EVALUATION OF TRANSPORT OPTIONS FROM KMS SHAFT TO THE MILL AT OBUASI MINE, ANGLOGOLD ASHANTI.

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfillment of the requirements of the Master of Science in Engineering (Mining)

Johannesburg, 2010

DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the Master of Science in Engineering (Mining) at the University of Witwatersrand, Johannesburg.

It has not been submitted before for any degree or examination in any other University.

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13th April 2010

ABSTRACT

The underground mine at AngloGold Ashanti Obuasi Mine in Ghana currently transports about 175,000 tpm from four shafts to the mill. Two major shafts, Kwesi Mensah Shaft (KMS) and Kwesi Renner Shaft (KRS) handle about 85-90% of this total tonnage. Transfer of ore from all the shafts to the mill is largely by means of contractor trucks. The mill is approximately 2.8 km and 1.5 km by road from KMS and KRS shafts respectively. Earlier plans to introduce a surface conveyor to the mill were found not to be economically viable largely due to the lower production level prevailing at that time. The objectives at that time were to decrease cost, improve availability and security, and to limit the numerous problems associated with contractor trucking.

The current Business Plan indicates a phased increase in the underground production from 175,000 tpm up to 220,000 tpm. The extra tonnage is to feed the new Tailings Sulphide Plant (TSP), located adjacent to the existing mill. With the plan to increase underground production, and the need to decrease cost and improve efficiency against the current financial downturn, this project serves to review the four ore transfer options that link the shafts to the mill. The options are the continued usage of contractor trucks, purchase mine-owned trucks, use surface or underground conveyors. The factors to be used in the selection process were categorised under economic, environmental and technical parameters. Secondly the options were multiple and consequently the appropriate selection method was the Analytic Hierarchy Process (AHP). This is a Multiple Criteria Decision Making (MCDM) methodology which is a widely used technique. The AHP is a very simple, structured and easily understandable method in which both non-numerical and numerical data are considered in the selection processes with multiple options, where the need for optimization is paramount.

The overall observation by the experts' favoured surface conveyors. However, the issue of capital in the present regime of the Obuasi mine, makes it quite difficult to obtain management approval in the immediate future. The surface conveyor however, has the potential to make adequate returns. From the financial analysis showing a six to ten year payback period in a mining environment, other forms of finance could be considered. Alternatively, the next highest ranking option, which is contractor trucking could be used but with two contractors. This would introduce competition which could improve cost and availability. This is the first time that a more structured approach has been used for equipment selection at Obuasi.

Dedication

To God be the Glory!

Dedicated to the big Owusu-Mensah family (Afua, Nhyira, Adom, Nkunim, Nyamekye and Nnsonyameye) and the entire staff AngloGold Ashanti Obuasi mine.

Acknowledgements

Great thanks to the Management of AngloGold Ashanti and especially Mr Richard Downing, Executive Manager (Mineral Resource Management) and the staff of the Mineral Resource Management (MRM) division of the Obuasi Mines, for helping to make this research report a reality. Many thanks go to Mr Cuthbert Musingwini (Research Supervisor, Witwatersrand University), Professor Dick Minnitt (Witwatersrand University), the families of Dr Winfred Assibey Bonsu, Mr Roger Kumi and my own family for their tremendous assistance and support.

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LIST OF ABBREVIATIONS

tpm	-	tonnes per month
tpa	-	tonnes per annum
mtpa	-	million tonnes per annum
tph	-	tonnes per hour
LOM	-	Life of Mine
AHP	-	Analytic Hierarchy Process
MCDM	-	Multiple Criteria Decision Method
LHD	-	Load-Haul-and-Dump machine

CHAPTER 1

INTRODUCTION

1.1 Statement of the problem

The underground mine at Obuasi currently transports about 175,000 tpm from four shafts to the mill. Two major shafts, Kwesi Mensah Shaft (KMS) and Kwesi Renner Shaft (KRS) handle about 85-90% of this total tonnage. Transfer of ore from all the shafts to the mill is largely by means of contractor trucks. The mill is approximately 2.8 km and 1.5 km by road from KMS and KRS shafts respectively.

Earlier plans to introduce surface conveyors from the two major shafts to the mill were found not to be economically viable largely due to the lower production levels prevailing at that time. The objectives at that time were to decrease cost, improve availability and security, and to limit the numerous problems associated with contract trucking.

The current Life of Mine (LOM) Business Plan indicates a phased increase in the underground production from present levels of 175,000 tpm to about 220,000 tpm. The extra tonnage is to feed the new Tailings Sulphide Plant (TSP) that is under construction close to the Sulphide Treatment Plant (STP). With the plan to increase underground production and the need to optimise cost and efficiency, this project serves to review the four ore transfer options that would link the shafts to the mill which are:

a. Continued use of contractor trucks
b. Mine to purchase own trucks
c. Install surface conveyor
d. Install underground conveyor

The current contract truck haulage system suffers from frequent breakdowns and has low truck availability. However, the company's inability to terminate the contract is based on the fact that there are few truck haulage contractors available with the required fleet size. Engaging new haulage contractors from outside the mining area may come at a higher cost. However, there is the opportunity to split the contract into two and reduce risk of availability and induce competition between two different contractors instead of sticking to one contractor. Besides, there are safety concerns with the big trucks moving through the town roads, and threats from fluctuating energy prices and theft due to illegal miners stealing from the trucks. The need for an alternative ore transfer system is thus paramount.

The current economic down-turn has impacted on all major industrial sectors. The mining industry has suffered similarly, and Obuasi mine's operating costs have consequently been increasing, though with the gold price improving slightly minimizing the impact. Obuasi mine's main competitive advantage for improved operational performance lies in increasing production and reducing cost. To solve this two-pronged issue, an optimal ore transfer with improved availability and efficient cost performance is required.

This evaluation has helped in the selection of the appropriate transfer system for ore delivery to the mill. Secondly, it has put into context all issues associated with environmental, security, cost effectiveness, labour issues, risk and availability factors, which will sustain the high production rate envisaged and the expected cost reduction.

1.2 Objective of research report

The objectives of the ore transfer system evaluation were:

1) To analyze environmental, security, risk and availability issues with the proposed increase in production.
2) To comparatively assess the best ore transfer system for the mine using several criteria for comparison.
3) To identify the most cost effective ore transfer system.

1.3 Methodology and scope of work

The methods used to achieve the objectives include:

- Description of problem and definition of evaluation criteria, such as capacity, capital cost, availability, operational cost, security and safety.

- Data collection on each of the four options for each of the criteria mentioned above. The sources of information include contractors, the mine and technical journals.
- Analysis of each alternative using the Analytical Hierarchy Process (AHP) methodology.
- Selection of the best alternative based on the AHP.

1.4 Reasons for using AHP

The selection of equipment in mining is a multi-tasked purpose involving several decision-making criteria that can be technical, economic and environmental in nature. This type of problem falls under Multiple Criteria Decision Making (MCDM). MCDM refers to making decisions in the presence of multiple, usually conflicting criteria

The broad categories of MCDA methods so far identified include ELECTRE (Elimination and Choice Translating Reality), PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation), MAUT (Multiple-Attribute Utility) and AHP (Analytical Hierarchy Process and Analytic Network Process (ANP) (Almeida, Alencar and Miranda, 2005; Varlan and Le Paillier, 1999). The methods can be classified according to the type of information given and the salient feature of the information whether it is ordinal (involves linguistic scales such as non-numerical scales such as low or high) or cardinal scale information (when involving real numbers). Linguistic scales can be assigned numerical values for example low may be 1-3 and high may be 7-10 on a 1-10 scale). ELECTRE and PROMETHEE methods are applicable to ordinal scale information while MAUT and AHP are applied when the information is cardinal.

