 2019).

The mine embarked on an expansion project after a successful deep-drilling exploration of the ore bodies which confirmed over 4 Mt of Mineral Resources at an *in-situ* grade of 5.2g/t and extending down to 34 Level. To achieve the planned expansion, the mine developed the Central Shaft from surface to 34 Level. This shaft is more central to all the ore bodies. The Central Shaft has been equipped and is now operational. To achieve the expected production according to the company`s production plan, mining commenced below 22 Level (750m) via declines using a trackless mining method. The lateral distances from the declines or targeted ore bodies at 30 Level and 34 Level are shown in Figure 1.2 as ER 1 & 2, ARS 1 &2 and B1 &2, representing distances from Eroica, AR and Blanket orebodies to the central shaft respectively.

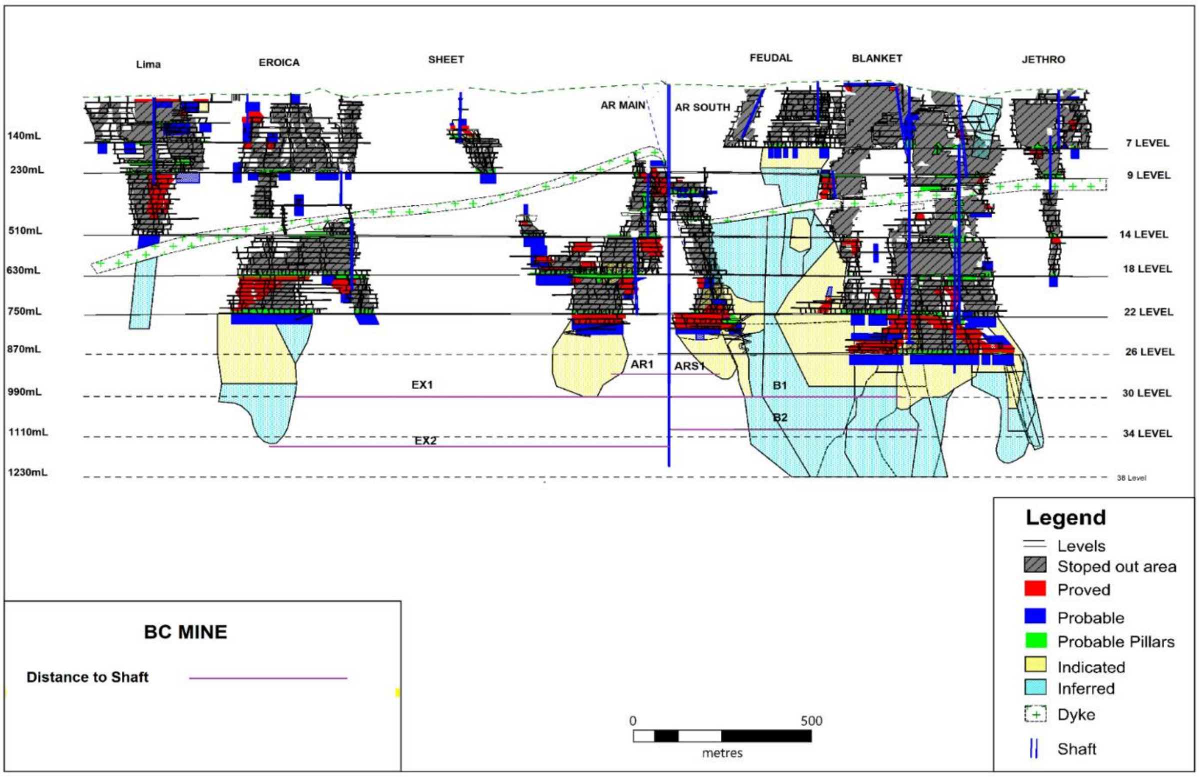

Figure 1.2: Layout of the declines for BM

(Source: Caledonia Mining Corporation, 2019)

Four declines were developed to access the AR South ore body (Decline 1), AR Main ore body (Decline 2), Eroica ore body (Decline 3) and Blanket ore body (Decline 4). These declines at 26, 30 and 34 Levels will be linked laterally by haulages to the Central Shaft, which will be used to hoist material produced from the respective ore bodies. Currently, lateral transportation of ore is done using 6t locomotives which tip at ore passes located at the main hoisting No.4 Shaft for eventual hoisting to surface.

The introduction of trackless equipment at the mine, which included trucks, load-haul-and-dump (LHD) equipment and belt conveyors, has created alternative options for ore transportation. This development has motivated a review of transport options, requiring the selection of the best lateral transport option. There are several factors that affect the decision of a transport choice. The decision on which transport system to select was evaluated using a multi-criteria decision analysis technique since there were multiple options and multiple criteria. This MCDA research dealt with the application of the Analytic Hierarchy Process (AHP), which is a multi-criteria decision analysis technique to determine the optimum option because it is easy to comprehend and apply (Waris *et al*., 2019).

1.3 Problem statement and research question

The expansion plan will result in the extension of the life of mine (LOM) and an increase of production to 80 000oz of gold by 2022 at a unit cost target of between US$700 - US$800 /oz at the forecasted gold price of above US$1 400/oz. The plan was communicated in the public domain to shareholders and a commitment was made by CMC management that it will be achieved (Caledonia Mining Corporation, 2019). To meet the increased production output, there is a need to have an optimum ore handling system. The optimal system should increase mining flexibility and production output, according to the company objectives whilst reducing costs strategically to counter any future challenges of depressed and volatile gold prices (Caledonia Mining Corporation, 2019).

The transport options will link the declines to the new Central Shaft for material transportation. Three options that have been considered by the mine are the belt conveyor, dump trucks, and rail transport system. In this research report, the rail transport system is used interchangeably with locomotive system. Given the available transport options and the number of factors to be considered, the selection of an effective transport system becomes an important factor to consider. This raises the research question, *"From the three feasible lateral ore transport options what is the optimal option to use at the Blanket Mine's expansion project?"*

1.4 Research aim and objectives

The aim of this research study was to find the most optimal ore transportation system for BM's expansion project. The objectives of this research study were to:

- Review literature on underground transportation systems applicable to gold mining deposits like those encountered at Blanket Mine.
- Review literature on MCDA techniques and justify preference on using the AHP technique for selecting an optimal lateral ore transportation system.
- Discuss the three ore transportation options available at Blanket Mine.

- Determine associated economic and mining requirements for each ore transportation option.
- Compare the three ore transportation options using the AHP decision-making technique to determine the optimal option.

1.5 Research significance

A consistent issue with most underground mines is that expansion plans tend to bring about challenges particularly with material handling as the depth of mining increases (Pareja, 2000). For most operations, the goal is to maximise the company`s profits through improved productivity and ensuring minimal operational challenges. The cost of ore transport underground is a significant cost in underground mines. At BM it accounts for more than 25% of total mine operating costs (Caledonia Mining Corporation, 2019). Likewise, this research considered the selection of an ore transport system to improve production, reduce production costs and increase profitability at BM. Additionally, the research findings can also be applicable to other mines.

1.6 Research scope

This research study reviewed the following three ore transportation options:

- Belt conveyor systems.
- Dump trucks.
- Rail system.

These three were selected because they are already available and operational at the mine. These options were considered for the same ore loading and tipping points on a lateral level. The scope was limited to loading points, haulages, and tipping points assuming adequate ore availability for 30 Level and 34 Level. The lateral distances are as illustrated in Figure 1.2. These three options were compared against each other to determine the optimum option using the AHP technique.

1.7 Research hypothesis

In all other upper mining levels at BM, the rail system has been the primary ore transportation system used. With this experience of using the rail transportation system, the BM management preferred the rail transportation system over other options. Therefore, this research study evaluated whether the management's preference is the optimum choice or whether other options were best suited for the expansion project.

1.8 Summary of Chapter 1 and report structure

The research report consists of six chapters. This introductory chapter gave background information pertaining to BM`s expansion project, the objectives of the expansion project and the project development with respect to the research question. The chapter also outlined the research aim, objectives of the research study, significance, and also scope of the research study. The chapter concluded by justifying the selection of the ore transport system as a multi-criteria decision analysis problem to be solved by MCDA techniques.

Chapter 2 discusses the objectives of transport systems in mine planning and design, the considerations in choosing a transport system and a broad description of the transport options in underground mining. The chapter gives an overview of MCDA techniques and justification for choosing AHP to evaluate the transport selection problem. Furthermore, this chapter gives a summary of case studies which applied MCDA techniques, in selecting optimal transport systems.

Chapter 3 describes how the selection of the evaluation criteria was done for BM's expansion project transport selection problem. The chapter describes the weighting assigned to the criteria and the development of an AHP model for the BM expansion project transport selection problem for further analysis.

Chapter 4 discusses the details of each transport option and their expected performance and efficiencies. Chapter 5 applies the AHP technique to select the optimal option. Chapter 6 concludes the research and provides recommendations for future study.

2 LITERATURE REVIEW

2.1 Overview of Chapter 2

This chapter presents the findings of a literature review conducted to find out the fundamental considerations in underground mining transport selection. The feasible transport options for Blanket Mine which are the belt conveyor system, truck system and rail system using a locomotive are discussed. The common criteria and objectives from previous related studies are discussed and reviewed in the chapter. From the review and discussions, it emerges that the problem in selecting the best transport system is an MCDA problem which is best solved using MCDA techniques. The MCDA technique that is best suited to solve the problem of selecting the best transport system for Blanket Mine's expansion project is the AHP. A detailed review of the AHP technique is presented in this chapter highlighting the stages taken to solve a problem using the AHP technique.

2.2 Objective of transport choice selection in mine design and planning

Mining operations should be carried out in an optimised way to realise optimal value from the extraction of mineral resources. Material transportation accounts for a substantial amount of operating costs for most mines, and mines should therefore establish strategies that increase the effectiveness, efficiency, and reliability of transport systems to keep operating costs low (Król *et al*., 2017). Since the transportation of ore, personnel and material in an underground mining environment contributes significantly to the mine`s running costs, it is ideal for the transportation to be achieved at the lowest unit cost possible (Aziz and Keilich, 2003).

The selection of a material transportation system must also satisfy a company's key objectives. The selected option should amongst other reasons; minimise operating and capital costs, maximise profits and return on invested capital, whilst ensuring that safety is not compromised. In this research study, only the belt conveyor, truck transport system, and rail system are discussed because they are appropriate and relevant to the expansion project for BM and are also currently used at the mine. The transport systems considered are on a horizontal haulage, hence the need to select the best lateral ore transportation system.

2.3 Factors to consider when selecting an optimum transport system

The selection of an optimal transport option is a complex process. As the depth of mining increases rock transportation time and cost also increases, presenting a challenge to mining operations when the aim is to increase mining volumes at lower production costs (Greberg *et al*., 2016). According to Owolabi (2019), the important factors to consider when selecting material and equipment transport systems are:

- Amount and size of material.
- Equipment type and size.
- Access method to the site.
- Tunnel dimensions.
- Conveyance distance and loading facilities.
- Haul road conditions.
- Compatibility to workforce transport system.

The selection process should try to avoid any unforeseen and costly factors, which may have a significant impact on the viability of the operation. Where there are alternatives, the options have different advantages and disadvantages on safety, capital cost, operating cost, set-up time and operational requirements, which are evaluated during decision making. An evaluation is necessary to understand the associated issues with each feasible option. The mine planning process in general determines and informs the profitability, rate of production, LOM, and the risk level of the plan, among other critical information. The technical and economic eligibility of transport equipment is important because transportation costs can affect the profitability of a mining operation (Gonen *et al*., 2012).

When comparing alternative transport systems, it is necessary to determine the operational parameters which include costs and production rate. According to Aziz and Keilich (2003), apart from capital costs there are two other costs to consider namely, owning costs which are borne by the company regardless of whether the equipment/machine is utilised or not and operational costs which are influenced by the nature of work, local prices, inflation, interest rates, and local labour costs, among other factors. Owning costs comprise of depreciation costs, investment cost, insurance, and taxes. Operational costs include wages, fuel, filters, repairs, tyre replacements and many others. Production rates are assumptions, based on variables obtained from experience or some simulations generated from computers using input data from operations (Aziz and Keilich, 2003). The production rates are affected by several transportation issues which include rolling resistance, acceleration, deceleration, variation in haulage gradient, loading and queuing time encountered by the transportation equipment (Aziz and Keilich, 2003).

2.4 Transport options for underground mines

Underground transport systems have developed from hand operations to mechanised and automated systems as technology progressed in extraction equipment and mining methods resulting in improved production and efficiencies (Hamrin, 2003). Some operations, however, still adopt primitive transport methods whilst others are at various levels of mechanised and automated transport system development and use. Over the years there have been improvements in technology in transport systems due to reasons which include the need to achieve higher production volumes and control transport costs. The transport systems may consume 15 – 30% of the overall investment costs as well as an ever-increasing portion of operational cost (Verhoef *et al*., 1997). The transport system must suit the desired production level at the minimum possible cost. The selection of transport systems is largely dependent on the following general conditions (Bartłomiej, 2019):

- Age of the mine. It's easier to plan the transport system of a new mine whereas for an old existing mine the selection is usually influenced by already existing infrastructure conditions and the need to balance compatibility between the old facilities and the new system.
- Design of the transport equipment with regards to capacity, strength, rigidity, and efficiency.
- Methods of setting up for operating control, ease of repair and modifications for possible future changes or additions.
- Flexibility of operation of the transport system.
- Maintenance requirements.
- Capacity of the system under normal or abnormal conditions.
- Standardisation of the equipment to benefit from the advantages of replicating apparatus for interchangeability of units, for availability of spare parts, and for reduction of repair parts inventory.

Material transportation in underground mines is done in several ways that include belt conveyors, dump trucks, and rail systems. Normally transport systems work in conjunction with other rock handling equipment and facilities (Greberg *et al.*, 2016). The three common underground transport systems are discussed in the next subsections.

2.4.1 Belt conveyors

Belt conveyors have application in many industries including underground mining. A belt conveyor system is considered amongst efficient means of rock transportation for short to medium distances (Rupprecht, 2003). The quality of material of a belt conveyer depends on the type and size of the material to be conveyed. The two main types of industrial belt conveyors include a general material handling type for factories such as those used in factories to move boxes and other materials and a heavy material type for handling material of large volumes such as encountered in mining and agriculture (Salama *et al.,* 2014). According to Wilson *et al.* (2004), there are two other alternative belts available although not best suited for underground mining operations and these are:

- Steel core belts: These are more expensive than rubber belts and can allow much longer single belt lengths.
- Cable belt: This is essentially a friction winder which drives cables with rubber belts resting on the cable. The belt has large steel wire ropes that serves to absorb tension and is not limited by the gradient.

The belt conveyor operating principles include the movement of a belt because of rotation of pulleys that are driven by motors. According to Rupprecht (2003), a basic belt conveyor is usually made up of the following:

- A continuous reinforced rubber belt supported by idlers, which are toughened on the carrying side.
- Drive pulley located on the head of the belt conveyor and a similar non-drive pulley located at the tail end from which the belt moves on.
- Tensioning arrangement for keeping the belt in proper tension.

The belt conveyor and all the accessory systems that ensure stability and efficient operation are mounted on a structure. The structure is a frame on which the belt conveyor is mounted and is usually metallic and varies in length, height, and shape. According to Rupprecht (2003), factors to consider when determining the carrying capacity of a belt conveyor for rock transportation, include:

- Width of belt conveyor.
- Belt conveyor speed.
- The belt conveyor troughing angle.
- The material properties.
- The strength of the belt conveyor.

The belt conveyor results in low operating costs when high tonnages are moved and high utilisation is achieved (Wilson *et al*., 2004). The width of the belt conveyor should be able to carry the tonnage requirements and the maximum size of material that can be loaded on the belt conveyor (Rupprecht, 2003). A belt conveyor with a design capacity of 80t/hr must be wider when loaded irregularly than would the same belt of similar capacity loaded at a constant rate with well graded ore (Rupprecht, 2003). Constant tonnage and well graded ore requires sizing and enough storage capacity before the belt conveyor is loaded (Wilson *et al*., 2004). Belt conveyors can be used to convey material horizontally, downgrade or up an incline. The inclination distance should not exceed 10 degrees to the horizontal unless the material is well sized in fragmentation and on a downgrade at about half the gradient but with an intense design and maintenance to avoid catastrophic failures (Wilson *et al*., 2004). In practice, any other angle from 10 degrees up to 14 degrees would result in big boulders rolling dangerously off the belt (Wilson *et al*., 2004).

On average, belt conveyors operate at less than 60 percent of their rated operating capacity when installed as the primary underground ore/waste transport systems partly due to constraints under which they operate (Willis *et al*., 2004). For example, the feed material to the belt conveyors from LHDs is normally in batches and not continuous. The discontinuous operation is normally interpreted as underutilisation and a cost to the operation. The determination of the correct size of a belt conveyor is important as belt conveyors are designed at a certain capacity so that when there is consideration to upscale production, this may require significant capital outlay (Kluge *et al*., 2017). Generally, underground transport systems should cope with the total output demand.

When designing excavations for belt conveyors it is critical to minimise changes in direction to minimise costs and operational challenges. This is because any change in direction requires additional changes such as electrical installations and chutes at the transfer points. There has been a lot of development work done to improve the belt conveyor systems operation, performance monitoring and maintenance. There are two different types of drives namely, side and central to which the engine power characteristics depend on the type of belt conveyor and the function. Belt conveyors are generally expected to run continuously throughout a shift and the system should be equipped with bunkers to allow for any unpredicted stoppages which may result in delays or problems upstream or downstream of the transport system. The belt conveyor system should have minimum time running unloaded as it results in energy loss. According to Król *et al*. (2017), the following can result in low energy consumption by a belt conveyor:

- Proper selection of the belt conveyor paying special attention to the rubber mix parameters selected specifically for the site operating conditions.
- Use of efficient idlers with less resistance to rotational motion.
- The exact sizing of conveyor components using computer aided design tools.

Accurate calculations and design specifications are critical in ensuring setting up of an ideal belt conveyor which suits the working environment. Design of belt conveyors is influenced by the type of material to be conveyed, gradient as well as distance to which the material is to be moved, the tunnel space and any other constraints in the system (Salama *et al*., 2014). The belt conveyor can be installed as a single length or a series of interlinked lengths. The advantages of belt conveyors are:

- They have a high carrying capacity and are the most economic material transport system (Salama *et al*., 2014).
- They have lower running costs when high tonnage operations are required.
- High utilisation of above 90% can be achieved (Wilson *et al*., 2004).
- They do not generate high heat output as compared to diesel trucks (Rupprecht, 2003).
- They can be maintained without stopping the whole operation by taking advantage of surge capacity installed along the belt conveyor system.
- They are energy efficient and cause low emissions to the underground workplace environment (Mahieu, 2018).
- They are safe and dependable (Rupprecht, 2003).
- They are compatible with multiple loading points (Rupprecht, 2003).

Belt conveyors have some disadvantages. The disadvantages of belt conveyors include:

- The use of multiple belt conveyors in series can disrupt production when one belt fails as it would affect the whole length conveyance. When compared to the truck and rail transport systems, a system breakdown normally causes the whole operation to stop unless there is a back-up system available (Mahieu, 2018).
- Belt conveyors are a fire hazard which can potentially impact the mine ventilation system in case of a fire.
- Installing belt conveyors in an intake airway is not favoured. The belt conveyor should be installed in a return airway with relative velocity of five metres per second between air and belt to prevent excessive dust pick-up and fire hazard (Wilson *et al*., 2004). In some cases, this may not be feasible because of the ventilation design which may be present before the installation of the belt conveyor.
- Belt conveyors are well suited for high constant flow of well fragmented rock which is very difficult to achieve in trackless mining resulting in high belt conveyor damages and high repair costs (Wilson *et al.*, 2004).
- Belt conveyors are difficult to install were there are curves. Installation in curved areas may require the establishment of a complex layout system and transition points which further increase capital costs (Mahieu, 2018).

2.4.2 Truck system

Truck transport systems are commonly employed in underground mines for transporting material from one point to another. The trucks can be diesel or electric powered. Electric trucks in comparison to diesel trucks produce less noise, move faster, reduce risk of diesel storage underground, make minimal demands for ventilation, and have lower operating costs (Salama *et al*., 2014).

Trucks used in underground mines can be classified into three groups namely, rigid-body rear dump trucks, articulated rear dump trucks and tractor-trailer units (Salama *et al*., 2014). The number of trucks to use at any given time in a truck transport system in an underground mine is limited by ventilation constraints, congestion, and queuing. A truck transport system is normally compared to shaft hoisting at depth with the latter being preferable at greater depths and when increased production capacity is envisaged. When selecting a truck in a truck transport system there are several factors to consider and these include road geometry, production rate, haulage distance, mining method, mineral reserve tonnage, haul road dimensions, safety, capital and operating costs, road intersections, required truck speed, corners and bends, road quality among other factors (Salama *et al*., 2014). The size of trucks is normally selected considering matching with the loading system or loading arrangement with an ideal combination resulting in the lowest loading time to ultimately reduce the load-haul-dump cycle time. This combination would amongst other issues help to quantify the fleet size required to achieve a certain production output. The advantages of truck transport systems are:

- Easy to change travel routes and fleet size (Mahieu, 2018).
- Diesel require low initial capital investment (Mahieu, 2018).
- Higher production rates can be achieved by using additional trucks whilst for lower production rates fewer trucks can be used. This works out perfectly when outsourcing truck transport services as it is much easier to scale up or down production when using truck transport systems by adding or subtracting units in the fleet.
- Truck transport systems are ideal for early production demands as the set-up time is shorter. The trucks can be contracted and allow revenue directly linked to usage with the advantage of system stoppage anytime with minimal costs (Wilson *et al*., 2004).
- They offer flexibility in both complex ramp layouts and variability in tonnage output (Wilson *et al.*, 2004).
- Dump trucks can operate at steeper gradients of up to 12 degrees compared to locomotives which cannot operate at gradients above two degrees (Rupprecht, 2003).

The disadvantages of a truck transport system are:

- High environmental pollution from diesel powered trucks which results in high costs of ventilation (Salama *et al.*, 2014).
- Relatively higher operating costs compared to other underground transport systems (Wilson *et al.*, 2004).
- High production capacities can be difficult to achieve reliably in single ends due to logistical challenges resulting from congestion as the number of trucks increases (Wilson *et al*., 2004).
- Ramp traffic increases when there is a need to increase production by adding more trucks.
- Blockages along the route in the event of a breakdown of one truck.
- Electric trucks have a higher initial investment and the use of electric cables over long distances is not feasible although some use batteries which are rechargeable after a few hours reducing flexibility when compared to diesel trucks (Salama *et al.*, 2014).

- The development haulage openings must be properly sized to accommodate ventilation ducting and other infrastructure as small tunnels may demand careful vehicle control reducing productivity, view, and safety (Mahieu, 2018).

2.4.3 Rail system

The rail transport system in underground mines involves locomotives which can be powered by diesel or electricity. The common types of locomotives used in underground mines are trolley type, battery powered, and diesel powered (Vermaak *et al*., 2000). The electric power is provided by batteries or electric cable lines for battery and trolley locomotives, respectively. In general battery locomotives and trolley locomotives are similar in construction with the only differences arising from the source of power which comes from battery bank stored in a metal casing carried by the locomotive and for the latter from an external conductor (Lamedica *et al*., 2020). Rail systems can be installed to run on the floor or roof of the tramming haulage (Salama *et al.*, 2014). The transport distances vary for different mining operations and rail tracks can be used as a transport system in mining to provide a fast means of transport of material over long distances of more than 1km underground (Govorushko, 2011). Battery powered rail locomotives were considered for this study because they are the ones currently used at the mine.

For a rail transport system in an underground mine, a locomotive moves on tracks pulling hoppers on rail. The hoppers and locomotives are available in different sizes. Different production demands, size of locomotive, gradient of rail tracks and size of haulage tunnel are amongst factors that determine which size of hoppers to use in a particular haulage tunnel. Bigger locomotives move high tonnage on wider gauges and wider haulages than smaller locomotives. Common rail gauges vary from 610 mm, 762mm to 1 065mm with wider gauges preferable to enable higher speed stability (Rupprecht, 2003). The speed and efficiency of rail transport systems depend upon roadway gradient, quality of installation, and track condition, otherwise, it can be very unreliable and slow due to derailments. A properly constructed and well-maintained rail system affects the efficiency and can offset the high capital required to set up the rail system (Lamedica *et al*., 2020).

Rail transport systems have several advantages and disadvantages. The advantages of rail transport systems include:

- They are energy efficient, appropriate for long tramming distance and have a high productivity (Salama *et al.*, 2014).
- They require smaller dimension haulages compared to trucks.
- They produce less emissions requiring lower ventilation demand than trucks which produce high emissions. Ventilation is a potential benefit of a rail transport system over the use of diesel trucks and LHDs as the rail system requires less ventilation infrastructure and costs (Dammers *et al.*, 2019).
- The rail system can handle higher volumes and heavier loads of more than 30 tonnes per load (Leduc, 2009).
- They are compatible with traffic control automation and monitoring systems which help with better management of the system (Rupprecht, 2003).
- They have lower power to load ratio. Rail transport systems have proven to be energy efficient (Mahieu, 2018).

The disadvantages of rail system are:

- The capital cost of a rail system in development and track work is high (Leavitt *et al.,* 1993).
- Cannot operate on gradients steeper than 1:60 (Rupprecht, 2003).
- Battery locomotives operate to a limited range of the number of cycles between the charges (Rupprecht, 2003).
- There is a need for several backup batteries for battery locomotives and battery charging facilities with serious consideration necessary for positions of the battery charging bays for ease of logistics when changing batteries.
- A rail system, like a belt conveyor requires a longer installation time compared to the truck system (Mahieu, 2018).
- Rail systems have restricted flexibility in cases which require varying output or decommissioning the system (Mahieu, 2018).

2.4.4 Tramming and haulage costs

The discussion in Sections 2.4.1 to 2.4.3 shows that transport systems have different factors that affect them. These factors must be considered in selecting an optimal transport system and require that decision-making techniques be applied to ensure that the best option is selected. Cost is one of the key factors to consider. Underground transport systems are multifaceted, require high capital costs and have been analysed by different analytical methods to assess performance of the systems (Greberg *et al.*, 2016). It is important to know the associated costs of each transport system to make an analysis or a comparison to assist in decision making. Benchmarking of costs from other mining operations may be difficult due to different activity costing practices. Some mines segregate waste and ore whilst others may include costs of maintenance of loading chutes or dump points or use total transport costs from various loading levels.

2.5 Decision making in mine design and planning

In strategic decision-making, businesses must simultaneously consider multiple objectives. Despite short-run profit being important, long-term factors such as market position, product quality, development, and production capability often conflict with it (Chen, 2006). The selection of mine transport systems is one of the most critical and difficult processes during mine design and planning. This is because several factors must be considered before an optimal design or plan is adopted as discussed in previous sections. Broadly, these factors can be classified into economic and non-economic and require some trade-offs to be made in the selection process.

Typical mine design and planning decisions are done based on multiple criteria which can be contradictory. For example, trying to achieve multiple competing goals simultaneously such as cutting costs contradicts with the need to increase production which may demand additional investment. Many alternatives exist during the project phase than in a production phase where options are limited. Multi-criteria decision analysis uses a set of tools and principles to guide a decision maker to solve a decision problem for a given set of options according to two or more criteria which are usually conflicting (Chen, 2006). The best decision from a given set of alternatives is the one which scores the highest consolidated score on all the criteria (Musingwini and Minnitt, 2008).

In mining transport systems, the requirement to ensure sufficient capacity and reliability issues may prevail over energy savings and cost savings (Król *et al.*, 2017). A certain choice may have some advantages over the other, but which may be countered by the disadvantages of the other. Therefore, the selection of the best transport option given alternatives requires the transport options to be evaluated against multi-criteria simultaneously whereby each criterion has relative importance in the overall decision. When evaluating alternative transport systems, the decision to select the optimum transport system should not be based on one category of factors only, but also on other relevant factors making the decision-making multi-criteria in nature (Elevli and Demirci, 2004).

Multi-criteria decision problems are problems that require pre-determined alternatives to be evaluated simultaneously using a set of pre-determined criteria. These decision problems are best solved using MCDA techniques. MCDA techniques evaluate each option based on criteria whereby each criterion has a relative degree of importance. These techniques rank the performance of each alternative to allow for decision making. The ranking is done based on defined criteria and must be consistent and logical. There are several MCDA decision-making techniques.

2.6 Overview of multiple criteria decision analysis techniques

The most critical stage in decision-making for MCDA problems is defining the relevant objectives and decision criteria derived from the objectives (Elevli and Demirci, 2004). According to Musingwini and Minnitt (2008), the generic process of an MCDA problem takes the following steps:

- Definition of objectives or goal.
- Mapping of the objectives into decision criteria.
- Allocating of criteria weights according to importance to the overall objective.
- Identification of alternatives or options.
- Determining the efficiencies of each possible option with respect to each criterion.
- Decision making on the choice of option by ranking of the alternatives or options.

The fundamental form of a MCDA problem involves decision making to choose an option "O_i from a set of options $O = \{O_1, O_2, \ldots, O_m\}$, such that O_i gives the best trade-off among evaluation criteria defined by a set $C = \{C_1, C_2, \ldots, C_n\}$" (Owusu-Mensah and Musingwini, 2011 p.112). "In total there are **m** options and **n** evaluation criteria such that the rating of Option 1 against Criterion 1 is R_{11} and the rating of Option i against Criterion j, is R_{ij} with relative importance or weight of C_i over C_j denoted as W_{ij}" (Owusu-Mensah and Musingwini, 2011 p.112). Table 2.1 shows the basic structure of a generic MCDA problem. The table, as described by Musingwini (2010 p. 59) denotes that "a decision maker requires to select an option or alternative, A_i from a set of alternatives $A = \{A_1, A_2 \ldots A_m\}$, such that A_i gives the best trade-off among decision criteria defined by a set $C = \{C_1, C_2 \ldots C_n\}$. The total number of alternatives and criteria is **m** and **n,** respectively. The efficiency of alternative **1** against criterion **1** is expressed as the outcome O_{11}, that of alternative **i** against criterion **j,** as outcome O_{ij} and so on".

Table 2.1: The structure of a generic MCDA problem

(Source: Musingwini, 2010)

		Criteria					
		C_1	C_2	...	C_j	...	C_n
Alternatives	A_1	O_{11}	...	...	...	...	...
	A_2	...	...	...	...	...	...
	...	...	...	...	...	...	...
	A_i	...	...	...	O_{ij}	...	...
	...	...	...	...	...	...	...
	A_m	...	...	...	...	...	O_{mn}

According to Musingwini (2010), the process of solving an MCDA problem is summarised into the following four steps:

1. Mapping objectives into criteria – Objectives should be mapped into criteria which must be measurable. The criteria must be defined for the project or problem. There are three types of criteria, namely natural, constructed and proxy criteria (Keeney, 1994). Natural criteria are those criteria that are commonly understood by everyone, constructed criteria are those criteria that are constructed for a specific decision. At times it is a challenge to recognise natural or constructed criteria such that proxy criteria are used (Chen, 2006). Natural criteria can be measured directly or are measured through a formulated index (for example, maximise production rate – measured in tonnes per annum) and constructed criteria (for example, maximise technical operating flexibility – measured through a flexibility index derived from a dimensionless scale). Proxy criteria which fall in between natural and constructed are indirect measures of an objective hence were not considered for this research. Criteria can be measured qualitatively by using scales or quantitatively as numerical data.
2. Assigning weights to criteria – a weight is assigned to each decision criterion according to the relative importance. According to Chen (2006), there are three principles that are followed when assigning weights. The first principle is the principle of preference

availability which requires the decision maker to show preference between any two outcomes based on a criterion. This would imply that O_{ij} must exist for all criteria and alternatives. The second principle, namely preference independence states that the decision maker's preference on one criterion must not have any influence on another criterion. The third is the principle of monotonicity which states that a criterion is a positive criterion if and only if larger values of O_{ij} are preferred; it is a negative preference criterion if and only if smaller values of O_{ij} are preferred and it is monotonic if it is either positive or negative. Weights indicate the level of importance of a criterion to the overall goal. The weight of criterion C_j is symbolised by w_j where $w_j \in R$ and $w_j > 0$ for all criteria. The weights are normalised to add up to 1 as defined by Equation 2.1 to aid the decision maker in understanding the relative importance of each criterion such that (Musingwini, 2010):

$$\sum_{j=1}^{n} W_j = 1 \qquad \textbf{(Equation 2.1)}$$

The weight vector for each option is given as $w = (w_1, w_2, \ldots, w_j \ldots, w_n)$ since the number of weights must be the same as the number of criteria.

3. Aggregating the weights and O_{ij} values – the results of efficiencies of options against criteria are normalised using value functions so that the O_{ij} score corresponds to a dimensionless value $V(A_i)$. The weights and the result of the performance of options are then combined as a linear additive value function, $V(A_i)$ given by Equation 2.2 (Musingwini, 2010):

$$\mathbf{V(A_i) = \sum W_j . V(A_i)} \qquad \textbf{(Equation 2.2)}$$

4. Implement decision - The combined values are then used to come up with the particular decision needed by the MCDA problem.

There are several alternatives to a decision problem and decisions must be made using several criteria to evaluate the merit of each criterion (Musingwini and Minnitt, 2008). According to Owusu-Mensah and Musingwini (2011 p.113-114), the challenges faced by MCDA techniques include the following:

- The best decision must be the one that carefully balances conflicting objectives by selecting the best trade-off.
- The evaluation criteria have different units of measure, and the challenge is to integrate more than two different criteria that are measured in different units.

- The human brain can easily configure the best decision such as maximising benefit and minimising cost when faced with a two-dimensional problem like xy in a Cartesian plane, or when the problem is three-dimensional expressed as a surface in xyz space. When the evaluation process involves evaluation criteria that exceed three dimensions as in an MCDA evaluation process, humans must rely on abstract thinking. Due to limitations in abstract thinking humans will always convert the problems back to two- or three-dimensional thinking for simple understanding.

The techniques for MCDA problems are structured to deal with these challenges and there are five commonly used techniques. These techniques are (Owusu-Mensah and Musingwini, 2011):

- Elimination Et Choix Traduisant la Re´alite´ (ELECTRE), a French version which was translated to an English version Elimination and Choice Translating the Reality.
- Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE).
- Multiple Attribute Utility Theory (MAUT).
- Analytic Hierarchy Process (AHP).
- Analytical Network Process (ANP)".