The AHP was selected over other MCDA methods in this study for three main reasons. Firstly, the method has significant advantages which are:

- Detection of inconsistent judgements and estimation of degree of inconsistency (Coyle, 2004). The AHP is supported by easy-to-use commercially available software packages such as Expert Choice ® (Geldermann and Rentz, 2005).
- The AHP can rank alternatives in the order of their effectiveness when conflicting objectives or criteria have to be met.

The AHP is thus a very simple, and understandable method when both non-numerical and numerical data are considered in selection processes with multiple options where the need for optimisation is paramount. Equipment selection is one of the prominent problems of mining engineering. Mining Engineers have to make difficult decisions at the equipment selection stage because the decisions in the equipment selection will radically influence the economic life of any mining scenario. So, the decision-maker can evaluate the subjective criteria in the problem of equipment selection. The decision-maker wants to maximise more than one objective criterion at equipment selection stage. Among the number of alternatives, the most suitable equipment must be selected according to objectives and alternatives. MCDM applications can help the decision-maker to reach the optimal solution for the equipment selection. In the mining industry, MCDM methods can be applied for equipment selection because the process includes subjective and objective criteria affecting the selection of equipment among alternatives.

The Analytic Hierarchy Process (AHP) is one of such structured techniques for dealing with such multiple decision processes. Rather than prescribing a "correct" decision, the AHP helps the decision- makers to find the one that best suits their needs and their understanding of the problem.

Based on mathematics and psychology, the AHP was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then. The AHP provides a comprehensive and rational framework for structuring a decision problem, representing and quantifying its elements, relating those elements to overall goals and evaluating alternative solutions. It is used around the world in a wide variety of decision situations, in fields such as government, business, industry, healthcare and education.

1.5 Organisation of the research project

The research project was organised under six main chapters: Chapter 1 contains a statement of the problem, objectives of the research report, methodology and scope and text organisation. Chapter 2 gives the general information about the mine. Chapter 3 is the literature review; Chapter 4 outlines the data collection and the field data analysis; Chapter 5 deals with the usage of AHP analysis process in selecting the best option. Chapter 6 discusses the various outcomes and the report finally ends with Chapter 7 on conclusions and recommendations.

CHAPTER 2

INFORMATION ABOUT ANGLOGOLD ASHANTI OBUASI MINE

2.1 Location of the mine

Obuasi, the capital of the Adansi West Municipality is located on latitude 6.19° N and longitude 1.66° W. It is about 57 km south of Kumasi in the Ashanti Region and about 270 km north-west of Accra the capital city of Ghana. Obuasi can be accessed by rail, road and air by helicopter. The current concession area of the mine is approximately 480 km^2. Figure 2.1 shows the location of Obuasi.

Figure 2.1 Map of Ghana showing the location of Obuasi

2.2 Brief history of the AngloGold Ashanti, Obuasi Mine

Until towards the end of the 19th century when Joseph E. Ellis and Chief Joseph E. Biney who were two Fante merchants from the Cape Coast, and their accountant, Joseph P. Brown crossed the River Pra into the kingdom of Adansi, Ashanti had its gold mined by the local gold seekers or “galamsey” for the local chiefs.

In March 1890, the partners negotiated the mining concession for 25,900 ha (100 square miles) of land in the Obuasi District. Among the foothills of the Moinsi and Kusa ranges, between the rivers Oda and Offin, they laid claim to what was and still is, one of the world’s richest goldfields (Ayensu, 1997). Ashanti Goldfields Corporation Limited was founded in 1897 to develop a mining concession in the area of the operations at Obuasi. In 1969, Ashanti became a wholly-owned subsidiary of Lonrho Plc (later Lonmin Plc; a UK-listed company which at that time had interests in mining, hotels and general trade in Africa). On the 19th of August 1974, Ashanti Goldfields Company Limited (Ashanti) was incorporated.

The government of Ghana acquired 20% of Ashanti from Lonmin in exchange for the extension of Ashanti's mining lease over its concession area. In 1972, the government of Ghana formed a Ghanaian company to take over the assets, business and functions formerly carried out by Ashanti, holding 55% of the outstanding shares.

AngloGold Ashanti was formed on 26th April 2004, following the business combination of AngloGold Limited (AngloGold) with Ashanti.

2.3 Mine ownership

The mine is now owned by AngloGold Ashanti which holds majority shares and the Ghana Government with the minority share. Headquartered in Johannesburg (South Africa), AngloGold Ashanti is an international company with a portfolio of long-life, relatively low-cost assets and differing ore-body types in key gold producing regions. The company's 22 operations are located in 10 countries namely; Argentina, Australia, Brazil, Ghana, Guinea, Mali, Namibia, South Africa, Tanzania and the United States of America. In addition AngloGold Ashanti also undertakes extensive exploration activities. The combined Proven and Probable Ore Reserves of the group amounted to 79 million ounces of gold as at 31st December, 2008 (AngloGold Ashanti Annual Report, 2008).

AngloGold Ashanti is listed with the following listing codes; Johannesburg (ANG), New York (AU), Australia (AGG) and Ghana (AGA and AADS), London Stock Exchange (AGD), Euro next Paris (VA) and Euro next Brussels (ANG) security exchanges.

2.4 Topography

The topography of Obuasi consists of undulating landscape with prominent ridges. The hills rise to a height of about 290 m above sea level, the highest being at the Moinsi and Kusa ranges.

2.5 Climate and vegetation

The concession is in the tropical rain forest region of Ghana that is characterised by long rainy periods from March to August peaking between June and July, averaging 178.5 mm per month. This is followed by brief periods of dryness with occasional rain from September to November. The average yearly rainfall is about 119.2 mm. The region is associated with moderate average temperatures ranging between 25 ºC (minimum) and 34.5 ºC (maximum).

2.6 Geological information on the mine

The AngloGold Ashanti Obuasi Mine is located in the Ashanti belt which stretches from Axim (west coast) to beyond Konongo (Ashanti). It is part of a prominent belt of Precambrian volcano-sedimentary and igneous rocks, which extend for a distance of about 250 km long and are about 40 km wide, in a north east, south-west trend. The belt consists of the Lower Birimian (Northeastern), the Tarkwaian, and the Upper Birimian formations, which occupy the southeastern portion of the mine. A notable feature about this portion of the belt is that the synclinal Tarkwaian rocks unconformably overlie the Birimian which is intruded by granitoids, with superficial deposits covering it (Kesse, 1985.)

There are three major mineralized trends in the concession from which gold is produced. These are the Main Trend, the Gyabunsu Trend and the Binsere Trend. The zone between the Upper and the Lower Birimian, constitute the main trend, which is made up of the Obuasi fissure, the Cote d'Or shear, the Main reef, and other minor shears such as, the Ashanti and the 12/74 fissures. The Obuasi fissure dips at about 65^{o} to a depth of about 165 m towards the west and stretches over 8 km. The Cote d'Or shear dips flatter than the Obuasi fissure averaging 55^{o} and lies to the east of the Obuasi fissure. In the central portion of the mine, the two shears join at about 1300 m below surface, and are predominantly made up of quartz with massive graphitic associations. The combined Obuasi fissure and the Cote d'Or shear constitute the Main Reef fissure (Bell and Little, 1991).