These techniques are grouped based on the information type gathered by the decision maker (Owusu-Mensah and Musingwini, 2011). The MAUT and AHP techniques are used when information is cardinal whilst ELECTRE and PROMETHEE are used when the information is ordinal (Owusu-Mensah and Musingwini, 2011). Data is ordinal when a linguistic or non-numerical scale is used such as low, medium, and high (Owusu-Mensah and Musingwini, 2011). This can be converted on a typical scale (1-10), interpreted as (1-3) low, (4-6) range medium and (7-10) range being high values. Data is cardinal when it is given as a real number. The ELECTRE and PROMETHEE techniques are both founded from an outranking procedure which is done to account for the fact that preferences and choices are not constant in time, not ambiguous, not independent and depend on situations and experiences (Owusu-Mensah and Musingwini, 2011). Table 2.2 shows a comparison of four broad MCDA techniques. In this research study the AHP was used over other MCDA techniques because it provides for consistency checks in the choice of the best option, it is easy to use and ranks alternatives in order of effectiveness when there are conflicting objectives (Owusu-Mensah and Musingwini, 2011). The AHP method is discussed in the next section.

Table 2.2: Comparison of four broad MCDA techniques

(Source: Owusu-Mensah and Musingwini, 2011)

	MAUT	**AHP**	**ELECTRE**	**PROMETHEE**
Foundation	Classic MCDA approach	Hierarchical approach	Outranking procedure	Outranking procedure
Theoretical basis	Utility function additive model	Pair-wise comparison (weighted eigen vector evaluation)	Pair-wise comparison (concordance analysis)	Pair-wise comparison (preference function)
Measurement of criteria	Numerical (non-numerical data must be converted to numerical scale)	Numerical (non-numerical data must be converted to numerical scale)	Numerical (non-numerical data must be converted to numerical scale)	Numerical (non-numerical data must be converted to numerical scale)
Determination of weights of criteria	Trade-off based weights using swing, direct ratio, or Eigen vector methods)	Trade-off (generate weights using Saaty`s Eigen vector and geometric mean; estimates consistency in judgments)	Non-trade-off (does not provide procedure to obtain weights)	Non-trade-off (does not provide procedure to obtain weights)
Result	Relative preference order	Relative preference order	A set of non-dominated alternatives	Partial and complete ranking order

2.7 The Analytic Hierarchy Process

The Analytic Hierarchy Process is a multi-criteria decision method that uses hierarchical structures to solve unstructured decision problems. To decide, the decision maker needs to know the problem, the need and purpose of the decision, criteria for the decision and their sub-criteria, stakeholders and groups of affected people, and the alternative actions to take (Saaty, 2008). Decisions involve a lot of tangibles that need to be traded off and these are measured alongside intangibles whose measurements must also be evaluated as to how well they serve the objectives of the decision maker (Saaty, 2008).

In the 1970s, Saaty created the AHP optimisation technique which is a structured method for problem solving using mathematical tools. The AHP is a comprehensive framework which is designed to cope with intuitive, rational, and irrational decisions when making decisions that are multi objective, multi-criteria, multi-factor with and without certainty for any number of alternatives (Harker and Vargas, 1987). The AHP method can incorporate quantitative and qualitative judgements in decision making. It is a theory of measurements through pairwise comparison and relies heavily on the judgements by experts to derive priority scales (Saaty, 2008). When using the AHP technique to model a problem, one needs a hierarchic or network structure to represent the problem and a pairwise comparison to establish relations within the structure (Saaty, 1987). The pairwise comparisons are used to establish the relative importance of the decision criteria as well as the relative performance of the alternatives according to each of the decision criteria (Triantaphyllou and Mann, 1995). The scales made of absolute judgements measure the intangibles in relative terms on how much more one element dominates the other with respect to a given attribute (Saaty, 2008). A hierarchical model in AHP starts with the overall objective, which is broken down to criteria, then sub-criteria, which are sub-divisions of the criteria then finally the alternatives from which the option is selected (Saaty, 1987). The technique has since been applied successfully in mine planning and optimisation problems. The AHP provides a flexible and easy way to understand and analyse complicated problems, helping decision makers with a rational basis for decision making (Ataei *et al.*, 2008).

The AHP method involves simple calculations which can be done in Microsoft Excel. According to Harker and Vargas (1987), when solving problems using the AHP method three principles that are to be recognised are: decomposition, comparative judgement, and synthesis of priorities. The decomposition principle requires the structuring of the hierarchy to capture the basic elements of the problem (Harker and Vargas, 1987). The principle is applied by structuring the problem with elements in a level being independent from those in succeeding levels, working downwards from the focus in the top level, to criteria being on the focus in the second level, followed by sub-criteria in the third level and so on (Saaty, 1987). The principle of comparative judgement is used to generate a ratio scale. It requires the setting up of a matrix to carry out purpose comparisons of the relative importance of the elements in a level with respect to the elements in the level immediately above it (Harker and Vargas, 1987). The principle of synthesis of priorities is used to generate the global or composite priority of the elements at the lowest level of the hierarchy (Harker and Vargas, 1987).

The AHP process starts with a pairwise comparison, which determines the relative importance of one criterion over another. In this study, some reference was done to criteria together with relevant weightings used in previous studies involving comparison of transport options. The comparison is converted into weights, which are then used to form a square matrix of some order number, which corresponds to the number of criteria being evaluated. An AHP model can identify the degree of inconsistency in judgements. The consistency measure enables the AHP model to be better than human judgements, which are usually inconsistent (Musingwini and Minnitt, 2008). Three features that differentiate the AHP technique from other MCDA techniques are (Ataei *et al.,* 2008):

1. The ability of the AHP technique to handle tangible and intangible attributes.
2. The ability of the AHP technique to structure a problem in a hierarchical manner and get an insight into the decision-making process.
3. The ability of the AHP technique to check for consistency on the decision-making process.

2.7.1 Axioms of the AHP

The AHP method is based on the following four axioms (Harker and Vargas, 1987):

1. Axiom 1 – the reciprocity axiom. Given any criteria C_i and C_j the degree of preference of C_i over C_j is an inverse of the complementary preference decision of C_j over $C_{i.}$ The axiom says that the comparison matrices constructed are formed of paired reciprocal comparisons. For example, if one stone is judged to be five times heavier than another, then the other must be one fifth as heavy as the first (Saaty, 1987).

2. Axiom 2 – the homogeneity axiom. Homogeneity is essential for meaningful comparisons as the mind cannot compare widely disparate elements (Saaty, 1987). When comparing two alternatives or two criteria, the scale of ratio of comparison is bounded.
3. Axiom 3 – the dependency axiom. The set of alternatives is dependent on the set of criteria if a fundamental scale can be defined to measure each alternative against each criterion (that is, the decision problem can be formulated as a hierarchy).
4. Axiom 4 – the expectation axiom. All alternatives and criteria which can impact a decision-making problem are represented in the hierarchy and assigned priorities compatible with expectations.

According to Harker and Vargas (1987), the mathematical representation of the axioms is as explained in the next paragraphs. The first initial step is to start with a pairwise comparison of the relative weights or importance of each criterion over another using the reciprocity axiom. The relative weight of C_i over C_j is denoted by w_{ij} such that $w_{ij} = 1/w_{ji}$, $\forall i \neq j$ and, $w_{ij} = 1, \forall i = j$ since a criterion is as important as itself where ∀ means for all.

The weights form a square matrix W = (w_{ij}), of order n, corresponding to the number of criteria. The matrix, W, is referred to as a reciprocal matrix because the inverse of the weight of one criterion over another is equal to the weight of the second criterion over the first one. For example, if capital cost is twice as important as operating costs in selecting a transport method, then it follows logically that operating costs will be half as important as capital costs. Table 2.3 shows the fundamental scale of absolute numbers. The weights are based on a scale that ranges from 1-9.

Table 2.3: 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 judgment slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment slightly 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
1,1-1,9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small number would not be too noticeable, yet they can still indicate the relative importance of the activities

The matrix of weights, W, is then evaluated for transitivity. A relationship is transitive if the relative importance is multiplicative. For example, if criterion C_2 is twice as important C_1 and criterion C_3 is three times as important as C_2, then logically criterion C_3 should be six times as important as C_1.

A matrix satisfying the transitive axiom represents consistent judgements. Typical human judgements are characteristically inconsistent to a greater or lesser degree and cannot satisfy the transitive axiom. The AHP methodology provides a way of measuring the degree of inconsistency in judgements. The transitive relationship between weights can be expressed mathematically as $\mathbf{w_{ik}} = \mathbf{w_{ij}w_{jk}} \, \forall \, \mathbf{i}, \mathbf{j}, \mathbf{k}$. A vector, **w,** of order **n** can be established such that $\mathbf{Ww} = \lambda\mathbf{w}$ (Musingwini, 2009)**.** The vector, **w,** is called an eigenvector of the matrix **W** and the constant λ is its corresponding eigenvalue. If the matrix, **w**, is consistent then $\lambda = n$. For inconsistent human judgements, the eigenvector, **w,** cannot satisfy the earlier condition but satisfies condition $\mathbf{Ww} = \boldsymbol{\lambda}_{max}w$ such that $\lambda_{max} \geq \mathbf{n}$ (Musingwini, 2009). The difference between λ_{max} and **n** indicates that there is some inconsistency in the judgements but, if $\lambda_{max} = \mathbf{n}$ then logically, the judgements were consistent (Musingwini, 2009).

Several methods are available for estimating the eigenvector. Of these, a close approximation of the eigenvector is obtained when geometric means are used to estimate the eigenvector elements. The rationale for geometric means is simple. If a typical scale of 1 to 10 is used to denote the relative weight, then from the reciprocity axiom, the reciprocal weights 0.1 and 10 will differ by an order of magnitude 100. A consistency index (*CI),* is then calculated from λ_{max} and **n** using Equation 2.3 (Musingwini, 2009).

$$\mathbf{CI} = \frac{(\boldsymbol{\lambda}\mathbf{max} - \mathbf{n})}{(\mathbf{n} - \mathbf{1})} \qquad \textbf{(Equation 2.3)}$$

To determine if judgements are reasonably consistent a consistency ratio (*CR),* is calculated by assessing the calculated *CI* against judgements that are made completely at random.
Equation 2.4 is used to calculate CR (Musingwini, 2009):

$$\boldsymbol{CR} = \frac{\boldsymbol{CI}}{\boldsymbol{RI}} \qquad \textbf{(Equation 2.4)}$$

Where RI is a random index. Saaty (1980) also established the random indices *(RIs)* for corresponding matrices of order between 1 and 15 as shown in Table 2.4.

Table 2.4: Random Index for an 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	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

If *CR* exceeds 0.1 then the judgements are likely to be too inconsistent to be reliable and the assignment of weights to criteria should be redone (Musingwini, 2010). The threshold ratio of 1.0 would therefore mean that the judgements are completely too random to be trusted. A *CR* ratio of 0 implies that judgements are perfectly consistent (that is, not random at all). *CRs* of more than 0.1 are sometimes accepted provided there is adequate justification for their acceptance (Coyle, 2004).

If the degree of inconsistency in judgements is acceptable, the efficiencies of all alternatives on a criterion, $O_{ij,}$ are then normalised to eliminate the effect of different units of measurement for each criterion. For ***m*** alternatives on a criterion, the normalised O_{ij} values denoted by $O^N_{ij,}$ are calculated using Equation 2.5 (Owusu-Mensah and Musingwini, 2011):

$$\boldsymbol{O^N ij} = \frac{\boldsymbol{Oij}}{\sum_{i=1}^{m} \boldsymbol{O_{ij}}} \qquad \textbf{(Equation 2.5)}$$

The matrix of normalised efficiency outcomes is finally multiplied by the eigenvector to obtain the aggregated AHP priority scores. The decision is then made based on the logic that the higher the AHP priority score for an alternative, then the preferable the alternative.

2.7.2 AHP limitations

There are three main limitations of the AHP methodology (Coyle, 2004). “Firstly, the method only works if the matrix for the criteria weights is a positive reciprocal matrix. Positive reciprocity is satisfied if criterion C_i is x times more important than criterion C_j and correspondingly C_j is 1 / x as important relative to criterion C_i. The second limitation is that when the scale of measuring the relative importance of criteria with respect to each other is changed, say from 1-10 to 1-20, the weight of the vector will also change and in some cases, this will affect the final decision. The third limitation is that as the number of criteria to be compared increases, the number of pairwise comparisons increases rapidly following a power function as shown in Table 2.5 thereby making the comparisons difficult” (Musingwini, 2009 p. 70). The AHP also has a rank reversal problem if a new copy of an existing option is added to a set of alternatives (Belton and Gear, 1983). The rank reversal problem is the changes to the ranking of alternatives for an MCDA problem because of addition or subtraction of alternatives.

Table 2.5: Relationship between number of criteria and comparisons

(Source: Kardi, 2006)

Number of criteria	1	2	3	4	5	6	7	n
Number of comparisons	0	1	3	6	10	15	21	$\frac{n(n-1)}{2}$

2.8 Review of previous work on selection of transport systems

Due to the cost implications and the effect on the overall mine economics, the selection of transport systems has generally received a lot of focus over the years. A lot of research has been done on the selection of material handling systems and equipment. The selection of optimal transport systems and equipment fleets is a multi-criteria decision-making problem as the selection process is unstructured and characterised by domain dependent knowledge (Karande and Chakraborty, 2013). The selection process of the best transport system is complicated by the fact that decision makers must consider quantitative criteria (such as capacity, energy consumption and costs among other criteria) and qualitative criteria (such as work environment, safety, flexibility among other criteria) which may be conflicting (Karande and Chakraborty, 2013). Most research highlighted common important factors to consider in the selection process. These can be classified into financial and non-financial factors, guided by the desire for organisations to ensure that the operational objectives are met as well as providing financial justification in the selection. Some of the examples of previous studies on selecting transport systems are discussed in the next subsections.

2.8.1 Ore transport selection for the Sintoukola potash project in the Republic of Congo

Kluge *et al.* (2017) undertook a research study on the selection of an ore transport system for the Sintoukola potash project. In the study MCDA technique was applied in assessing transport systems which compared operability, economic analysis, and safety, health, and environment. The study highlighted that the selection of an optimal material transport system can have a significant effect on the success of a mining project. The research study indicated that there are numerous factors to consider when selecting a transport system making the problem to be solved by multi-criteria decision analysis approaches. The research study compared the use of hauling trucks against an overland belt conveyor and concluded that the belt conveyor was the optimal option. The study emphasised the importance of the relationship and impact of choice of transport system and the financial factors especially capital outlay and operating costs.

There was a previous study that was conducted on the same project comparing the same transport systems which concluded that the rail system and belt conveyor system were discarded due to high initial capital cost, whilst the pipeline system was rejected for operability challenges (Kluge *et al*., 2017). The latter study however further justified the need to understand the objectives and constraints of the project in the selection of a transport system as well as gathering all information related to the project. The absence of both detailed geotechnical data and an Environmental and Social Impact Assessment resulted in overestimation of costs for the overland belt conveyor system and underestimation of costs for the haul road system resulting in the wrong conclusions hence the need for all project information prior to undertaking a study (Kluge *et al.*, 2017).

Kluge *et al.* (2017) indicated that numerous factors should be considered using a MCDA optimisation technique to select an optimal transport system. They made selection of a transport system for the Sintoukola project based on minimising:

- Capital and operating costs for the entire working life of the system.
- Environmental consequences.
- Safety risks associated with the system.

The selection was based on the following three criteria (Kluge *et al*., 2017):

- Operability which dealt with the impact of the transport system on the overall project. This included water availability, power, stockpile size and availability, employees, and maintenance.
- Net present cost which justified that economic profitability and return on investment underlies all projects. This involved an analysis of operating costs, capital, and sustaining capital, and the impact these would have on the project`s value.
- Safety, health, and environmental assessment which focused on showstoppers that excluded a system from further consideration and to weigh and compare those impacts that can be mitigated.

Kluge *et al*. (2017) gave these three criteria equal importance although these may have different weights depending on the organisation and management philosophy. Three similarities can be drawn from the study by Kluge *et al*. (2017) and that for BM expansion project. Firstly, the demonstration of the multi-criteria nature of the transport system selection problem. Mine transport system selection involves the consideration of several factors which must be optimised. Modern mining practice should consider the impact of environmental and social factors alongside the traditional technical and economic considerations when optimising projects (Kluge *et al.*, 2017). Secondly, the study emphasized the importance of selecting a transport system as transportation has a significant bearing on the success of a mine. Thirdly, the study dealt with main objectives of the transport system in the selection that are similar to BM.

A conclusion derived from Kluge *et al.* (2017) study was that before a decision is made, a comprehensive study of trade-offs should be conducted to make an appropriate decision. The process helps in avoiding costs associated with erroneous evaluation due to understating or overstating of certain costs or impacts of the project. The main criteria, sub-criteria and the weights that were used in the Sintoukola potash project are shown in Table 2.6. The criteria weights were allocated on a scale rating of 1 to 3 with 1 as low, 2 as medium and 3 as highest.

Table 2.6: Evaluation criteria and respective weights for the Sintoukola potash project

(Source : Adapted from Kluge, *et al*. 2017)

Category	Criteria	Weighting
Health and safety aspects	Risk of accident and injury	3
	Risk of unauthorised access	3
	Night operation	2
	Driver fatigue	2
	Fire	3
Environmental aspects	Noise	2
	Dust/particulates	3
	Exhaust gases	1
	Carbon footprint	1
	Light pollution/visual intrusion	2
	Animal strike	2
	Spills (hydrocarbon/product)	3
	Land surface impact (cut and fill)	3
	Hydrocarbon logistics	1

In the study the comparison of trucks and conveyor belt was assessed based on weights that were assigned to environmental, health and safety. Technical and economic assessments were not weighted hence not indicated in Table 2.6. The Sintoukola potash project is referred to as Study 1 in the next chapters.

2.8.2 Application of PROMETHEE multi-criteria methods to select an ore transport system for the Dedeman underground mine

Elevli and Demirci (2004) evaluated the choice of an ore transport system for Dedeman Mine, which is an underground chromite mine in Turkey using MCDA. The study indicated that the selection of the best transport system should not be based on a one-dimension criterion of cost but should also consider a multi-dimensional objective system called benefit analysis. Elevli and Demirci (2004) used eight steps in the selection process, namely:

i. Analysis of the existing situation: At this stage, all relevant data is collected.
ii. Problem definition and definition of criteria: The step outlines the present state and the desired state indicating the objectives and the criteria to reach those objectives.
iii. Determination of alternatives based on the problem.
iv. Analysis of alternatives based on each criterion.
v. Evaluation of alternatives: Alternatives are compared to each other on the defined criteria.
vi. Decision making.

vii. Development plans: Detailed engineering calculations are done on the selected alternative.
viii. Implementation plans: The solution is implemented and put into operation.

These steps outline a logical approach which is ideal. Different approaches can be adopted but somehow following the listed steps. Elevli and Demirci (2004) emphasised that the important part of the decision-making process is the determination of relevant objectives from which decision criteria are derived. There may be several alternatives, but the criteria define the feasible alternatives. In their study, the selection of the optimal transport system was made based on three broad criteria namely economic, environmental/safety and technical factors. The study compared five alternative transport systems against three broad criteria to extract additional ore reserves discovered at a depth of 500m below the mine`s current hoisting limit. The study revealed that developing an internal ramp haulage mined from the bottom of the existing shaft at a gradient of between 10% and 15% was the preferred transport option when compared to the following alternatives (Elevli and Demirci, 2004):

- Deepening an existing hoisting shaft down to 500m and developing a 2 182m long haulage drift and a 900m crosscut.
- Deepening the existing hoist shaft to 310m level then sinking an internal shaft from 310m level to 500m level and developing a 1 282m long haulage drift and a 900m crosscut.
- Sinking a new hoisting shaft from surface down to 500m level and developing a 1 917m long haulage drift and a 900m crosscut.
- Developing a 2 443m internal ramp haulage from the bottom of the existing shaft to the lower levels and a 900m crosscut.
- Developing a 4 210m external ramp haulage from surface and a 900m crosscut for trucks to move the mined ore from underground to surface.

The study found that decision making is significantly dependent on weights of criteria given by decision makers. This is more biased towards the knowledge and preference of the decision maker and the conditions of the operation. Minor changes to the weight given to a criterion can influence a decision towards another alternative. The study also showed that multi-criteria decision-making methods are able to successfully answer mining engineering problems (Elevli and Demirci, 2004). The main criteria, sub-criteria, and the weights for the study on the application of PROMETHEE multi-criteria method to select an ore transport system for the Dedeman underground mine are shown in Table 2.7.

Table 2.7: Evaluation criteria and respective weights for the Dedeman Mine

(Source: Adapted from Elevli and Demirci, 2004)

Category	Criteria	Weighting
Technical	Ore production	20.6
	Risk of reserve	8.4
Economic	Haulage cost	21.7
	Net present value	13.9
	Ease of systems	10.9
	Investment cost	24.6

Elevli and Demirci (2004) highlighted that there is no generally accepted technique to obtain weights. The Dedeman Mine study is referred to as Study 2 in the next chapters.

2.8.3 Selecting of ore transport system for a metalliferous underground mine with increasing mining depth and production capacities

Gonen *et al.* (2012) evaluated different transport systems for an underground mining scenario under different mining depths of up to 1,000m and production capacities up to 1Mt/yr. The transport systems evaluated were conventional shaft hoisting, mine trucking transport in declines and flexowell vertical belt applications. The study dealt with multiple transport system alternatives and multiple criteria hence proving that the decision was based on a MCDA approach. The study compared investment cost and operating costs for the three transport systems at different production capacities and depth. Gonen *et al*. (2012) identified the important factors that affect the choice of ore transport system as ore reserve, production capacity, underground mining method, ground conditions, thickness, depth and dip of ore body, planned LOM, development schedule, and price of selected machine-equipment, amortisation, and discount rate. These factors were categorised under three main broad criteria namely economic, environment/safety and technical. The study found that (Gonen *et al.*, 2012):

- The ramp truck transport system is most economic for small to medium sized mines with low investment cost.
- The ramp truck transport system appears to be economical in mines whose production capacity is under 300,000t per year for all the depths.
- At high production capacity and increased depth, despite the initial high investment cost the shaft hoisting system is the most economic method.

- The optimum changeover depth from decline haulage to shaft hoisting becomes shallower as production rate increases.
- Small sized deposits may be economically served by ramp and truck transport systems to a vertical depth of as much as 500m.
- The vertical band conveyor system was found to be technically ideal up to a depth of 250m for medium to high production capacities.

The findings from the study by Gonen *et al*. (2012) that are relevant to this research study for Blanket Mine are:

- Investment cost and production capacity affect decisions on an optimal transport system.
- Optimal solutions in transport systems should take into consideration the operating costs of the selected system.
- The study discussed the common challenges faced with deepening mines that have decreasing ore reserves and grade which compel mining operations to reduce cost to maximise economic value. A mining transport system is one of the major cost drivers and as such should be optimised. The cost of ore transportation affects the overall profitability of a mine (Gonen *et al.,* 2012).

In the study, the transition of production rate with depth was discussed with more emphasis on productivity and costs. The study however concluded that although a transport system maybe economically attractive, there are technical limitations associated with transport systems which must also be considered. For example, in the study the vertical band conveyor was found to have a depth limitation of 250m. It was also concluded that an optimal transport system should be developed by taking into consideration the lifespan of selected machinery-equipment and the net present value under dynamic conditions (Gonen *et al.,* 2012). In their study, no weighting and pairwise comparison was done for the criteria used in the transport selection decision. This study is referred to as Study 3 in the next chapters.

2.8.4 Evaluation of ore transport options from the Kwesi Mensah shaft to the mill at Obuasi Mine

A study by Owusu-Mensah and Musingwini (2011) successfully applied the AHP technique in evaluating transport options from the Kwesi Mensah Shaft to the mill at Obuasi Mine in Ghana.

The study revealed that use of surface belt conveyors was the best option when compared to the use of underground conveyors, purchasing mine-owned trucks and the use of contractor trucking. Obuasi Mine was operating at 175 000 tonnes per month using contractor trucking. The business plan required ore production to be increased from 175 000 to 220 000 tonnes per month. Four transport options were compared namely, contractor trucking, owner trucking, and use of belt conveyors. The criteria used for the selection were economic, environmental, and technical. The study was not the first to evaluate transport options at the mine as earlier studies and subsequent plans had been made, resulting in a decision to introduce surface belt conveyors as they were found to be economically viable at the time due to lower production levels (Owusu-Mensah and Musingwini, 2011). The objectives of the first study were to lower cost, improve availability and security and limit the several challenges linked with trucking. However, the challenge was that the conclusion was subjective as there was no structured technique followed in selecting the best option (Owusu-Mensah and Musingwini, 2011).

The study by Owusu-Mensah and Musingwini (2011) involved the selection of a transport option for a mine expanding ore production. It also applied the MCDA technique. The transport selection problem was structured into a basic AHP hierarchy which defined the objective, criteria and options or alternatives. The study also confirmed and proved that the AHP model can be used in mine planning during the decision-making process. The main criteria, sub-criteria and the weights which were used in the case study are shown in Table 2.8.

Table 2.8: Evaluation criteria and respective weights for Obuasi Mine

(Source: Adapted from Owusu-Mensah and Musingwini, 2011)

Criteria	Sub-criteria	Weight
Economic	Capital cost	13.0
	Operating unit cost	3.4
	Maintenance cost	4.2
	Energy cost	3.5
Environmental	Noise levels	11.9
	Emissions levels	9.3
Technical	Productivity	5.2
	Repair easiness	2.0
	Topography	1.2
	Safety	28.2
	Durability	4.2
	Availability	6.3
	Ease of setup	1.4
	Flexibility	2.1
	Spares supply	4.1

In the Obuasi Mine study, the identification of the criteria relative importance and weighting of the criteria was done by a team of five practitioners from the mine. The practitioners included two mine planning engineers with more than 10 years mine planning experience and two production managers from the mining department and an engineering manager from the mine (Owusu-Mensah and Musingwini, 2011). The assumption in the study was that the practitioners had sufficient experience and their opinion was representative of the company`s position with regards to the selection process of the transport system. From the study, the practitioners ranked the environmental criteria higher than the economic and technical criteria. According to Owusu-Mensah and Musingwini (2011), the interpretation for ranking environmental criterion higher has been influenced by the increased global environmental and climate awareness which is in contrast with the Obuasi Mine`s priorities.

The study concluded that the AHP methodology is reliable and designed to permit repeatability of the decision-making process which is important in guaranteeing transparency and good corporate governance. The transport system selection evaluation outcome was shared with the mine management who agreed with the outcome. Management however expressed reservation with the selected option due to a constraint on installation capital required resulting in a short-term resolution which was however costly in the long run. According to Owusu-Mensah and Musingwini (2011), the financial assessments revealed that the contract trucking transport system resulted in a cumulative transport cost of US$22.0 million over a period of 9 years whereas the total projected cost for the conventional overhead surface conveyor was US$12.32 million whilst an underground conveyor would cost US$ 8.95 million. It was further stated in the study that the payback period was between 9-10 years for contractor truck option and about 6-7 years for underground conveyor. The short-term decision taken by management could however be mitigated by introduction of competition to truck transport charges by contractors. The evaluation done for Obuasi Mine demonstrated that management can be well informed and properly guided when making decisions if they make use of structured techniques like AHP. The Obuasi Mine study is referred to as Study 4 in the next chapters.

2.8.5 Selecting an optimal rock transportation system at Trojan Mine using the Analytic Hierarchy Process

In this study, Karembera (2020) used the AHP to select an optimal rock transportation system at Trojan nickel mine located in Bindura, Zimbabwe. The mine had plans to extend the LOM by extracting mineral reserves below 35/0L which was the lowest level at that time. The plan was supposed to contribute an additional two-year life at a projected depletion rate of 65 000tpm, up from a rate of 40 000tpm which was currently being mined at the time. This plan was undertaken against challenges of low ore grades which were expected at the lower levels, low nickel prices in addition to increased depth and an expected increase in operating costs. Karembera (2020) indicated that the cost of rock transport system at Trojan Mine was estimated to be 20 % of total mining costs. The mine had been using rail transport system for the 35/0L haulage level and all upper-level haulages and no formal studies had been undertaken on the mine to investigate alternative ore transport systems.

The aim of the study by Karembera (2020) was to identify alternative underground transportation systems that could be used at Trojan Mine and select an optimal rock transport system to use at the main haulages at the mine. The study discussed the mine transport systems applicable to Trojan Mine namely rail transport system, belt conveyor system and the truck transport system. It was also emphasised by Karembera (2020) that the decision which is part of mine planning was a multi-criteria decision problem.

A team of five experts who were employees of Trojan Mine with the relevant experience and qualifications to decide which is representative of company’s interest were selected. The experts identified the evaluation criteria of the optimal transport system, assigned weights to each criterion, and did the pairwise comparison. A total of 24 criteria identified were classified under three broad categories which were economic, environmental and technical. The weights were assigned a number between 0 and 10, with 0 indicating that the criteria is not important and 10 being very important in the selection decision of the transport system. The average scores from the experts were obtained and the top three criteria under each broad criteria were chosen to make nine criteria. The selection of nine criteria was defined as the limit for human judgement in abstract thinking when dealing with MCDA problems. Table 2.9 shows the consolidated evaluation criteria and weights from the experts which were used for the Trojan Mine transport system selection.

Table 2.9 Selected criteria and weights for Trojan Mine transport system selection

(Source: Adapted from Karembera, 2020)

Category	Criteria	Weighting
Economic	Capital cost	9.4
	Unit operating cost	8.4
	Labour cost	6.2
	Maintenance cost	7.4
	Unit energy cost	7.6
Environmental	Aesthetics	3.8
	Emissions	7.2
	Noise	6.4
	Dust	6.4
	Heat	6.2
Technical	Productivity	7.6
	Safety	8.8
	Availability	8.8
	Ease of configuration	6.4
	Degree of automation	6.2
	General supervision required	5.6
	Maintainability	6.4
	Power source (diesel, electric)	6.0
	Auxiliary machine required	2.8
	Logistic support or management	4.6
	Drive system (hydraulic, electric, mechanical)	7.2
	Administration	4.2
	Operator capability	5.8
	Site or deposit parameters	3.0

A consistency check was done for the judgements by the experts as part of the AHP process. The efficiencies of each transport system were evaluated and used together with criteria pairwise comparison judgements from the experts in the AHP model to rank the alternatives. The belt conveyor was identified as the optimal transport system, followed by the rail system and the truck system. The study concluded that the AHP technique was a sufficient tool in optimisation. The Trojan Mine transport system selection study is referred to as Study 5 in the next chapters.

2.9 Application of AHP in selecting the optimal transport system for Blanket Mine

For this study of selecting the optimal transport option amongst the three possible options for the BM expansion project, the following criteria were selected: unit labour cost, capital cost, maintenance cost, dust, safety, noise, availability, productivity and ease of use. This selection was based on several related similar studies in the selection of transport systems, some of which were reviewed in this chapter. In addition, as noted by Elevli and Demirci (2004), there is no prescribed way for obtaining criteria and their associated weights, hence the approach taken in this study to use previous studies for a more balanced view.

2.10 Summary of Chapter 2

One of the objectives of mine planning is to make decisions and develop plans for operations to optimise their return on investment. Decision making in mine design and planning is an important process which should be aligned to a company's strategic goals and objectives. Before a decision is made, it is essential that a clear understanding of the objectives is done to gather as much detail as possible and allow for the determination of alternative solutions. The selection of an optimal transport system is one of the important decisions in mine design and planning due to its impact on the profitability of mining operations. It is also important to get an appreciation of the merits and demerits of each option where there are alternatives available. This may include benchmarking with other operations where similar problems have been solved to understand the processes taken in the selection process. Chapter 2 discussed the objectives of mine transport systems in mine planning, the factors to consider when selecting transport systems and the transport options available for underground mines. Literature on similar and related transport selection studies was reviewed in the chapter.

The literature reviewed show that the selection of an underground mine transport system is a multi-criteria decision-making problem which requires MCDA techniques to select the optimal system. There are many types of MCDA techniques, including the AHP technique. For this research the AHP technique was selected to analyse the optimal transport system selection problem for the BM expansion project. Examples of MCDA techniques were discussed in Chapter 2 and a justification for the selection of the AHP technique was given. The formulation of the AHP model to select the optimal transport system for the BM expansion project is done in the next chapter.

3 DATA COLLECTION AND METHODOLOGY

3.1 Overview of Chapter 3

Transport selection is an MCDA type of problem as explained in previous chapters. For this study, the AHP methodology was selected for use in determining the optimal transport system for Blanket Mine's expansion project due to its advantages discussed in Chapter 2. Chapter 3 discusses the criteria selected for the problem and the weighting of each decision criterion in determining the optimal transport system. The chapter also describes the methodology that was used to select the criteria and assigned weights for evaluation to determine the optimal transport system.

3.2 Selection of evaluation criteria

The AHP methodology requires identification of criteria and the determination of weights of each of the optimisation criteria. The main objectives for these studies were common to that of the BM expansion project. As highlighted in Chapter 2, the criteria selected for this research study were derived from the most common criteria identified from literature review. From the literature review the criteria and weights were identified and then the arithmetic mean was calculated to determine the weights of criteria for the BM expansion project. The following assumptions were made in the compilation of the criteria weights for the BM expansion project study:

- The weights were derived from four transport selection case studies done at other mining operations.
- The arithmetic mean of the aggregated weights is assumed to be representative to that of the BM expansion project.
- The weights for each study criterion were recorded in Table 3.1 as they were assigned in each study.
- A weighting score range of 0 -10 was used, with zero indicating a criterion which is not important in the selection of the transport system and 10 being the criterion which is extremely important in the selection of the transport system. Where weights of case studies used had a range more than 10, normalisation was done to reduce the weight scores to be within the range 0 - 10 and similarly where the weighting range was less than 10 it was adjusted to be within the range 0 -10.