2.7 Ore types

The five main ore types in Obuasi are quartz veins, sulphide ore, transition ore, oxide ore and primary ore (Amanor and Gyapong, 1989). These are briefly described below.

2.7.1 Quartz veins

This is mainly quartz with free gold in lesser amounts of various metal sulphides, such as iron, zinc and copper. They are generally fine grained and occasionally visible to the naked eye.

2.7.2 Sulphide ore

This ore includes gold in the crystal structure of a sulphide material. The gold is extremely fine grained and locked up in arsenopyrite crystals. Smaller arsenopyrite crystals come with higher grades. The sulphide ore is generally refractory.

2.7.3 Transition ore

These are partially oxidised sulphide ores, hard to process due to their structure, and thus generally associated with lower recoveries than sulphide and oxide ores.

2.7.4 Oxide ore

When chemical decomposition occurs, sulphide ore degenerates into oxidised material. In Obuasi, weathering activities can degrade surface and near-surface sulphides, to a depth of 30 m to 40 m, depending on the topography and other factors.

2.7.5 Primary ore

This is non-weathered component of non-refractory granitoid mineralization. It is not oxidised.

2.8 Mine operation

The Obuasi mine is currently dominated by underground mining with many production divisions (Figure 2.2). Mining dates back more than 100 years and still has potential to go beyond another 25 years according to the current LOM business plan. Various mining methods are being used underground but the most productive is the open stoping method. Production is currently steady at about 175,000 tpm and plans are in place to step it up above 200,000 tpm. Further details of the mining operations are found in section 4.2.

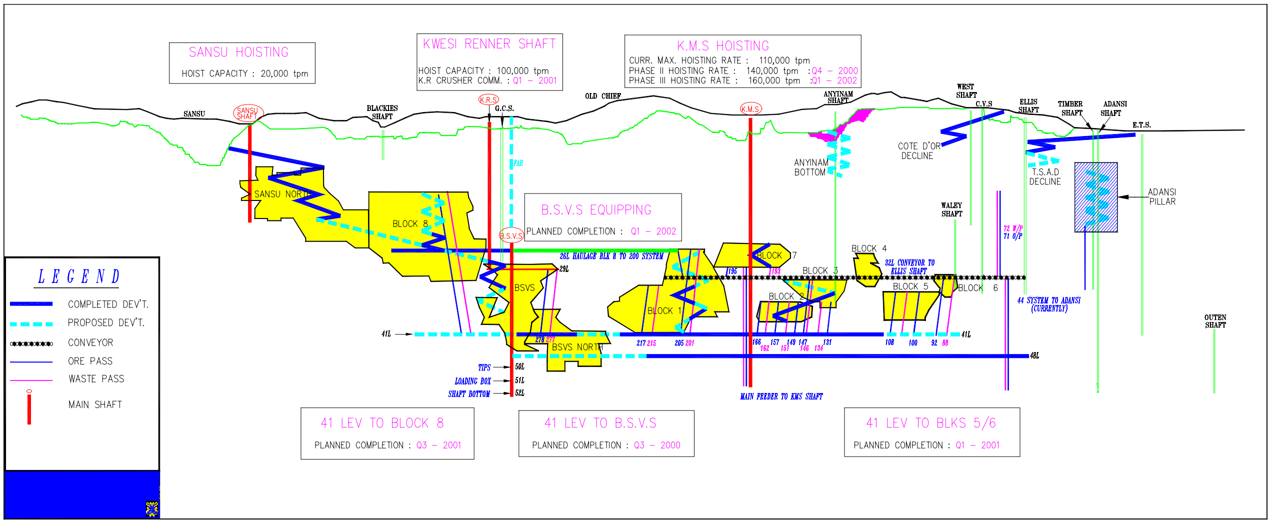

Figure 2.2 Vertical projection of Obuasi Mine showing major mining blocks, open pits, shaft systems and infrastructure

2.9 Underground Material Transport.

Transport of material mined in Obuasi is by horizontal (hauling) and vertical (hoisting) transport. Horizontal haulage of ore underground at Obuasi Mine is by LHDs and dump trucks, rail transport (Locomotives) and belt conveyors. The mine is about 8 km along strike and 1.5 km (50 Level) deep. However major production and development activities are within the 20 Level to 38 Level with 30m intervals between levels. The major tramming levels are 20 Level, 26 Level, 41 Level and 50 Level (Figure 2.2). The most important major haulage level currently is 41 Level. It handles about 60-70% of total mine ore and waste. It has a 3 ft (1m) guage rail line and uses 20-tonne bottom dump trucks.

Vertical handling of ore from underground is through raises and shafts. The mine has six shafts along the 8 km stretch for both material and men handling. Two of the shafts (Ellis and Adansi) at the extreme north of the mine have low production and are being decommissioned. GCS shaft is also for men transportation only. This leaves only the 3 major shafts for ore and waste handling to surface. Of the 3 shafts, Sansu which is located at the extreme south of the mine is limited to 16 Level (about 450m depth) and has a maximum capacity of 22, 000 tonnes per month (264,000 tpa), KRS (together with Brown Sub-vertical shaft, BSVS) and KMS are the only shafts that hoist from 50 Level. They are located at the centroid of current production set-up, and are rated at 78,000 tpm

(936,000 tpa) and 135,000 tpm (1,620,000 tpa) hoist capacities respectively. The two shafts, hoist about 85-90% of total mine material.

Further expansions have been planned for the two shafts to hoist up to 100% of underground production and also to meet the projected production increase from the current 175,000 tpm to about 220,000 tpm. Hence the urgent need to review and optimise the surface ore handling system from the two shafts to the ROM pad. KMS shaft hoists most of its ore and waste from 41 Level and has a crusher on 43 Level. KRS and BSVS shafts are connected on 26 and 27 Levels.

2.10 Surface Material Transport

Ore from KMS and KRS mine is presently conveyed to the Sulfide Treatment Plant (STP) by means of trucks. The trucking system is under a haulage contract. The KMS-STP contract is being handled by A.J FANJ Ltd, whilst KRS-STP haulage is being undertaken by RAK CAMWAY Ltd. Contract haulage forms about 30% of mining cost. The companies use trucks with sizes ranging from 30 to 45 tonnes. Fleet sizes and varying truck availability are some of the issues that impact on ore production.

The haulage distance from KMS to STP, which passes through the community road network, is about 2.8 km. That of KRS is about 1.5 km. However straight distance which would be the choice for the underground or surface conveyors from the two shafts are about 2.04 km and 1.24 km respectively. Figure 2.3 shows the distances from KMS and KRS to STP. Haulage of ore is one of the cost components of mine operations and this project seeks to compare the current contract trucking system from the two major shafts to the mill with other alternatives namely company buying own trucks, installing surface or underground conveyors. The objective is to assess which option would enable the mine to achieve the most cost-effective ore handling system with the projected production increase.

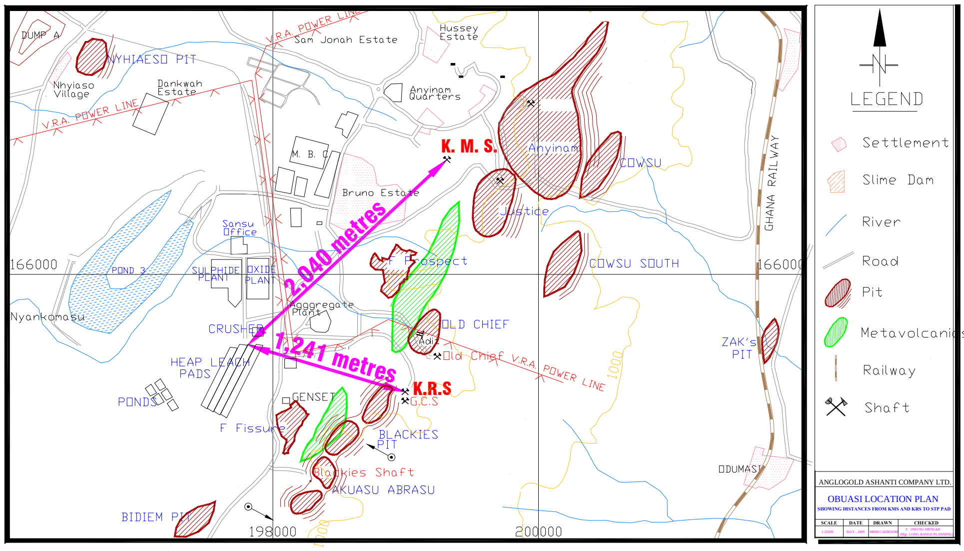

Figure 2.3 Obuasi location showing distances from KMS and KRS to STP pad

2.11 Treatment Process - Sulphide Treatment Plant

Currently, Obuasi mine operates two mills, the Sulfide Treatment Plant (STP) and the Tailing Treatment Plant (TTP). A third mill, Tailing Sulphide Plant (TSP) is about to be commissioned in 2010. The TSP is expected to treat both underground ore and reclaimed tailings from the tailings dams. It has a capacity of about 180,000 tonnes per month and is expected to have improved recovery of about 40% instead of the existing 25% by the TTP. The TSP is to replace the existing TTP facility.

The STP processes sulphide refractory ore and consists of crushing, milling, flotation and stirred tank bio-oxidation of the flotation concentrate. Flotation tailings and bio-oxidised concentrate are leached in CIL facilities. The stirred tank bio-oxidation facility is the largest of its kind in the world and has been operating successfully since startup in 1994. Its capacity is close to 200,000 tonnes per month and together with the TSP would handle the planned increase in underground tonnage. The sulphides consist of arsenopyrite, pyrite and some pyrrhotite. The Tailing Treatment Plant also has 200,000 tonnes per month capacity. It processes material that is hydraulically reclaimed from old dams and consists of CIL facilities.

The planned increase in production augments the need for an efficient ore handling system. Various forms are being considered in the research report and the literature review in the next chapter addresses the concerns on the various optimisation methodologies and handling options.

CHAPTER 3

LITERATURE REVIEW

3.1 Literature Review

Cost continues to be a challenge to many investment decisions. On the order hand, it has helped to fuel many innovative schemes which have enabled many companies to survive the current financial downturn. The current global downturn has resulted in rising cost and low demand for commodities. Many, especially in the mining sector, have faced severe consequences. To survive, many of such companies and corporations have initiated many schemes and optimisation methodologies to surmount the impact of the downturn. The objective and choice of some of these methodologies for the optimisation process are being reviewed as part of this research report. Alternative surface ore transfer options are also reviewed, leading to the focus on trucking and conveyor systems.

Survival may be the driving force for most mine optimisation strategies, but another aspect of these innovations is to keep companies' financial books healthy, ensure growth and generate adequate returns for the shareholders. Additionally, a major benefit of such growth strategies is for long term viability through continuous focus on optimisation in good times as well as in bad times. As quoted in Wallace (2009, p10), Tim Horsley said *"A thorough study can provide compelling ways of streamlining a mine's current operations and would provide a life-of-mine optimisation model which can be periodically updated, and optimisations re-run with minimal effort. Keeping such a model current provides a valuable tool for scenario analysis planning and allows a mine operator to react very quickly to changing circumstances"*. This is the real worth of mine optimisation.

Mine optimisation may be defined as putting together a portfolio of assets in such a way that "return is maximised for a given risk level, or risk is minimised for a given expected return level or to modify to achieve maximum efficiency in time or cost" (Investorwords, 2009). This description fits in well with the objective of this research report, to optimise the current ore transport system between the KMS (and KRS) shafts and the processing plant (STP).

Optimisation of mine transport is essential because the transport of ore or waste forms a crucial part of a mining operation. Besides exploration and other indirect activities, the three salient mining activities are drilling and blasting, ore/waste handling or transport and processing. Material handling serves as a linkage to the two other major processes and also forms part of the main mining activities. In essence, optimisation of this process is a step towards major mine improvement strategy and operational efficiency. As quoted in Wallace (2009, p10), Tim Horsley said "*mine optimisation doesn't need to take a lot of time or be an expensive exercise, but it has very real potential to add significant value, sometimes in the order of hundreds of millions of dollars over the life of an operation*"

Underground ore is transported by means of vertical and/or horizontal transport systems. Once on surface, conveyor or truck arrangements are usually the systems used to transport the ore to the treatment plants. Other innovative systems include transfer through pipes where the material is already in slurry form. The transportation of ore from the loading point to the disposal point has always been a critical activity and one of the most vital cost components of mining operations. Indeed, mine haulage has been observed to be as high as 30% of the entire mine's cost (Narayana, 2009). Over the years, significant technological and systematic improvements have been undertaken to optimise mining haulage by balancing costs and performance. Truck haulage and conveyors are systems that have successfully stood the test of time. Other forms of ore/waste mine transport systems include rail transport, pipe lines for slurry type materials and in lesser cases, mono rail transport. The decision to use either trucks or conveyor systems is not at all easy. The advantage of the truck system is its flexibility and mobility such as when mines develop into new, more distant parts of a deposit, which would be prohibitively expensive to move a fixed conveyor system. However in this research the loading and dumping points are fixed.

Conveyors require electricity to run, but are however more efficient in terms of energy consumption and less vulnerable to cost fluctuations. While these large conveyor operations may compete with trucks in certain conditions, most surface mines are still served by excavators with truck haulage. In another research by Frizzell (1980) a high angle conveying system was incorporated into three hypothetical mining operations. The associated haulage and crushing costs for each system were compared with similar costs for a conventional truck haulage system. The results showed 10% to

15% return on investment after taxes. The savings are due in part to the reduction in the number of trucks, resulting in lower total fuel consumption and truck operating costs, thus making the mine less sensitive to fuel cost fluctuations and availability (Frizzell, 1980). High angle conveyor systems in open pit mining and conveyors in general offer many advantages over the traditional truck-only-haulage systems, including (Santos, 2002):

(1) Superior energy efficiency
(2) Less dependency on petroleum products
(3) Less sensitivity to inflation
(4) Less labour
(5) Less excavation for the amount of ore recovered
(6) Less ramp construction and maintenance costs.

On the other hand, off-road trucks are the most flexible means of transport in surface mining, but very poor in energy efficiency. In summary, conveyors are much more economical, but less flexible and limited with respect to the transportable lump size (Benecke,2008).

Technological improvements in trucking have taken place in terms of size, operational capability and efficiency. Truck sizes have been on the increase over the past 40 years, with 50-tonne, 70-tonne and +100-tonne trucks currently in use in some major mines with better operational efficiency in the areas of cost and productivity. At Obuasi mine these changes and technological improvements are far from reality as major manufacturers' facilities are distant from site. This makes spares supply availability and taking advantage of model changes a challenge. Thus Obuasi mine has to contend with the local contract haulage trucks available which are smaller in size and a challenge both environmentally and operationally.