- The arithmetic mean was calculated considering only the weight scores recorded. For example, where there are only two weight scores, the arithmetic mean was an average of the two weight scores.
- Where a sub-criterion was not reported on in a study, the score was indicated as N/A.
- Risk of accident and injury and exhaust gases in Study 1 were synonymously referred to as safety and emissions, respectively in this research study.
- Ore production, investment cost, ease of system, and haulage cost in Study were synonymously referred to as productivity, capital cost, ease of use and operating cost, respectively in this research study.
- The aggregated weights were compiled only for the criteria considered for the BM expansion project.

The rating produced was assumed to be relevant and applicable to the BM expansion project. The views and judgements from the studies are deemed to represent a balanced view of the interests and objectives of the BM's transport selection problem. The criteria chosen and their ratings were assumed to be consistent with the perspective of mine management and representative of the objectives of BM. This was based on regular planning meetings at the mine where it was established that the key focus areas were environmental/safety, mine economics and technical issues. All these meetings were attended by the experts on the mine and supporting head office staff. Therefore, the criteria adopted from the five case studies are applicable to BM.

In using the AHP method to model the transport selection problem a hierarchic structure is needed to model the problem and some weighting comparisons to formulate relations within the structure (Saaty, 1987). Three main categories of criteria as noted in Chapter 2 were identified as critical and relevant in evaluating the transport system selection problem. These categories are economic, environmental/safety and technical with a total of 9 sub-criteria. The transport selection problem was mapped into a basic AHP hierarchy model. The AHP model showing the objective, options, and criteria is shown in Figure 3.1.

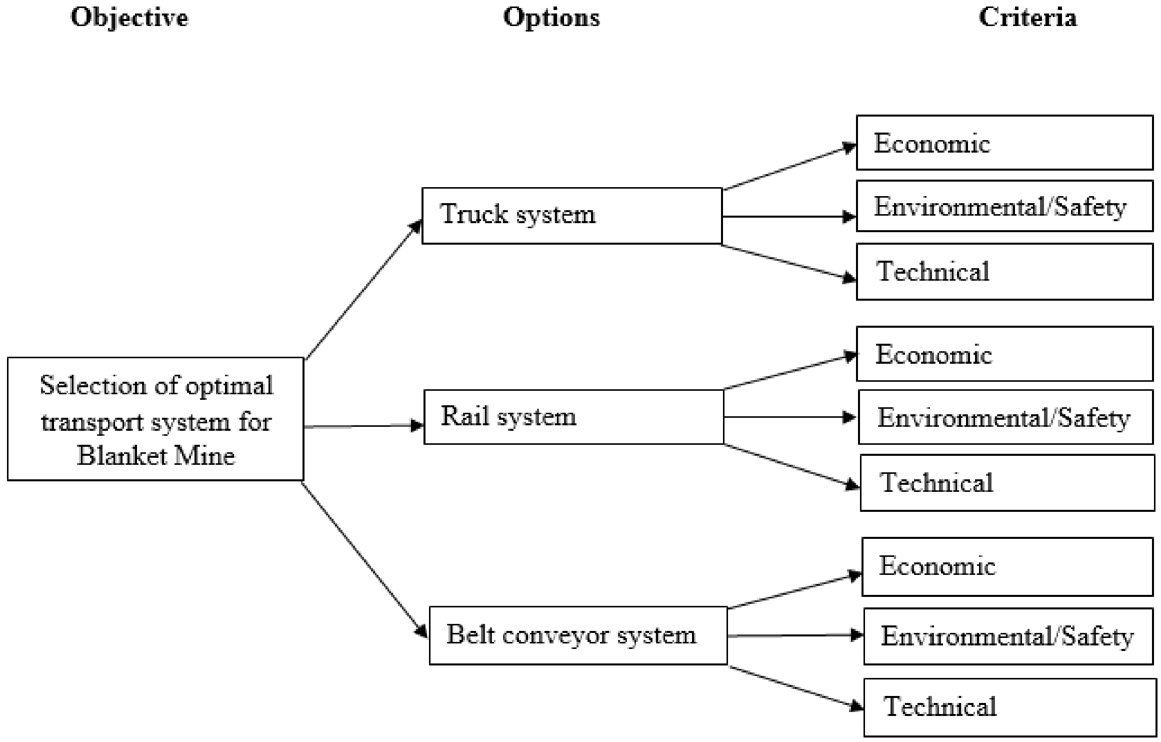

Figure 3.1: A schematic structure of the AHP hierarchy for Blanket Mine ore transport selection process

To make comparisons there is a need of weights that indicate how many times more important or dominant one criterion is over another criterion with respect to a criterion or element to which they are compared (Saaty, 2008). A ranking score of weight was used for the BM expansion project study indicating the highest and lowest weight score. The weight score indicated the level of importance of a criterion in the transport selection problem. The weight scores had a range from 0-10. The criteria which are most important were rated 10, the least important were rated 1 and criteria which were not important were rated 0. Averages were calculated for the scores under each category and the three highest scores were selected for use in the AHP model to make a total of nine evaluation criteria.

The use of a maximum nine evaluation criteria was based on the assumptions that human judgements are limited when it comes to abstract thinking in MCDA (Musingwini and Minnitt, 2008). The number of criteria should be enough to make a meaningful comparison of alternatives but also noting that if the number of criteria is too large the comparison may be very difficult (Harker, 1987). According to Table 2.5, seven criteria require 21 comparisons whilst nine criteria require 36 comparisons and so on. The same argument was presented by Saaty and Ozdemir (2003), Yavuz and Pillay (2007a), Yavuz and Pillay (2007b), and Acaroglu *et al.* (2006) who recommended that more reliable pairwise comparisons are achieved when the maximum number of criteria is nine. These human performance limitations are often referred to as ‘central computing space’, ‘channel capacity’, ‘attention span’ or ‘memory span’ (Yavuz and Pillay, 2007a). The scores were compiled, and the mean scores were calculated.

The weight scores for the studies were analysed under the three main broad criteria namely economic, environmental/safety and technical. For the BM study the economic criteria considered were capital cost, operating cost, unit labour cost and maintenance cost. The criteria considered for environmental/safety were safety, dust noise and emissions. Lastly, for technical criteria productivity, availability, ease of use, flexibility and spares supply were considered.

As mentioned in Chapter 2, the Sintoukola potash project, Dedeman underground mine transport system study, selection of ore transport system for a metalliferous underground mine with increasing depth and production capacity, Obuasi Mine study, and Trojan Mine study are referred to as Study 1, Study 2, Study 3, Study 4, and Study 5, respectively. Study 3 had no weighting done; therefore, it was excluded for further analysis in this study. From the remaining four studies, only criteria which are applicable to BM expansion project were considered for further analysis. Table 3.1 shows, the main categories, criteria weight scores for the criteria used in the BM expansion project study.

Table 3.1: Criteria and sub-criteria weights for five transport selection problem studies applicable to BM expansion project

Criteria	Sub-criteria	Study 1	Study 2	Study 4	Study 5
Economic	Capital cost	N/A	24.6	13.0	9.4
	Operating cost	N/A	21.7	3.4	8.4
	Unit labour cost	N/A	N/A	N/A	6.2
	Maintenance cost	N/A	N/A	4.2	7.4
Environmental /Safety	Safety	3	N/A	28.2	8.8
	Dust	3	N/A	N/A	6.4
	Noise	2	N/A	11.9	6.4
	Emissions	1	N/A	9.3	7.2
Technical	Productivity	N/A	20.6	5.2	7.6
	Availability	N/A	N/A	6.3	8.8
	Ease of use	N/A	10.9	1.4	6.4
	Flexibility	N/A	N/A	2.1	N/A
	Spares supply	N/A	N/A	4.1	N/A

The criteria which were not weighted in the four studies are indicated as N/A in Table 3.1. Study 1 had weight scores with a range 1-3, Study 2 and Study 4 had weight scores with a range exceeding 10, and lastly Study 5 had weight scores with a range 0 – 10.

3.3 Application of the AHP technique

As mentioned in the previous chapters, the AHP process was applied to the selection of the optimal transport system for BM`s expansion project. The normalised scores for the Studies 1, 2, 4 and 5 and the arithmetic mean values for the transport studies are shown in Table 3.2.

Table 3.2: Normalised aggregated criteria and sub-criteria for the five transport selection problem studies applicable to BM expansion project

Criteria	Sub-criteria	Study 1	Study 2	Study 4	Study 5	Mean score
Economic	Capital cost	N/A	3.16	1.46	9.4	4.67
	Operating cost	N/A	2.79	0.38	8.4	3.86
	Unit labour cost	N/A	N/A	N/A	6.2	6.20
	Maintenance cost	N/A	N/A	0.47	7.4	3.94
Environmental /Safety	Safety	10	N/A	3.16	8.8	7.32
	Dust	10	N/A	N/A	6.4	8.20
	Noise	6.7	N/A	1.34	6.4	4.81
	Emissions	3.3	N/A	1.04	7.2	3.85
Technical	Productivity	N/A	2.65	0.58	7.6	3.61
	Availability	N/A	N/A	0.71	8.8	4.76
	Ease of use	N/A	1.40	0.16	6.4	2.65
	Flexibility	N/A	N/A	0.24	N/A	0.24
	Spares supply	N/A	N/A	0.46	N/A	0.46

To keep the scores in the range 0 – 10 as described in Section 3.2 for the studies with weight scores with a range above 10, a normalisation process was done. After normalisation the arithmetic mean was calculated for each criterion.

Study 1 had weights with a rating up to 3 as the maximum therefore, the weights were scaled to be within the range 0 -10 which was used for the BM expansion project study. The maximum score 10 was divided by the maximum rating in Study 1 (that is 10 ÷ 33=3.33) and the result was used to scale all Study 1 ratings in Table 3.1 by multiplying them by 3.33. Each weighting score in Study 1 was then multiplied by 3.33. For example, the normalised score for noise in Table 3.2 was calculated as 2 multiplied by 3.33 equals 6.7 and similarly for emissions was calculated as 1 multiplied by 3.33 equals 3.33.

The normalised scores for Studies 2 and 4 whose scores both ranged above 10 were calculated using a similar approach as follows. The sum of the weight scores in Table 3.1 was calculated for each study. The criterion scores were then divided by the sum of weights to normalise the scores and the results were multiplied by 10. For example, for Study 2 the sum of the weight scores is (24.6 + 21.7 + 20.6 + 10.9) = 77.8. The weight score input for capital was calculated as (24.6 ÷ 77.8) x 10 = 3.16. The same approach was taken for the other criterion weight scores for Study 2 and Study 4. Where a sub-criterion has not been reported on, the score is indicated as N/A and was excluded in calculations.

The normalised scores for Study 5 were taken as reported by Karembera (2020). This was because the weight scores` range of 0 -10 matched that which was used for the BM expansion project study. For example, the weight score of 9.4 under capital criterion in Table 3.2 was taken to be the same value as was reported for Study 5 in Table 3.1. The same was done for all Study 5 scores in Table 3.2.

The normalised weight scores were used to calculate the arithmetic mean as indicated in Table 3.2. For example, the arithmetic mean for the flexibility criterion was calculated as 0.24 ÷ 1 = 0.24 and that for availability criterion was calculated as (0.71 + 8.80) ÷ 2 = 4.76. The calculated mean scores of the sub-criteria were ranked and the top three were selected. The top three evaluation criteria under each category are shown in Table 3.3.

Table 3.3: Evaluation criteria for the BM expansion project and their respective scores and rankings

Criteria	Sub-criteria	Mean score	Ranking
Economic	Unit labour cost	6.20	1
	Capital cost	4.67	2
	Maintenance cost	3.94	3
Environmental /Safety	Dust	8.20	1
	Safety	7.32	2
	Noise	4.81	3
Technical	Availability	4.76	1
	Productivity	3.61	2
	Ease of use	2.65	3

An equal number of sub-criteria was considered to ensure equal weighting of each main criterion. The total number of sub-criteria was made nine as explained in Section 3.2. The mean score for each criterion indicates the weight of that criterion. The criteria, sub-criteria and the mean scores were used in the evaluation of the selection of the optimal lateral ore transport system for the BM expansion project.

3.4 Assumptions

The following assumptions were used in the analysis and comparison of transport systems:

- Production plan is based on the LOM plan.
- The comparison used the existing equipment`s operating parameters, type, brand, and derived capacity.

- The haulage dimensions would be the same in each transport option.
- The quoted capital costs for equipment and other capital jobs were assumed to be the same as the prevailing performance rates at the mine.

3.5 Ethical considerations

The costs and other assumptions were confirmed by the engineering department, mine planning department, and finance and administration department responsible for mine purchasing and accounting at Blanket Mine. The data provided is to the best interest of the company in selecting an optimum transport system for the BM expansion project. The data is kept confidential according to the ethical consideration and research study confidentiality agreement signed by the researcher, University of the Witwatersrand, and BM management.

3.6 Summary of Chapter 3

The selection of criteria, pairwise comparison and evaluation were based on five transport selection problems for mines identified in the literature review. The objectives and findings from the studies were justified as being comparable to the Blanket Mine expansion project transport selection problem. This is due to similar or common factors by mining operations which seek to improve profitability and positive returns on investment. From those studies, the criteria and weights were identified. The weights of the criteria, judged from the studies were obtained and classified as Studies 1 – 5. The weights from four of the five studies were then aggregated to derive the associated criteria and weights for the BM expansion project. Analysis and performance assessment are done in the next chapter.

4 PERFORMANCE AND EFFICIENCIES OF TRANSPORT OPTIONS

4.1 Overview of Chapter 4

Chapter 4 discusses the proposed set-ups of the three transport options being compared in this study namely, belt conveyor, dump truck and rail transport (locomotive) systems. All the three transport options were assumed to have the capacity to satisfy the required production target of 18 000tpm according to the LOM production schedule. The designs of the transport options set-up adopted the current operating parameters at BM. For all the options ore is collected from source at Eroica section and moved to the Central Shaft laterally for eventual hoisting to surface.

There are two main ore bodies to be mined according to the LOM targets, namely Eroica and Blanket which are located 1,298m and 798m, from the Central Shaft, respectively. Eroica is the furthest ore body to be mined on 30 Level and 34 Level and is expected to produce 18 000tpm. Therefore, this study only focused on transportation of ore from Eroica to Central Shaft on 30 Level. The current bottom most main production haulage is 26 Level after which comes 30 Level and 34 Level haulages. It is assumed that the 34 Level haulage set up would adopt the same option as selected on 30 Level as the configuration of the workings and respective distances are similar. The chapter also discusses performance parameters of each transport option based on the main criteria namely economic, environmental/safety and technical to select the optimum transport option.

4.2 Operating parameters

The production output according to the LOM schedules from Eroica section at 30 Level is planned to be 18,000tpm. The mine operates two tramming shifts with 8 hours and 10 hours for day and night shift, respectively, resulting in an effective 18 hours per day working time. The mine uses Fermel Liberator 14T dump trucks with a rated capacity of 10.5 tonnes per load, several belt conveyor systems of capacities varying from 75-100tph and 6t Goodman locomotives which pull 24t per cycle.

For this research study it was assumed that the mine would continue to use the same type of fleet for several reasons which include ease of maintenance, uniform spares stocks, advantages of familiarisation with the equipment and possibility of shifting the equipment around depending on the production demand. It was also assumed that minimal to zero waste tonnages were to be moved once the area has been commissioned for production. In the event that there would be some waste tonnes to be moved an extra 25% redundancy provided in the plan would cover for it. The current operational parameters were used to determine the capital cost, unit operating cost of each transport system and other criteria for comparison of the options. The following sections describe each transport system set up and operational parameters according to the mine design.

4.3 Belt conveyor system

The total distance for the belt conveyor design layout for Central Shaft to Eroica section as shown in Appendix 1 is 1,298m long. For the design in Appendix 1, material is loaded from box chutes and is moved laterally to Central Shaft for eventual hoisting to surface. Capital cost assumptions include the purchase of the belt conveyor and accessories, the civils work cost and the assembly of the belt conveyor and the structures. The belt will be operated by belt attendants working along the belt length from Eroica section to Central Shaft. The capital costs used were obtained from the mine`s LOM equipment schedule with quotations sourced from the mine`s procurement department.

The design and infrastructure set up of the belt conveyor is according to the LOM mine`s plan. Appendix 2 shows the parameters for the belt conveyor system operating at 30 Level from Eroica to Central Shaft for a lateral distance of 1,298 m. The belt conveyor system will be supported and maintained by engineering maintenance for the belt, structure, and the infrastructure. The labour costs of the operators, haulage maintenance crews, and the engineering maintenance crews were calculated based on the mine`s current USD rated salaries. The maintenance equipment and accessories were assumed to be at the mine`s current average costs being achieved for similar working belt conveyors on the mine. Belt conveyor productivity rates and design parameters were derived from the mine`s LOM schedule design.

4.3.1 Capital cost for the belt conveyor system

The capital cost for the belt conveyor transport system set up and design was based on the mine`s LOM production plan. The capital cost includes the cost of the civils, the belt conveyor structure and the belt conveyor and the installation costs. The belt was designed to be fed with rock from an ore box by means of a chute at Eroica section near the tail end and moves to discharge rock at the Central Shaft tip. The summary of the capital costs for the belt conveyor transport system is shown in Table 4.1.