Conveyor development has advanced over the years with the introduction of high angle conveyor systems to suit the various surface mining operations. Goodyear Engineering Products has developed Easyrider conveyor belt cover that can reduce belt operating costs by up to 12%. It has used innovative low-rolling resistant rubber cover compound that enables the conveyor to minimise energy consumption. Easyrider recovers its shape more quickly than conventional rubber compounds. The belts can move more efficiently over idlers, reducing the amount of energy required to run the system. It manages pulley indentation, which can consume 60% of the power on a long horizontal conveyor system. The conveyor uses the low-rolling resistant technology, which was developed for truck tyres designed to improve fuel economy. It operates more efficiently and creates less heat thus extending belt life. The technology can also produce savings for the long operations (Colish, 2006).

According to Ganguli (1979), a sizable portion of the overall mining costs comes from ore handling. Material handling equipment selection is an important function in the design of a material handling system, and thus a crucial step for facilities planning. Using proper material handling equipment can enhance the production process, provide effective utilisation of manpower, increase production, and improve system flexibility. The importance of material handling equipment selection cannot therefore be overlooked. However, with the wide range of material handling equipment available today, determination of the best equipment alternative for a given production scenario is not an easy task. Material handling accounts for 30-75% of the total cost of a product, and efficient material handling can be responsible for reducing the manufacturing system operations cost by 15-30% (Sule, 1994). These values underscore the importance of material handling costs as an element in improving the cost structure of a product. The determination of a material handling system involves both the selection of suitable material handling equipment, and the assignment of material handling operations to each individual piece of equipment. Hence, material handling system selection can be defined as the selection of material handling equipment to perform material handling operations within a given working area considering all aspects of the products to be handled (Sujono and Lashkari, 2005).

One of the parameters that provide minimum cost for the targeted production in a mine is the suitability of the equipment selected. Moreover, equipment selection directly affects pit design and production planning. In open pit mining and surface ore/waste transfer, equipment selection is made according to many factors related to the ore and mining conditions. These factors can be qualitative and quantitative in nature. The main purpose of equipment selection is to choose the optimum and cost-effective equipment by installing a decision-support system, which can analyse various and complex factors. The term optimum here implies that the equipment selected must comply with the mining conditions or constraints and meet the basic requirements and preferences of the mine

(Bascetin, 2003; Samata, Sarkar, and Mukherjee, 2002). Various types of equipment selection models are available for optimisation purposes. These models are life cycle cost analysis (Sharmma, 1999), net present value analysis (Sevim and Sharma, 1991), linear breakeven model (Cebesoy, 1997), linear programming (Petty, 2001) and decision making tools such as reliability analysis, knowledge based expert systems and analytic hierarchy processes (Denby, 1990; Tam, 2001).

The most important factors for the selection of surface mining equipment may broadly be classified into three major categories namely *technical*, *economic* and *environmental*. These categories were used in the research report. The technical issues were identified as site or deposit parameters, organisational culture, adaptability to change, production performance, operator capability, machinery life, performance monitoring facilities, administration, manufacturer's reputation, delivery lead time and warranty, reliability of machinery, employee participation in the decision-making process (maintenance and operation), drive system (hydraulic/ electric/mechanical), maintainability, power source required (diesel/electric), available training facilities, auxiliary machines required, general supervision required, logistics support or management, degree of automation, operating condition, level of safety, and ease of configuration. The environmental factors considered include aesthetics, emissions, and noise levels. The economic indicators which were all financial in nature include capital, operating cost, labour, operating unit cost, and fuel cost (Samata, Sarkar, and Mukherjee, 2002). All the individual factors in all three categories add up to 31. However, most of these were aggregated into 15 sub-criteria which is also the maximum number required by the Canadian Conservation Institute (CCI) AHP model (Canadian Conservation Institute, 2005). The basic principle in equipment selection is to define the degree of priority or governing factors among the ones given above and then determine the matching equipment and the alternatives to these parameters comparatively.

In most instances, however, it is difficult to determine the equipment meeting all the requirements stated (Aykul, 2009). In such cases a Multi-criteria Decision Making (MCDM) methodology, such as AHP becomes handy for the optimisation of the selection process. The selection of equipment in mining is a multi-tasked purpose involving several decision-making criteria in areas that are technical, economic and environmental in nature. MCDM refers to making decisions in the presence of multiple, usually conflicting criteria (Chen, 2006). The broad categories of MCDM methods so far identified for equipment selection and the reasons for choosing AHP are as stated in Section 1.4.

Equipment selection is one of the prominent problems of mining engineering. Mining engineers have to make difficult decisions at the selection stage because the decisions in the equipment selection will radically influence the economic life of any mining operation. Musingwini and Minnitt (2008) proposed the preferential use of AHP for mining engineering problems which are multi criteria in nature as the most cost-effective solution.

Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analysed independently. The elements of the hierarchy can relate to any aspect of the decision problem, tangible or intangible, carefully measured or roughly estimated, well- or poorly-understood, or anything at all that applies to the decision at hand.

Once the hierarchy is built, the evaluators systematically evaluate its various elements by comparing them to one another two at a time. In making the comparisons, the evaluators can use concrete data about the elements, or they can use their judgments about the elements' relative meaning and importance. It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations (Saaty, 2008).

The AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared to one another in a rational and consistent way. This capability distinguishes the AHP from other decision making techniques. In the final step of the process, numerical priorities are calculated for each of the decision alternatives. These numbers represent the alternatives' relative ability to achieve the decision goal, so they allow a straightforward consideration of the various courses of action. The highest ranking alternative based on the weighting is then selected.

3.2 The Analytic Hierarchy Process

The AHP used is based on 4 main axioms which are (Wikipedia:Analytic Hierarchy Process, 2006):

.Defining a goal and setting up a hierarchy of the alternatives and criteria/sub-criteria.

.Pair-wise comparison of these alternatives under any criterion on a reciprocal ratio scale.

.Assessing consistency of pair-wise comparisons.

.Computing the relative weights of each alternative.

The AHP enables a person to make pair-wise comparisons of importance between decision criteria with respect to a scale, and the consistency of those comparisons. For example in a pair-wise comparison if one says "I like apples more than oranges", "I like oranges more than bananas", then, "I like bananas more than apples", would make the pair-wise judgments inconsistent but, “I like apples more than bananas” would make the pair-wise judgments consistent.

In the AHP, before computing the weights based on pair-wise judgments, the degree of inconsistency is measured by the Consistency Ratio. According to (Saaty, 1980), the acceptable maximum threshold ratio is 0.1. The AHP uses various mathematical techniques such as eigen value, mean transformation, or row Geometric mean for its computation. The technique employed in this research report is the eigen value for computing the weights under the AHP in this research report.

Since the comparisons are carried out through personal or subjective judgments, some degree of inconsistency is expected. To guarantee that the judgments are consistent, the final AHP operation called consistency verification, which is regarded as one of the advantages of AHP is incorporated. The intent is to measure the degree of consistency among the pair-wise comparison by computing the Consistency Ratio (CR). If it is found that the CR exceeds the threshold limit, which is 10%, the decision makers should review and revise the pair-wise comparison. Once the pair-wise comparisons are carried out in every level, and prove to be consistent, the judgment can then be synthesized to find the priority ranking of each alternative and its attributes.

3.3 Application of Analytic Hierarchy Process

Equipment used in ore transfer or transportation systems is a resource input into the ore production process. Selection of an ore transfer system is therefore a resource allocation decision. AHP has been instrumental in numerous resource allocation decisions – some involving billions of dollars. The following list demonstrates the versatility of the AHP process in decision making in various areas of decision-making:

i) British Columbia Ferry Corporation in Canada (B.C. Ferries), uses AHP in the selection of products, suppliers and consultants. B.C. Ferries is a provincial crown corporation that provides passenger and vehicle ferry service to 42 ports of call throughout coastal British Columbia. Its 40 vessels operate all year round and carry more than 22 million passengers and 8 million vehicles annually. Carol Wyatt, Manager of Purchasing, Planning and Technical Services uses AHP for many different applications including determining the 10 best sources of fuel which is the single largest expense for B.C. Ferries; contracting professional services such as legal, banking, insurance brokers, and ship designers; evaluating major computer systems; selecting service providers such as grocery suppliers, and vending and video game companies; hiring consultants; and evaluating various product offerings (Forman and Gass, 2002).

ii) National Aeronautic and Space Administration (NASA)/ Department of Energy (DOE) decision conference to recommend a power source for the first lunar outpost used AHP to consider criteria such as safety, performance, reliability, and flexibility in evaluating alternatives ranging from photo-voltaic cell farms to nuclear reactors (Forman and Gass, 2002).

iii) Car designers on the General Motors' Advanced Engineering Staff use AHP to evaluate design alternatives, perform risk management, and arrive at the best and most cost-effective automobile designs (Forman and Gass,2002).

iv) Dessureault and Scoble (2000) used AHP in a mine to decide whether to purchase new drill-monitoring technology, maintain status quo, or retrain drillers and surveyors to work more productively and safely. The three alternatives were compared on the basis of six criteria.

v) Karadogan, Kahriman and Ozer (2008) used AHP based fuzzy multiple attribute decision-making methodology to select the most suitable underground method for the Ciftalan Lignite Mine in Turkey. Five possible mining methods were compared on the basis of 18 criteria.

vi) Ataei (2005) used AHP to select the best location of an alumina-cement plant in Iran. Five possible locations were compared on the basis of five criteria.

vii) Kazakidis, Mayer and Scoble (2004) used AHP based Expert Choice ® software to model mining scenarios for selecting the best rockbolt support system from 14 possible rockbolt support systems on the basis of ten criteria. They also used it to improve tunneling advance rates based on seven criteria.

Other AHP applications include the following (Musingwini and Minnitt, 2008):

- the performance evaluation of line managers for promotion.
- performance evaluation of operating shafts,
- ranking of projects competing for funding,
- measuring company performance on Mining Score Card in meeting the requirements of the Mining Charter in South Africa.
- comparison of different ore haulage systems,
- evaluation of different support systems for production stopes.

In conclusion, the literature review has established the importance of material handling in many industries as well as its significant role in the mining sector and the challenge it presents to management. As a major cost factor, the review has shown that the optimisation of the ore handling systems has enormous benefits. The methodology is also important as the critical factors to be considered may involve technical, economic and environmental issues. Approaches that include more than one measure of performance in the evaluation process are termed multi-attribute or multi-criteria decision methods. Examples of such methods include AHP, ELECTRE, MAUT and PROMETHEE. The AHP was chosen to analyse the transport system from the KMS Shaft to the processing plant for reasons stated in Section 1.4 and is expected to provide an optimal ore transfer system for the Obuasi mine. The mine has been in operation for more than 100 years and definitely has used one form of ore transfer or the other. To attempt to use AHP to evaluate the ore transfer system would primarily require a detailed description of the Obuasi operation. This is done in the subsequent chapter.

CHAPTER 4

MINE OPERATION AND ORE PRODUCTION TRANSFER OPTIONS

4.1 General Mine Operations

Obuasi Mine has been operating a dual ore transfer system using conveyors and trucks. This dual conveyor/truck transport system is the most prevalent ore transfer system in most mining establishments. The choice between the two has largely been dependent on economic, technical and environmental factors.

Obuasi mine used to transfer ore to the decommissioned Pompora Treatment Plant (PTP) by a 1 km long conveyor stretching from Ellis Shaft in the extreme north of the mine to PTP which was also located in the north section of the mine. Trucking at that time was on a minor scale. Trucking actually increased on the mine at the start of the open pit operation and the transfer of ore to the STP. The STP is located at the south section of the mine close to the open pit operation. During that time Obuasi mine operated a fleet of 12 trucks and 6 loaders (Figure 4.1).

Figure 4.1 Assembly of some of Obuasi open pit machinery in 1999

(Photo Courtesy Mining Technology 1999)

After about 10 years of operation of the open pit, reserves at near surface were exhausted and operations gradually decreased. A number of the open pit trucks were then used in tandem with other mine-owned trucks which were purposely dedicated to the underground operations to transfer ore from the shaft to the plants. With the closure of the PTP as part of a strategic decision process for the mine, all the mined ore would be transferred to the STP. The few mine-owned trucks and some of the remaining open pit trucks were used. The mine-owned trucks consisted of Astra trucks of 30 tonne capacity. These hauled underground ore from the 4 shafts to the STP plant. Tonnage levels were about 1,500,000 tonnes per annum. The fleet size was about 20 trucks. The longest distance at that time was from the Ellis shaft to the STP plant which is about 9 km and the haulage route passed through the township. The shortest routes were between KRS and KMS shafts which were also the shafts hoisting the bulk of the underground ore. The mine-owned trucks were also used for waste disposal and many other haulage activities.

After the year 2000 the mine faced a series of financial difficulties in raising much needed capital for its growth strategy. The open pits were near exhaustion at Obuasi and underground production had to be increased to make up for the ounces shortfall. The only option available at that time at the Obuasi mine to meet the increasing underground production was to employ contract haulage trucking system. The contract haulage trucking system is still employed to move ore from the KMS shaft to the processing plant (STP).

4.2 Underground Mine Operations

The Obuasi mine ore production is predominantly from underground mining. Surface mining operations are on old stockpiles or tailing dams. Actual surface mining is on a very small scale. The underground mining operation is divided into two sections namely, North and South mines. Each is managed by a Mine Manager, reporting to the General Manager Mining. Mining operations began around 1897 around the Northern part of the mine (the oldest and deepest) and expanded from a production rate of about 4,500 tonnes per year in 1907, to approximately 880, 000 tonnes per year in the early 1980’s. The tonnage from the underground operations increased from 1.14 million tonnes per annum in 1994 to 2.5 million tonnes per annum in 2001 but fell to 2.2 million tonnes in 2005. Average grades also dropped from above 10.5 g/t to 7.90 g/t over the period between 1995 and 2005. Production has since been steady at this level. Future production targets are however expected to increase to about 2.5 million tonnes per annum in 2015 and remain stable afterwards (Figure 4.2).

Production within this period would largely be sourced from the deeper portion of the mine (Deeps Project – Level 2), which is beyond current infrastructure.