Table 4.1: Capital cost for belt conveyor transport system

(Source: Caledonia Mining Corporation, 2020)

Belt conveyor capital	**USD**
Belt conveyor material (mechanical + electrical)	455,855
Belt conveyor structural	145,116
Belt conveyor civils	47,008
Belt conveyor installation labour	50,586
Total	698,565

4.3.2 Operating cost for the belt conveyor system

The costs were obtained from the current operational and performance data of similar belt conveyors operating on the mine. The breakdown and total operating costs are as shown in Table 4.2. The maintenance and operating statistics were adopted from the average costs of similar belt conveyors on the mine and estimated for the belt conveyor set up for the Eroica section to Central Shaft belt conveyor design. The figures were extracted from the mine`s cost databases and operating parameters. The unit costs were then derived from the total operating costs and the planned production rate of 18,000tpm.

Table 4.2: Operating costs for belt conveyor transport system

(Source: Caledonia Mining Corporation, 2020)

Belt conveyor operation	**Monthly average**
Electricity cost (USD)	120.00
Labour cost (USD)	2,700.00
Consumables spares (USD)	
Consumables electrical (USD)	2,200.00
Consumables structure (USD)	
Total maintenance cost (USD)	4,860.00
Monthly average tonnage per month (tpm)	18,000.00
Unit labour cost (USD/t)	0.15
Maintenance (USD/t)	0.27

4.4 Truck transport system

The mine design for 30 Level for the dump truck transport system has dump trucks operating from Eroica section to Central Shaft as shown in Appendix 3. The dump trucks will be loaded at ore chutes and travel along the haulage for 1,298m one way to the Central Shaft grizzly for tipping and return to load again until the production target is met. Turning loops are provided at the grizzly and at the loading chute. A dump truck moves towards the grizzly tip for offloading and goes around a loop coming back to the chute for loading. It turns back on a loop passing through the centre of the workshop at Eroica to turn back to the direction of the grizzly. A workshop is provided for maintenance and repairs for the dump trucks. The type of dump trucks considered for the haulage are reconditioned Fermel Liberator 14T which are already operational at the mine.

The dump truck will be operated by one driver. There will be a crew of 10 people for haulage maintenance, and an engineering maintenance crew for the dump truck which is the standard working arrangement set up at the mine. The labour costs of the dump truck drivers, haulage maintenance crews, and the engineering maintenance crews were calculated based on the mine`s current USD rated salaries for the crews. The maintenance equipment and accessories were assumed to be at the current mine planned costs as per budget for the same equipment on other working haulages. Equipment productivity rates were also set at the mine`s budget performance rates.

4.4.1 Capital cost requirement for the truck transport system

The capital cost for the truck transport system set up was derived from the mine`s production plan and current standards for equipment productivity rates. The capital cost includes the cost of installing complete haulage infrastructure, purchasing the dump trucks, and establishing workshop facilities. The mine will own and operate the dump trucks. The equipment requirements were derived from the production rate according to the mine`s LOM production schedules. The input cost of the equipment and activities for the capital cost were obtained from current costs, quotations from mine suppliers and purchase invoices obtained from the mine. The calculation for the number of dump trucks needed to achieve the production plan was derived as shown in Appendix 4. The summary for the capital cost requirements for the dump truck system for Eroica is shown in Table 4.3. The number of trucks was determined based on budget set up parameters according to the mine`s LOM schedules.

Table 4.3: Capital cost for the dump truck transport system

(Source: Caledonia Mining Corporation, 2020)

Truck transport system capital cost	**Parameter**
Fermel Liberator 14T (USD)	280,000
Number of trucks	4
Total cost (USD)	1,120,000

4.4.2 Operating costs for the truck transport system

Operating costs were adopted from the mine`s current operational and performance statistics of the same dump trucks. The cost split of the total operating costs are shown in Table 4.4. The unit costs were then derived from the planned production rate of 18 000tpm including ore and waste from Eroica section on 30 Level. Maintenance cost includes mining roadway maintenance crew, the equipment maintenance crew, and the associated material.

Table 4.4: Operating cost for the dump truck system

(Source: Caledonia Mining Corporation, 2020)

Dump truck operation	**Monthly average**
Fuel cost (USD)	10,880.00
Lubricants (USD)	3,998.80
Engine Spares (USD)	34,278.00
Tyres (USD)	26,989.20
Auto-electrics (USD)	
Body maintenance (USD)	
Hydraulics and fire suppression (USD)	
Axles and transmission (USD)	12,542.00
Total labour cost (USD)	58,140
Maintenance cost (USD)	120,780
Total tonnage (tpm)	18,000
Unit labour cost (USD/t)	3.23
Maintenance cost (USD/t)	6.71

4.5 Rail or locomotive transport system

The 6t Goodman locomotives will run on a single rail with a gradient of 1: 400 whilst pulling eight 4t capacity granby cars. The locomotives will be powered by 84V cell batteries which will be charged at the end of each shift by an electrical charger. Ore /waste will be loaded from chutes using radial doors and transported for tipping on a single rail track to the Central Shaft ore pass tips. The tramming route is shown in Appendix 5. For capital cost assumptions, each locomotive will be purchased complete with a charger and two sets of batteries. A total of 11 granby cars will be purchased for each locomotive with two being used as spares and one for riding of the assistant locomotive driver resulting in 8 loaded cars per trip. The capital costs used were obtained from Blanket Mine's LOM equipment schedule with quotations sourced from the mine`s procurement department. The design and infrastructure set up is according to the mine's LOM plans. Appendix 6 shows the parameters for the rail transport system operating at 30 Level from Eroica to Central Shaft.

Redundancy in equipment capacity was set at 25% of nominal capacity as a contingency in case of unplanned stoppages. The redundancy was based on the mine`s standard design parameters to cover for unexpected stoppages. For the rail transport system from Eroica to Central Shaft, a 6t locomotive travels 1 298m one way on 45lb rails. The payload is estimated to be 75% (3t) for each granby car. A total of four locomotives are planned to work in the haulage to move in a single rail track with some potential queuing either at the grizzly tip or at the loading chute at rail track over run provided. Each locomotive is provided with a charging bay and a workshop is provided for maintenance and repairs for the locomotives.

The locomotive will be operated by a locomotive driver and one assistant. There will be a crew of haulage maintenance, engineering maintenance team for the granby cars and the locomotive. The labour costs of the operators, haulage maintenance crews, and the engineering maintenance crews were calculated based on the current USD rated salaries at the mine. The maintenance equipment and accessories were assumed to be at the current mine average costs being achieved for the same equipment on current working haulages. Equipment productivity rates were also set at current mine`s average performance parameters.

4.5.1 Capital cost requirement for the rail transport system

The capital cost for the rail transport system set up was derived from the system requirements derived from the production plan and the current standards on the mine for equipment productivity rates standard. The capital cost includes the cost of installing complete rail infrastructure, purchasing of locomotives complete with each a set of chargers and granby cars. Table 4.5 shows the equipment requirements and the cost for the rail transport system for Eroica section to Central Shaft. The detailed capital costs are shown in Appendix 7. The equipment requirements were derived from the production rate according to the mine`s LOM production schedule.

Table 4.5: Capital cost for the rail transport system

(Source: Caledonia Mining Corporation, 2020)

Rail transport system capital cost	**USD**
Equipment schedule mechanical plus electrical	802,205
Locomotive bay structural	6,046
Locomotive bay civils	1,959
Rail transport system set up labour	17,618
Total	827,828

4.5.2 Operating costs for the rail transport system

The operating costs were derived from the mine`s current average maintenance and operating statistics for locomotives. The figures were obtained from the mine`s cost databases and operating parameters. The unit costs were then derived from the planned production rate of 18 000tpm planned for the level production from Eroica section. The breakdown of the costs is shown in Table 4.6.

Table 4.6: Operating cost per tonne for the rail transport system

(Source: Caledonia Mining Corporation, 2020)

Locomotive operation	**Monthly average**
Electricity cost (USD)	1,920
Lubricants (USD)	1,200
Consumables mine cars (USD)	4,800
Consumables spares (USD)	5,600.00
Consumables other (USD)	
Maintenance (engineering and mining) (USD)	55,800
Labour cost (USD)	30,6000
Total tonnage (tpm)	18,000
Unit labour cost (USD/t)	1.70
Maintenance cost (USD/t)	3.10

4.6 Transport system performance parameters

The performance data were obtained from the company`s mine planning records captured over a two-year period (2019 and 2020) and averages were calculated for each transport system. These were considered under the main categories of economic, environmental/safety and technical. Productivity was assumed to be 100% for each of the three options because the target for each system is 18 000tpm as per the mine`s LOM plan. Table 4.7 shows the transport system performance parameters for the BM expansion project.

Table 4.7: Transport system performance parameters

(Source: Caledonia Mining Corporation, 2020)

Transport system performance parameter	Belt conveyor	Dump truck	Rail system (locomotive)
Dust (mg/m^3)	2.00	2.20	0.20
Safety Risk/probability scale (0-1)	0.10	0.35	0.20
Noise level dB(A)	0.72	0.84	0.81
Availability (%)	0.93	0.85	0.90
Productivity (%)	100.00	100.00	100.00
Ease of use	0.95	0.80	0.90

Productivity which is defined as the monthly production capacity for the system was assumed to be the same since all the transport systems were designed to meet the production target at 18 000tpm with 25% of nominal capacity as additional capacity. The additional capacity was adopted as the mine`s transport system contingency measure in case of unforeseen challenges or breakdowns. The transport systems` availabilities were derived from the mine`s average performance as recorded from the mine during the two years from 2019 to 2020.

Ease of use is an aggregated parameter measuring the overall transport systems` performance in breakdown frequency, ease of repair, spares supply and availability, and flexibility of the system according to the mine`s experience. The ease-of-use figures shown in Table 4.7 show that the mine has more experience with the rail transport system and belt conveyors than the dump truck transport system which was introduced later at the mine. The mine also purchased rebuilt dump trucks and LHDs which experienced frequent breakdowns coupled with maintenance challenges and operating skills shortage hence the lower availability and ease of use of the truck system as shown in Table 4.7. Noise level is a relative measure of the sectional average noise to the maximum threshold limit of 90dB (A). This is according to the guidelines permitted by the Mining (Management and Safety) Regulations, 1990 of Zimbabwe Statutory Instrument 109 of 1990, Section 192. The measured readings were 76dB (A), 65dB (A) and 73dB (A), whose relative levels, when compared to the threshold limit of 90dB (A) were 0.84, 0.72 and 0.81, respectively, for the belt conveyor, dump truck and rail transport systems.

Dust was identified as a hazard to the health of underground workers. Measurements were taken for dust samples for each transport system in the existing workings. The measure of safety was a measure of the frequency of safety incidents and accidents recorded for each transport system over the period 2019 to 2020 for the mine. It was a ratio of the accident and incident free shifts over the number of worked shifts using the transport system for the period. Management of safety is critical in mine transport systems.

4.7 Aggregated efficiencies

The performance efficiencies for the transport systems are summarised in Table 4.8. The efficiencies show different performances for each transport system for different criteria. Some criteria such as productivity, safety performance and availability, must be maximised, whilst others such as noise, dust, gas emission, capital cost, operating cost, and energy costs must be minimised. This was considered when calculating the AHP priority score, where a maximisation criterion was treated differently to a minimisation criterion, as explained in Section 5.11. As discussed earlier in Section 2.3, a transport system may not satisfy the conditions of the nine criteria, making it difficult for decision making. In that case, the choice of the best transport requires consideration of all the criteria simultaneously. The best decision which balances the conflicting criteria on the transport systems requires the application of MCDA optimisation techniques such as the AHP as explained in earlier chapters.

Table 4.8: Aggregated efficiencies for the three transport systems

Transport system performance parameter	Objective	Belt conveyor	Dump truck	Rail system
Unit labour cost (US$ /tonne)	Minimise	0.15	3.23	1.70
Capital cost (US$)	Minimise	698,565	1,120,000	827,828
Maintenance cost (US$ / tonne)	Minimise	0.27	6.71	3.10
Dust (mg/m^3)	Minimise	2.00	2.20	0.20
Safety Risk/probability scale (0-1)	Minimise	0.10	0.35	0.20
Noise level dB (A)	Minimise	0.72	0.84	0.81
Availability scale (0-1)	Maximise	0.93	0.85	0.90
Productivity (%)	Maximise	100.00	100.00	100.00
Ease of use (relative)	Maximise	0.95	0.80	0.90

The best transport system is one that maximises availability, productivity, and ease of use whilst minimising risk of accidents, operating costs, capital cost, labour cost, noise, and dust level produced. The analysis for the aggregated efficiencies shown in Table 4.8 is done in the next chapter.

4.8 Summary of Chapter 4

Chapter 4 discussed the layout and operation of the systems according to the mine`s LOM plan. The target production was indicated and used to determine the equipment requirements. The equipment requirements were calculated using a zero-base approach by relying on the mine`s current equipment standards and experience. The cost of equipment was obtained from current quotations for the same equipment from the mine`s procurement department as it was assumed that the mine would continue using similar equipment in the study according to the mine`s LOM plan. The operating parameters adopted were also derived from the same assumptions using the mine`s current average performance rates. The mine`s current transport system performance rates were used to estimate the capital cost required for each transport system. Performance efficiencies were obtained with respect to each transport system for the nine different criteria. These efficiencies were used to determine the ranking of the three transport options, as shown in Chapter 5.

5 SELECTION OF THE OPTIMAL TRANSPORT SYSTEM

5.1 Overview of Chapter 5

This chapter focuses on the application of the AHP which is the MCDA technique selected to determine the optimal transport system in this study. It has already been established in earlier chapters that the criteria for selection of the optimal transport system were multiple and conflicting, making the MCDA technique appropriate to solve the problem. The AHP model was applied starting with an establishment of structural hierarchy, followed by the establishment of comparative judgements and synthesis of priorities and measurement of consistency.

The analysis involved the calculation of the expected efficiencies of the three transport options. Through this methodology the alternatives were evaluated and compared. The results were put in a matrix format and analysed in Microsoft Excel to normalise them and estimate the degree of consistency. The weights were aggregated to produce transport option scores for each criterion to get an overall AHP score for each of the options. The aggregate AHP priority scores for each transport option were calculated. Finally, the AHP was used to rank the transport systems, determining the optimal transport system.

5.2 Application of the AHP

The process followed the steps described in Section 2.7. According to the AHP process, the application started with developing a hierarchical structure of dependency as shown in Figure 3.1. Comparative judgements or pairwise comparisons of relative importance of criteria elements were then done in a matrix format. Table 5.1 shows the pairwise comparison results. The table was derived from Table 3.3. Appendix 8 shows the pairwise comparison of all criteria. Each criterion was compared to nine criteria including itself. The comparison was divided into rows with the 1st row comparing unit labour cost against the remaining eight sub-criteria, the 2nd row comparing capital cost against the remaining seven sub-criteria, the 3rd row comparing showing maintenance cost against the remaining six sub-criteria. The same applies to the remaining rows in Appendix 8. For example, a pairwise comparison of criteria weights of capital cost against maintenance cost is 1.19 calculated as (i.e. 4.67 ÷ 3.94) and a comparison of unit labour cost against noise is 1.29 calculated as (i.e. 6.20 ÷ 4.81). The figures 1.19 and 1.29 are highlighted in blue Table 5.1

Table 5.1: Pairwise comparison matrix

Crterion	Unit labour cost	Capital cost	Maintenance cost	Dust	Safety	Noise	Availability	Productivity	Ease of use
Unit labour cost	1.00	1.33	1.57	0.76	0.85	1.29	1.30	1.72	2.34
Capital cost	0.75	1.00	1.19	0.57	0.64	0.97	0.98	1.29	1.76
Maintenance cost	0.64	0.84	1.00	0.48	0.54	0.82	0.83	1.09	1.49
Dust	1.32	1.76	2.08	1.00	1.12	1.70	1.72	2.27	3.09
Safety	1.18	1.57	1.86	0.89	1.00	1.52	1.54	2.03	2.76
Noise	0.78	1.03	1.22	0.59	0.66	1.00	1.01	1.33	1.82
Availability	0.77	1.02	1.21	0.58	0.65	0.99	1.00	1.32	1.80
Productivity	0.58	0.77	0.92	0.44	0.49	0.75	0.76	1.00	1.36
Ease of use	0.43	0.57	0.67	0.32	0.36	0.55	0.56	0.73	1.00

5.3 Pairwise comparison matrix

The pairwise comparison weights in Appendix 8 were then developed into a 9 x 9 square matrix of weight scores as shown in Table 5.1 since there were nine criteria. The pairwise comparison matrix is composed of two entries namely the upper field and the lower field which then make up the pairwise comparison a complete filled matrix. The upper field refers to the entries above the figures highlighted in yellow diagonally in Table 5.1. These diagonal figures with a value of 1 indicate that a sub-criterion is as important as itself. The upper fields were completed first then the lower fields to produce a complete filled 9 x 9 matrix. Number entries in the lower field matrix are reciprocals of the corresponding entries in the upper field. For example, the criteria highlighted in green entries 0.78 (1 ÷ 1.29) and 084 (1 ÷ 1.19) are reciprocals of 1.29 and 1.19, respectively. The reciprocal assumption is explained in Section 2.7.1.

5.4 Normalisation of pairwise comparison results

The normalisation process of the pairwise comparison matrix (Table 5.1) was done. The normalisation process starts off with calculation of sum of columns as shown in Table 5.2.