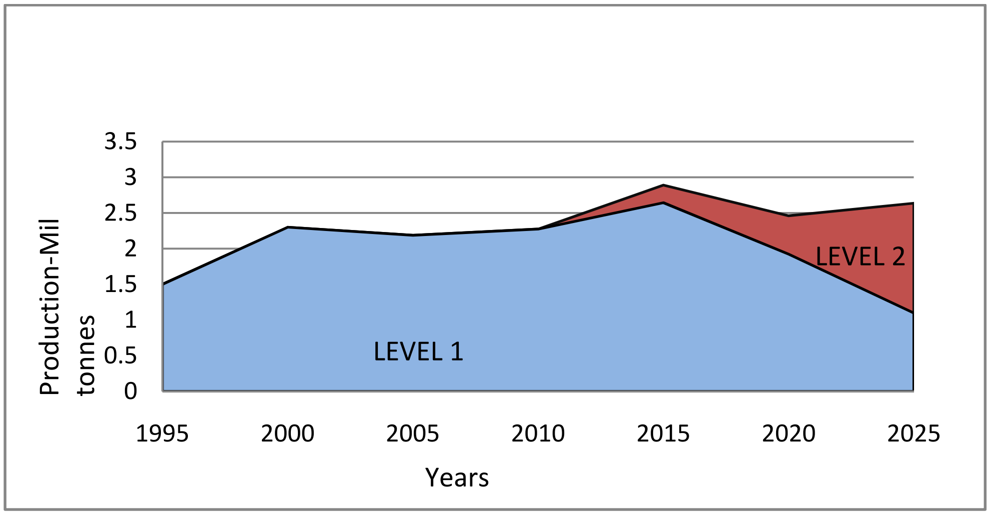

Figure 4.2 Obuasi Mine-U/G Production (tpa)

Currently the range of mining methods employed across the mine includes mechanised open stoping (accounting for 60% of total mine ore production), sub-level retreat and reclamation (accounting for 20% of total mine ore production), mechanised cut and fill (accounting for 5% of total mine ore production), and stope preparation (accounting for 15% of total mine ore production).

4.3 Underground Material Transport.

Transport of material mined in Obuasi is by both horizontal transport (hauling) and vertical transport (hoisting). These are discussed below.

4.3.1 Horizontal

Horizontal haulage of ore underground at the mine is by LHDs and dump trucks (Figure 4.3), rail transport (locomotives) and belt conveyors. The main tramming levels are the 20 Level, 26 Level, 41 Level and 50 Level. The most important major haulage level currently is the 41 Level. It handles about 60-70% of total mine ore and waste. It has a 3 ft (1m) gauge rail line and uses 20 tonne bottom dump trucks (Figure 4.4).

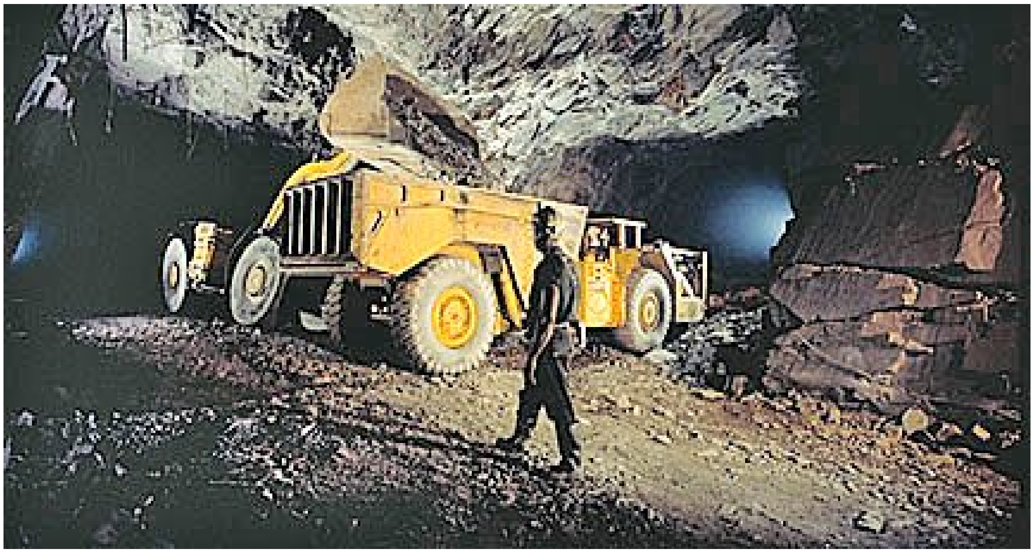

Figure 4.3 A Scoop loading into a dump truck underground

Figure 4.4   20-tonne bottom dump loco truck on 41 Level

4.3.2 Vertical

Vertical handling of ore from underground is through raises and shafts. The mine has six active shafts. Two of the shafts (Ellis and Adansi) on the extreme north of the mine have low production and are being decommissioned. Production from this area will be transferred to the KMS shaft (Figure 4.5). Another shaft, GCS, is also for men riding only. The remaining 3 shafts are used for ore and waste handling to surface. Of the 3 shafts, Sansu which is located at the extreme south of the mine is limited in depth to 16 Level (about 450m depth) and has a maximum capacity of 22, 000 tonnes per month (264,000 tpa). KRS (together with BSVS –internal shaft) and KMS shafts are the only shafts that can hoist from 50 Level. They are located approximately at the centroid of current production set-up, and are rated 78,000 tpm (936,000 tpa) and 135,000 tpm (1,620,000 tpa) respectively. The two shafts together hoist about 85-90% of total mine material.

Figure 4.5 A view of Kwesi Mensah Shaft (KMS) from the west.

Further shaft upgrades have been planned for the two shafts to hoist up to 100% of underground production and also to meet the projected production increase from the current 175,000 tpm to about 220,000 tpm. There is therefore the urgent need to review and optimise the surface ore handling system from the two shafts to the STP mill pad. KMS shaft hoists most of its ore and waste from 44 Level with a crusher on 43 Level. The main haulage is on 41 Level. KRS and BSVS shafts are connected on 26-27 Levels.

Table 4.1 KMS skip configuration data

KMS Data	
Storage Bin capacity	1000 tonnes
Skip Bucket Factor	12.02 tonnes
Skip Cycle Time	3 mins from 44 Level to Surface
No. of Skips /Hour	20 Skips
Current Opearting Max capacity	125,000/month
Desired Capacity of Conveyor system	150,000/month

4.3.3 Ore characteristics

Tests conducted on the ore samples revealed that the material is very abrasive with a maximum abrasive index of 150 on the ASTM scale. The ore has an angle of repose of 38° and angle of surcharge of 23°. The maximum lump size of the material is about 350 mm with a weight of 122 kg. The bulk density of the material is 2.75 g/cm^3 (2750 kg/m^3) and average moisture content of 5%.

4.4 Surface Material Transport - Trucks

Ore from KMS and KRS shafts is presently conveyed to the STP mill by means of trucks. The trucking system is under a haulage contract. The KMS-STP contract is being handled by A. J. FANJ Ltd, whilst the KRS-STP haulage is contracted to RAK CAMWAY Ltd. Contract haulage takes about 30% of mining cost. The companies use trucks with sizes ranging from 25 to 40 tonnes (Table 4.2). Effective payloads are about 10% lower than the rated nominal capacities. Truck models include Benz, Astra and Iveco. Some use Deutz engines. They are all rear dump trucks (Figure 4.6). The cycle time between KMS shaft and the pad is about 40 minutes over a distance of 2.8 km. Fleet sizes and varying truck availability are some of the issues that impact on production. About 6-8 trucks are ideally required. Though the contract trucking systems is beset with numerous problems namely pollution from noise, dust and smoke, frequent breakdowns, and escalating cost, safety concerns on the roads, fuel shortages, however the vital considerations are its convenience, flexibility, and protection of the mine from equipment obsolescence. An additional advantage is the low initial capital required.