Table 5.2: Sum of columns for the pairwise comparison matrix

Crterion	Unit labour cost	Capital cost	Maintenance cost	Dust	Safety	Noise	Availability	Productivity	Ease of use
Unit labour cost	1.00	1.33	1.57	0.76	0.85	1.29	1.30	1.72	2.34
Capital cost	0.75	1.00	1.19	0.57	0.64	0.97	0.98	1.29	1.76
Maintenance cost	0.64	0.84	1.00	0.48	0.54	0.82	0.83	1.09	1.49
Dust	1.32	1.76	2.08	1.00	1.12	1.70	1.72	2.27	3.09
Safety	1.18	1.57	1.86	0.89	1.00	1.52	1.54	2.03	2.76
Noise	0.78	1.03	1.22	0.59	0.66	1.00	1.01	1.33	1.82
Availability	0.77	1.02	1.21	0.58	0.65	0.99	1.00	1.32	1.80
Productivity	0.58	0.77	0.92	0.44	0.49	0.75	0.76	1.00	1.36
Ease of use	0.43	0.57	0.67	0.32	0.36	0.55	0.56	0.73	1.00
Sum of columns	7.45	9.89	11.72	5.63	6.31	9.59	9.70	12.78	17.42

The sums of each column of Table 5.1 are shown in the last row of Table 5.2. The highlighted entry 9.89 and 17.42 under capital cost and ease of use are equivalent of the summation of entries under capital cost and ease of use respectively. For example, the sum of capital cost column was calculated from (1.33+1.00 +0.84+…+0.77+ 0.57) = 9.89. The sum of columns for ease of use was calculated from (2.34 + 1.76 + 1.49+…+ 1.36 + 1.00) =17.42. The same calculations were done for the other columns.

To normalise the pairwise comparison matrix shown in Table 5.2 each entry in a column was divided by its corresponding column sum in Table 5.2. For example, the first entry highlighted under capital cost column was calculated from (1.33 ÷ 9.89) = 0.13, the second entry highlighted in the same column was calculated from (0.57 ÷ 9.89) = 0.06. All other entries in Table 5.3 were calculated the same way to produce a normalised matrix. The normalised comparison matrix is shown in Table 5.3.

Table 5.3: Normalised matrix

Criterion	Unit labour cost	Capital cost	Maintenance cost	Dust	Safety	Noise	Availability	Productivity	Ease of use
Unit labour cost	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Capital cost	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Maintenance cost	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Dust	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Safety	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Noise	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Availability	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Productivity	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Ease of use	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Sum of columns	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

5.5 Eigen vector calculation

The Eigen vector or criteria weights shows the relative importance of each criterion to the overall goal. Table 5.4 shows the criteria weight or Eigen vector values.

Table 5.4: Eigen vector results

Criteria	**Criteria weights/Eigen vector**
Unit labour cost	0.13
Capital cost	0.10
Maintenance cost	0.09
Dust	0.18
Safety	0.16
Noise	0.10
Availability	0.10
Productivity	0.08
Ease of use	0.06

The criteria weight values were obtained from the arithmetic average for each row of criteria in Table 5.3. For example, 0.13 = (0.13 + 0.13 + 0.13+…+ 0.13 + 0.13) ÷ 9 is the average of for the normalised matrix of the elements for the unit labour cost row in Table 5.3. Similarly for capital cost 0.10 = (0.10 + 0.10 + 0.10+…+ 0.10 + 0.10) ÷ 9. The same calculations were done to obtain the other criterion weights in Table 5.4. From Table 5.4, the broad criterion environment/ safety had the two top weight scores namely dust and safety with scores 0.18 and 0.16, respectively. This can be interpreted as the increased awareness of environmental and safety issues in decision making for mining projects. Unit labour cost at 0.13 was the third highest weight score also indicating its importance in mining process, operations, and management.

5.6 Weight of sums vector (Ws)

The weight of sums vector is a value calculated by multiplication of the original criteria pairwise comparison matrix shown in Table 5.1 and the Eigen vector shown in Table 5.4. For example, the value of 1.214 was obtained by multiplying each entry under unit labour cost row by a corresponding entry in the Eigen vector column and summing up all to get the value as follows (1.00 x 0.13 + 1.33 x 0.1+…+1.72 x 0.08 + 2.34 x 0.06) = 1.214. The same calculation was done for the remaining rows. Table 5.5 shows the weight sums vector for each criterion.

Table 5.5: Weight of sums vector

	Unit labour cost	Capital cost	Maintenance cost	Dust	Safety	Noise	Availability	Productivity	Ease of use	Criteria weights/Eigen vector	weight sums vector
Unit labour cost	1.00	1.33	1.57	0.76	0.85	1.29	1.30	1.72	2.34	0.13	1.214
Capital cost	0.75	1.00	1.19	0.57	0.64	0.97	0.98	1.29	1.76	0.10	0.913
Maintenance cost	0.64	0.84	1.00	0.48	0.54	0.82	0.83	1.09	1.49	0.09	0.772
Dust	1.32	1.76	2.08	1.00	1.12	1.70	1.72	2.27	3.09	0.18	1.603
Safety	1.18	1.57	1.86	0.89	1.00	1.52	1.54	2.03	2.76	0.16	1.432
Noise	0.78	1.03	1.22	0.59	0.66	1.00	1.01	1.33	1.82	0.10	0.943
Availability	0.77	1.02	1.21	0.58	0.65	0.99	1.00	1.32	1.80	0.10	0.932
Productivity	0.58	0.77	0.92	0.44	0.49	0.75	0.76	1.00	1.36	0.08	0.705
Ease ofuse	0.43	0.57	0.67	0.32	0.36	0.55	0.56	0.73	1.00	0.06	0.518

5.7 Consistency vector and Eigen value calculation

Table 5.6 shows the Eigen vector, weight of sums vector, consistency vector and the Eigen value. The Eigen vector and weight of sums vector columns in the table are the second last and last column of Table 5.5, respectively. Consistency vector was calculated by dividing the weight sums vector of each criterion and the criterion weight. The Eigen value is the arithmetic mean of the consistency vector.

Table 5.6: Consistency vector and Eigen value calculated

	Criteria weights/eigen vector (W)	Weight sums vector (Ws)	Consistency vector	Eigen value
Unit labour cost	0.13	1.214	9.339	9.011
Capital cost	0.10	0.913	9.134	
Maintenance cost	0.09	0.772	8.573	
Dust	0.18	1.603	8.906	
Safety	0.16	1.432	8.950	
Noise	0.10	0.943	9.426	
Availability	0.10	0.932	9.320	
Productivity	0.08	0.705	8.818	
Ease of use	0.06	0.518	8.630	

The average value of the consistency vectors gave the Eigen value λmax of 9.011. The Eigen value is greater than 9 (the order of matrix) that is, λmax > 9, hence the judgements are inconsistent. The degree of inconsistency must be calculated in this case.

5.8 Consistency calculation

Table 5.7 shows the calculations for the consistency index (CI) and consistency ratio (CR). CI was calculated using Equation 2.3. The Eigen value λmax in Table 5.6 = 9.011 and n = 9.

$$CI = \frac{(\lambda max - n)}{(n-1)}$$

$$CI = \frac{(9.011 - 9)}{(9-1)}$$

=0.0014

The results of the calculations of the consistency ratio and the decision to accept and proceed with the evaluation are shown in Table 5.7. The value of the random index (RI) is 1.45 for a matrix of order 9 was obtained from Table 2.4. The consistency ratio CR was calculated using Equation 2.4.

$$CR = (CI/RI) = (0.0014/1.4500) = 0.001$$

Table 5.7: Estimation of consistency ratio

Parameter	Symbol	Value	Decision
Average of consistency vector elements	λmax	9.011	Inconsistent
Order of matrix	n	9.000	
Consistency index	CI	0.0014	
Random Index	RI	1.4500	
Consistency ratio	CR	0.001	Accept

As shown in Table 5.7 CR=0.1% which is less than 10 %. As discussed in Section 2.7.1, if CR is less than 10 % it therefore implies that the weighting and the subsequent performance comparison is within acceptable range to allow for AHP modelling and calculation.

5.9 Aggregated transport system efficiencies

Table 5.8 shows the aggregated efficiencies of the transport systems and the sum of columns. The aggregated system efficiencies shown in Table 5.8 have different units. Therefore, the table was normalised starting with a calculation of the sum of columns for each criterion column. For example, the highlighted sum of unit labour cost column is a summation of 0.15, 3.23 and 1.70 which is 5.08. The same process was done to calculate the sum of column entries under each category of criteria / parameter measured.

Table 5.8: Aggregated transport system efficiencies with sum of columns

Transport system /parameter	Unit labour cost ($/t)	Capital cost ($000)	Maintenance cost ($/t)	Dust (relative)	Safety /relative	Noise /relative	Availability (relative)	Productivity (%)	Ease of use (relative)
Belt conveyor	0.15	698.57	0.27	2.00	0.10	0.72	0.93	100	0.95
Dump truck	3.23	1 120.00	6.71	2.20	0.35	0.84	0.85	100	0.80
Rail system	1.70	828.83	3.10	0.20	0.20	0.81	0.90	100	0.90
Sum of columns	5.08	2 647.40	10.08	4.40	0.65	2.37	2.68	300	2.65

5.10 Normalised efficiency scores

The efficiency scores in Table 5.8 were normalised resulting in normalised scores shown in Table 5.9. The entries in Table 5.9 were calculated by dividing an entry in Table 5.8 with the corresponding the sum of the column. For example, the normalised efficiency score for unit labour cost under belt conveyor row was calculated as 0.15 ÷ 5.08 = 0.03. The same calculations were done for all entries in Table 5.9

Table 5.9: Normalised efficiency scores

Transport system / parameter	Unit labour cost	Capital cost	Maintenance cost	Dust	Safety	Noise	Availability	Productivity	Ease of use
Belt conveyor	0.03	0.26	0.03	0.45	0.15	0.30	0.35	0.33	0.36
Dump truck	0.64	0.42	0.67	0.50	0.54	0.35	0.32	0.33	0.30
Rail system	0.33	0.31	0.31	0.05	0.31	0.34	0.34	0.33	0.34

5.11 Normalised efficiency priority scores, eigenvector and AHP scores

Table 5.10 shows the normalised efficiency priority scores, the Eigen vectors and the AHP scores. The AHP scores were calculated based on the objectives of the respective criteria. The objectives of the criteria were either to be maximised or minimised. In the case of maximisation, the normalised entry was taken as calculated in Table 5.9 and for minimisation the entry was input as the difference from 1 because minimising a score is akin to maximising its complement. For example, the unit labour cost score for the dump truck system was calculated as 1-0.64=0.36 since the objective is to minimise the cost.

Table 5.10: Normalised efficiency priority scores, eigenvector and AHP scores

Parameter	Unit labour cost	Capital cost	Maintenance cost	Dust	Safety	Noise	Availability	Productivity	Ease of use	Criteria weights	AHP score
Objective	Maximise complement	Maximise complement	Maximise complement	Maximise complement	Maximise complement	Maximise complement	Maximise	Maximise	Maximise		
Belt conveyor	0.97	0.74	0.97	0.55	0.85	0.70	0.35	0.33	0.36	0.13	0.675
Dump truck	0.36	0.58	0.33	0.50	0.46	0.65	0.32	0.33	0.30	0.10	0.440
Rail system	0.67	0.69	0.69	0.95	0.69	0.66	0.34	0.33	0.34	0.09	0.646
										0.18	
										0.16	
										0.10	
										0.10	
										0.08	
										0.06	

The rationale approach to the first six columns was to maximise the complement so that the matrix is a positive reciprocal matrix. This is stated by Coyle (2004) on limitations of AHP. The limitations are discussed in Section 2.7.2.

The criteria weights/eigen vectors in Table 5.10 were extracted from the second column of Table 5.6. The sum product of efficiency priority scores for each transport system and the criteria weights was the AHP score for each transport system. For example, the AHP score of 0.440 for the dump truck transport system was obtained from the following calculation, (0.36 x 0.13 +0.58 x 0.10 +…+ 0.33 x 0.08 + 0.30 x 0.06) and the AHP score for the locomotive transport system of 0.646 equals (0.67 x 0.13 + 0.69 x 0.10 + … + 0.33 x 0.08 + 0.34 x 0.06). A similar calculation was done for the AHP score for the belt conveyor transport system. Table 5.11 shows the AHP scores and ranking for the three transport systems.

Table 5.11: Final AHP scores and ranking

Transport system	AHP score	Ranking
Belt conveyor	0.675	1
Rail system (locomotive)	0.646	2
Dump truck	0.440	3

The ranking number 1 indicates that the belt conveyor is the optimal transport system with an AHP score of 0.675 followed by the locomotive or rail transport system and dump truck transport system with AHP scores of 0.646 and 0.440, respectively. The AHP score for the belt conveyor system is about 4% higher than the score for the rail system. This shows the competitiveness of the rail system as the next best alternative transport system. These results were shared with the mine management who accepted the outcome as a form of validation of the process.

5.12 Summary of Chapter 5

The chapter applied the AHP methodology in evaluating the three transport systems namely, belt conveyor, rail transport system and dump truck transport system for the BM expansion project. The results are also presented in the chapter. The AHP found that the belt conveyor is the optimal transport system.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Overview of Chapter 6

This chapter summarises the research and provides conclusions and recommendations. The limitation of the research and potential areas of future research are also presented in the chapter.

6.2 Research summary

BM is pursuing a production ramp up which is planned to be achieved at a cost of between US$700 - US$800/oz of gold produced. The operating costs have however been increasing gradually as the mine is getting deeper and exhausting high-grade ores from the upper levels above 750m level. Generally, the mine had been operating as a low-cost producer producing at an average unit cost of US$600/oz and this background demanded a review of mining activities to manage costs. Against this background, the selection of an optimal transport system was identified as one of the mine`s operating costs driver (Caledonia Mining Corporation, 2020). Therefore, optimising rock transportation will enable the mine to achieve its objectives. The AHP was used to select an optimal transport system.

Transport system selection in a mining operation is a critical and strategic issue in the mine design and planning process. The selection process can be more complex when several factors with conflicting objectives are involved in the selection process. In some cases, the selection of transport systems is done based on previous experience which is not always appropriate as opportunities for lower cost and efficient alternatives may be missed. A consultative and an integrated approach should be used in selecting an optimal transport system. Advocating those economic issues should be considered as important as environmental/safety and technical issues. Consideration of all factors would enable mining engineers to have adequate detail for selection of an optimum transport option for a particular mining operation.

This research study discussed the selection of an underground ore transport system based on three main broad criteria namely, environmental/safety, economic and technical factors. The study applied the AHP technique in evaluating transport options for the BM expansion project. Three transport systems applicable to BM were analysed. All the three transport options could be applied as they are already used at the mine, though at different efficiencies. The comparison of the transport options for BM was based on studies of five similar related research work on selection of transport systems. Deliberations from the planning, strategic planning meetings and review sessions by BM management and experts support the literature review findings. The criteria and weights were identified and pairwise comparison for the criteria was done to establish the relative importance of each criterion.

6.3 Conclusions

After applying the AHP technique, the study showed that the belt conveyor transport system was the optimal option over the rail transport system, and truck transport system. The evaluation also revealed that the safety and dust criteria carried the highest weight relative importance at 0.16 and 0.18, respectively. This is in line with the current environment where BM has been faced with a thrust to reduce accidents (Caledonia Mining Corporation, 2020). The company policy puts safety first and has been conducting a lot of safety programs on the mine. Although equipment selection at the mine has been done before, this is the first time that a structured approach was used at BM. The approach used in this research study can be applied by other mines in solving their various mine planning decision problems.

6.4 Recommendations

It is recommended that the mine adopts the use of the belt conveyor system as it proved to be the optimal transport system. The mine already has extensive experience in operating belt conveyors though mainly in the process plant and can extend the same to the underground operations. It would be advisable in future that the mine`s decision makers consider the AHP methodology to select the best decision amongst competing options. This would help in ensuring that the evaluation of decisions is done considering all factors that would otherwise be omitted. The main important step is to identify the criteria to be used in the choice and then a multi-criteria decision model for evaluation of options can be applied. Mine operational decisions are getting more pressure from regulatory bodies to include environmental/safety factors in addition to the traditional economic and technical factors. These factors are often multiple, conflicting, and contradictory and require some trade-offs to be made simultaneously. The AHP model used in this research study being an MCDA technique is one such tool that can be applied to help in such decision making. Operational decisions and research studies can be evaluated by considering similar related case studies done for other operations.

6.5 Research limitations

The following are the limitations of the research:

- The study was limited to the selected three main criteria namely, technical, environmental/safety and economics. The challenge is however that as the number of criteria increases the number of pairwise comparisons increases thereby clouding judgement and making it difficult to achieve consistency. It may be difficult to establish a pairwise comparison for a lot of criteria. The number of criteria is often reduced by grouping the criteria.
- The research did not further consider the time factor such as payback period in comparison of the transport systems for implementation.
- The research was only limited to one haulage at 30 Level and assumed the same conditions for 34 Level and other levels at constant production which is rather an ideal set up.
- The research assumes the same haulage dimensions for the three transport systems. However, the dimensions may be different for each transport system which in a way results in different ranking. The transport options were not analysed for optimisation and the research study assumed the current performance efficiency parameters.
- The research only applied AHP. Different results may be obtained if other MCDA techniques are used. The arithmetic mean was used in calculations and not geometric mean. The two may give different outcomes.
- The research was done based on the current mine operating parameters which could change with time as mine operating conditions and efficiencies change.

6.6 Recommendations for future research

The following are areas of possible future research:

- Carrying out a sensitivity analysis of the conditions and efficiencies on the selection of the optimum transport system.
- Investigating the outcome of the comparison if other MCDA techniques are used. The same could also evaluate the use of geometric mean in calculations instead of arithmetic mean.

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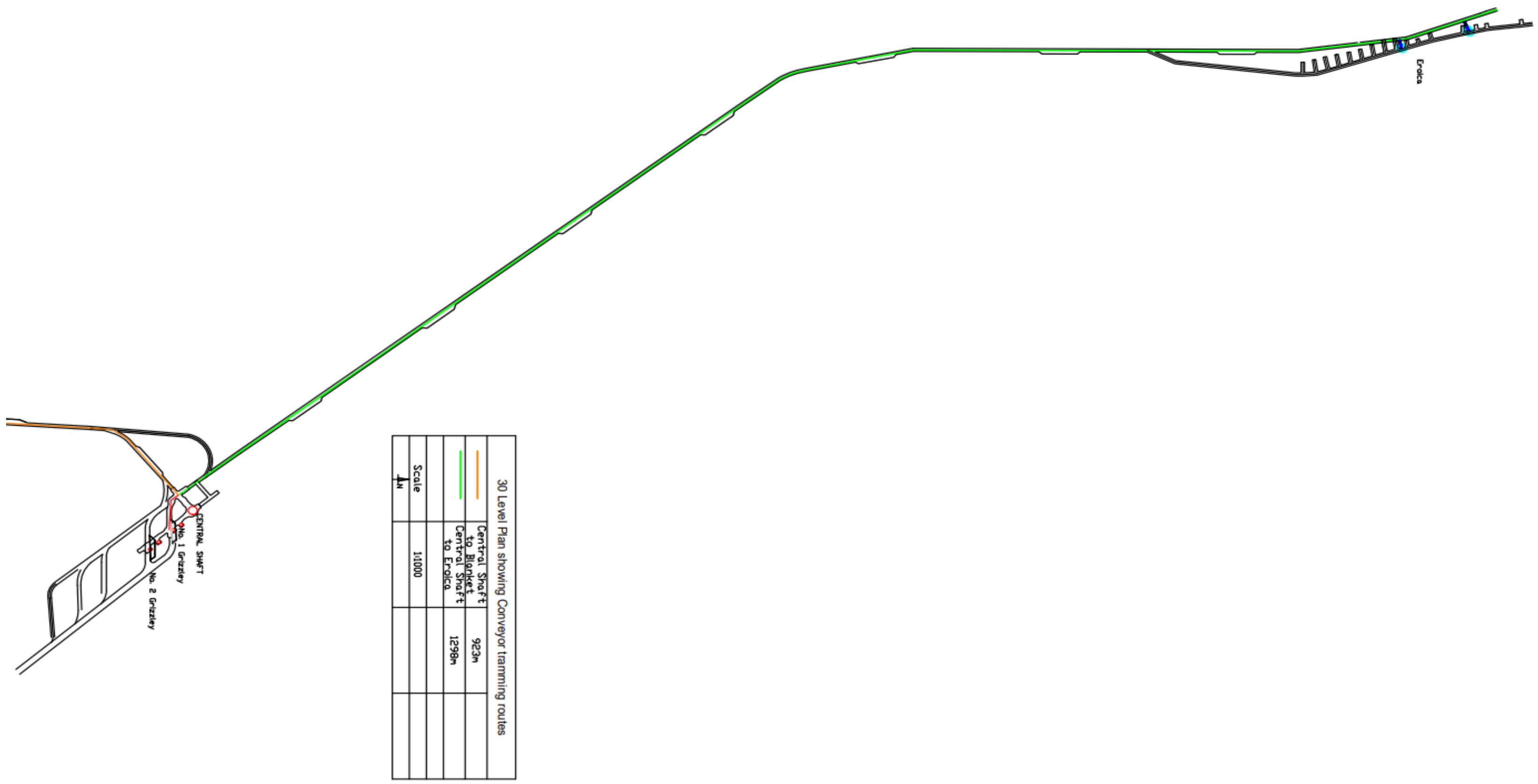
Appendix 1: Layout for Belt conveyor system

(Source: Caledonia Mining Corporation, 2020)



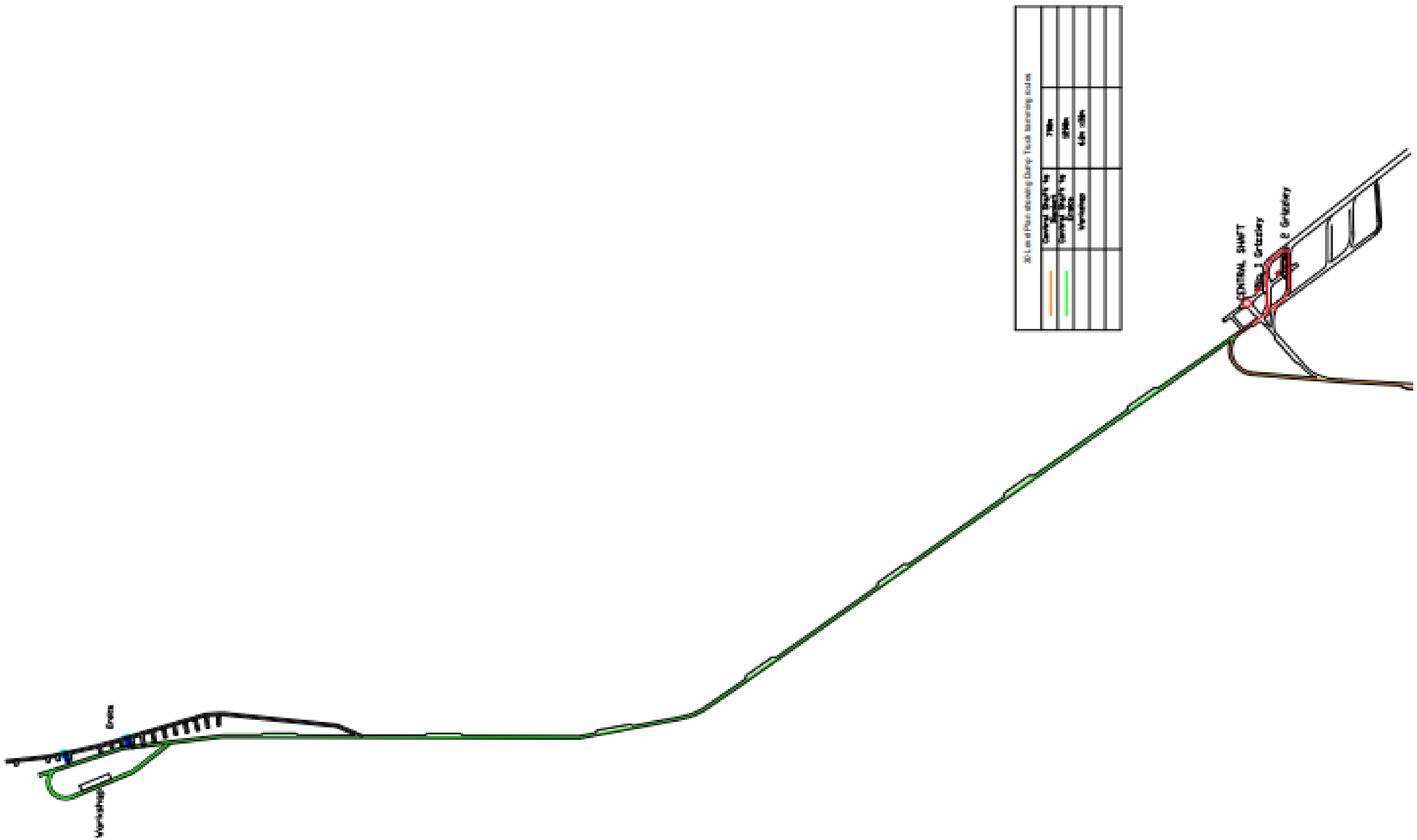
Appendix 2: Capital cost for the Belt conveyor system

(Source: Caledonia Mining Corporation, 2020)

Material requirements description	**USD**
Transition/Troughing/Impact /Flat return Idlers	60,364
Support frame code OS - 20 900 (for 127 Diameter roll)	82,092
Head, tail, and snub pulley arrangement (as per drawing)	38,106
Fag plummer block bearing assembly (Tail and head pulley plummer block)	12,843
Fag pillow block bearing assembly (Snub pulley pillow block) - Type SG 56208 (Housing SG 208 S, Bearing 56208)	5,107
CONVEYOR BELT 900mm CLASS 500/ 4PLY COVER=6.3/1.6mm Type M Covers. MOULDED EDGE	180,000
Flender Gear Motor Unit FDA 108B-K2X-132 and accessories	39,717
Brelko 900 Belt head pulley scraper type E901 TT (Twist Tension mounting) complete with 150mm wide polyurethane blades. Total 5 blades.	7,716
Flexco Return Belt V-Plough - 900 belt	10,350
M12 x 40 bolts and nuts + screws	19,560
Belt conveyor (Mechanicals + Electricals) materials	455,855

Appendix 3: Dump truck system layout

(Source: Caledonia Mining Corporation, 2020)



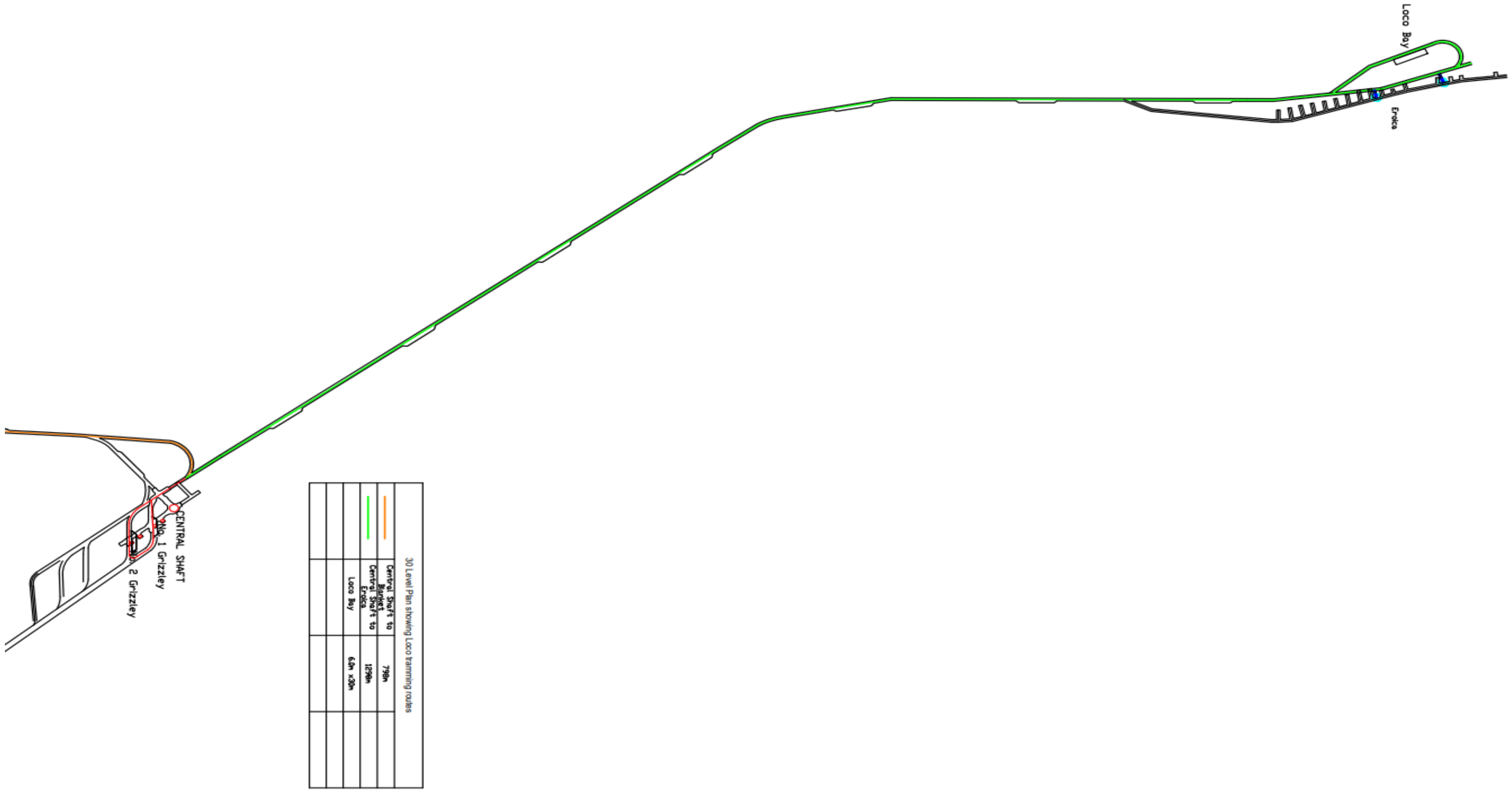
Appendix 4: Dump truck transport system requirements

(Source: Caledonia Mining Corporation, 2020)

Assumptions	Eroica haulage set up
Total distance to Central Shaft (m)	1298
Dump/truck capacity (t)	10.5
D/truck tramming distance (m)	2596
D/truck speed (m/hr)	8000
D/truck speed (m/minute)	133.3
D/truck total travelling distance (m)	2596
D/truck travelling time (mins)	19
D/truck tipping time (mins)	3
D/truck loading time (=Box loading time)	5
Total D/truck cycle time	27
No of D/truck loads /hr	2.2
Tonnage moved/hr	23
Potential tonnes per working day	367
Equipment availability	0.75
Utilisation	0.85
Effective total tonnes moved/day	234
Total tonnes per month- LOM	18000
Average number of shifts per month	30
Total tonnes (tpd)	600
D/trucks	3
Swing trucks	1
Total Dump trucks required	4

Appendix 5: Rail system layout

(Source: Caledonia Mining Corporation, 2020)



Appendix 6: Rail transport system requirements

(Source: Caledonia Mining Corporation, 2020)

Assumptions	Eroica haulage set up
Total distance to Central Shaft (m)	1298
Locomotive capacity (t)	24
Locomotive tramming distance (m)	2596
Locomotive speed (m/hr)	4000
Locomotive speed (m/minute)	67
Locomotive total travelling distance (m)	2596
Locomotive travelling time (mins)	39
Locomotive tipping time (mins)	3
Locomotive loading time (=Box loading time)	8
Total locomotive cycle time	50
No of locomotive loads /hr	1.2
Tonnage moved/hr	29
Potential tonnes per working day	461
Equipment availability	0.75
Utilisation	0.85
Effective total tonnes moved/day	294
Total tonnes per month- LOM	18000
Average number of shifts per month	30
Total tonnes (tpd)	600
Locomotives	3
Swing locomotives	1
Total locomotives required	4

Appendix 7: Capital cost summary for the rail transport system

(Source: Caledonia Mining Corporation, 2020)

Material requirements description	**USD**
Rails 45lb /m	79,798
Wooden sleepers	96,525
Corch screws	2,064
Fish plates	4,350
Rails tools, accessories, fish plate bolts and nuts	4,700
Rails 45lb /turn out switches	32,685
Granby cars	220,000
6 Tonne locomotive complete with charger and 2 battery banks	360,000
Locomotive charging station/ Electricals	2,085
	802,205
Locomotive workshop structural	6,046
Locomotive workshop civils	1,959
Total set up labour	17,618
Grand total	827,828

Appendix 8: Pairwise comparison

(Source: Caledonia Mining Corporation, 2020)

1st row	Unit labour cost	Capital cost	1.33
	Unit labour cost	Maintenance cost	1.57
	Unit labour cost	Dust	0.76
	Unit labour cost	Safety	0.85
	Unit labour cost	Noise	1.29
	Unit labour cost	Availability	1.30
	Unit labour cost	Productivity	1.72
	Unit labour cost	Ease of use	2.34
2nd row	Capital cost	Maintenance cost	1.19
	Capital cost	Dust	0.57
	Capital cost	Safety	0.64
	Capital cost	Noise	0.97
	Capital cost	Availability	0.98
	Capital cost	Productivity	1.29
	Capital cost	Ease of use	1.76
3rd row	Maintenance cost	Dust	0.48
	Maintenance cost	Safety	0.54
	Maintenance cost	Noise	0.82
	Maintenance cost	Availability	0.83
	Maintenance cost	Productivity	1.09
	Maintenance cost	Ease of use	1.49
4th row	Dust	Safety	1.12
	Dust	Noise	1.70
	Dust	Availability	1.72
	Dust	Productivity	2.27
	Dust	Ease of use	3.09
5th row	Safety	Noise	1.52
	Safety	Availability	1.54
	Safety	Productivity	2.03
	Safety	Ease of use	2.76
6th row	Noise	Availability	1.01
	Noise	Productivity	1.33
	Noise	Ease of use	1.82
7th row	Availability	Productivity	1.32
	Availability	Ease of use	1.80
8th row	Productivity	Ease of use	1.36