Table 4.2 FANJ Trucks Data

TRUCK NUMBERS	CONTRACT NO.	GROSS WEIGHT	TARE WEIGHT	NET WEIGHT
C2173		**TONNES**	**TONNES**	**TONNES**
AS 9688Z	**48.43**		**15.80**	**32.63**
AS 9094Z	**45.73**		**16.55**	**29.18**
AS 9692Z	**48.31**		**15.55**	**32.76**
AS 9095Z	**58.47**		**16.95**	**41.52**
AS 9693Z	**48.03**		**15.80**	**32.23**
AS 4234W	**39.76**		**13.05**	**26.71**
AS 7552Z	**55.60**		**15.95**	**39.65**

Figure 4.6 Contract truck at the KMS loading bin

The haulage distance from the KMS shaft to STP mill, is about 2.8 km and the haulage route passes through the company and community road network. That of KRS is about 1.5 km. However straight distances from the two shafts to the mill which would be used in designing an underground conveyor are about 2.04 km and 1.24 km respectively. Figure 2.3 shows the distances from KMS and KRS shafts to the STP mill. Haulage of ore is one of the cost components of mine operations and this project seeks to compare the current contract trucking system from the two major shafts to the mill with other alternatives namely company buying own trucks, installing surface or underground conveyors. The objective is to assess which option would enable the mine to achieve the most cost effective ore handling system with the projected increase in production.

4.5 Surface Material Transport - Conveyors

The mine has used and continues to use conveyors in some aspects of the ore/waste transfer system. They have been used both on surface and underground. A belt conveyor system (Figure 4.7) is used for transporting materials from a start point to an end point by driving an endless belt that is tensioned over a set of idlers. The idlers are sufficiently spaced to give adequate support to the belt. A successful design of a conveyor belt must begin with an accurate consideration of the characteristics of the materials to be conveyed.

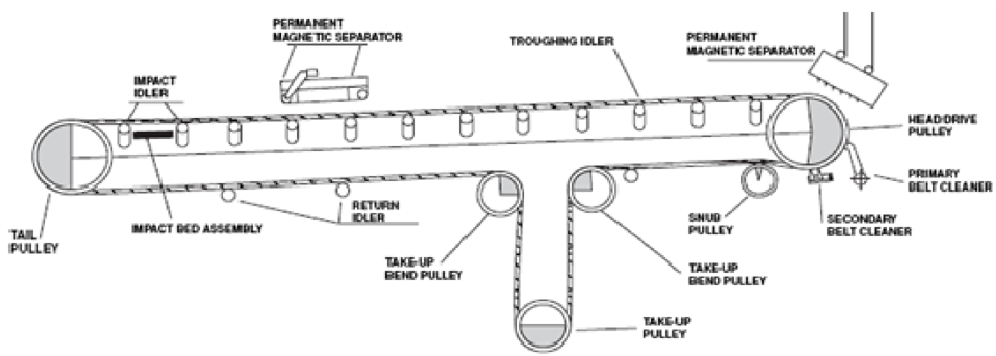

Figure 4.7 Components of a belt conveyor (Anon, 1979)

Some of the important characteristics affecting a conveyor system include angle of repose, angle of surcharge, material density, the physical and chemical nature of the ore material. Conveyors offer continuous transfer of the material subsequently giving comparatively higher availability and utilization.

The mine has previously installed an underground conveyor on 32 Level. This used to run from the center of the mine to the extreme north for a distance of 3km to the Ellis shaft. This was also supported by another conveyor on surface running from the Ellis Shaft to the North processing plant. In view of the fact that reserves in the north section of the mine have been depleted most of these structures have been decommissioned. The north Processing Plant (PTP) has now been replaced by the Bio-oxidation plant which is at the South section end of the mine. Currently conveyors continue to be used on a very small scale in the transfer of ore/waste to the shafts and to the surface bins.

4.5.1 Conveyor Options

The KMS shaft to STP is the route transferring about 65-70% of total underground ore and is the one being used for this research report. The outcome could however be applied to both shafts. The options available include surface conveyors or underground conveyors. The surface conveyors could also be overhead, or ground conveyors. The general models referenced includes conventional and cable belt types. The proposed conveyor for the options under consideration will be a 1,200mm wide belt conveyor with a designed output of 650 tph. The conveyor will start from the KMS load-out bins and follow the haul road to the STP ROM pad area.

4.5.1.1 Option -1 Underground Conveyors

The reason for the consideration of underground conveyors is the security threats to surface conveyors, disruption to surface routes, and aesthetics issues. Additionally the underground conveyors are expected to be the shortest in terms of distance to the plant and largely have no topographical challenges.

This is expected to impact on the capital required as a development drive would have to be developed to link the two points. The major challenges are the means to transfer the ore back to underground conveyor once hoisted. This could be by surface to underground raises and also at the plant a ramp to the stock pile as the outlet. It is however expected that the restricted area would impact on accessibility and ease of maintenance.

4.5.1.2 Option 2 Surface Conveyors

In most surface operations conveyors are often used for ore transportation. In situations of high demands on productivity, lower operating cost, long distance, high topographical challenges, high environmental concerns and availability of initial capital then conveyors are the best choice. However if loading points and dumping points often change then they become a major constraint. The loading and dumping points between the KMS shaft and the STP mill are fixed. The distance is 2.4 km. This is longer than that for the underground conveyor option but shorter than the trucking routes. The conveyors could either be overhead or on the ground.

4.5.1.3 Option 2a - Ground Level Conveyor

Option 2a considers a ground-level conveyor system with a total length of 1.7 km supported on concrete footings. The conveyor will be covered, with walkways and wire mesh fence on either side. Long patrol and service roads that are 3m wide by 1.7km long would be provided on one side of the conveyor. The conveyor and the service roads would be fenced along the entire length with 2.7m high chain-link topped with razor wire.

4.5.1.4 Option 2b - Overhead Conveyor

The overhead conveyors (Figure 4.8), with a total length of 1.7 km , will be fully enclosed, with walkways on either side and supported on trestles to give a clearance varying from 3m - 12m. A total of seven sections with varied lengths quoted by Continental Conveyor Ltd were used to develop the cost estimates for the optimal route.

Figure 4.8 Overhead conveyor model at Obuasi mine (Old AngloGold Ashanti Structure)

With the increased tonnage at KMS shaft, it is envisaged that the following problems associated with truck haulage are going to be more pronounced. These are namely:

- Frequent breakdowns and disruption to production
- Truck movement through town to the processing plant and associated delays.
- Illegal miners jumping into moving trucks to steal ore for illegal processing, which has resulted in four deaths to date.
- Increase of fuel consumption and corresponding cost due to increased haulage distances.

It is on the basis of these that the optimisation is being undertaken to bring into perspective the different dimensions in the selection of alternative transport system which could enhance management's drive to increase production and improve profitability. The different selection criteria (which are 15 in number) which encompass technical, environmental and economic are multi-criteria in nature and require optimisation techniques of a multi-criteria nature. An appropriate technique, the AHP was used to evaluate the optimal ore transfer system as discussed in Chapter 5.

CHAPTER 5

RESULTS AND DATA ANALYSIS

5. 1 Results and Data Analysis

In the choice of a transfer system between KMS shaft and the processing plant, the Sulphide Treatment Plant (STP), the goal is to select the optimal ore transfer system based on the following identified criteria and sub-criteria (Figures 5.1 and 5.2)

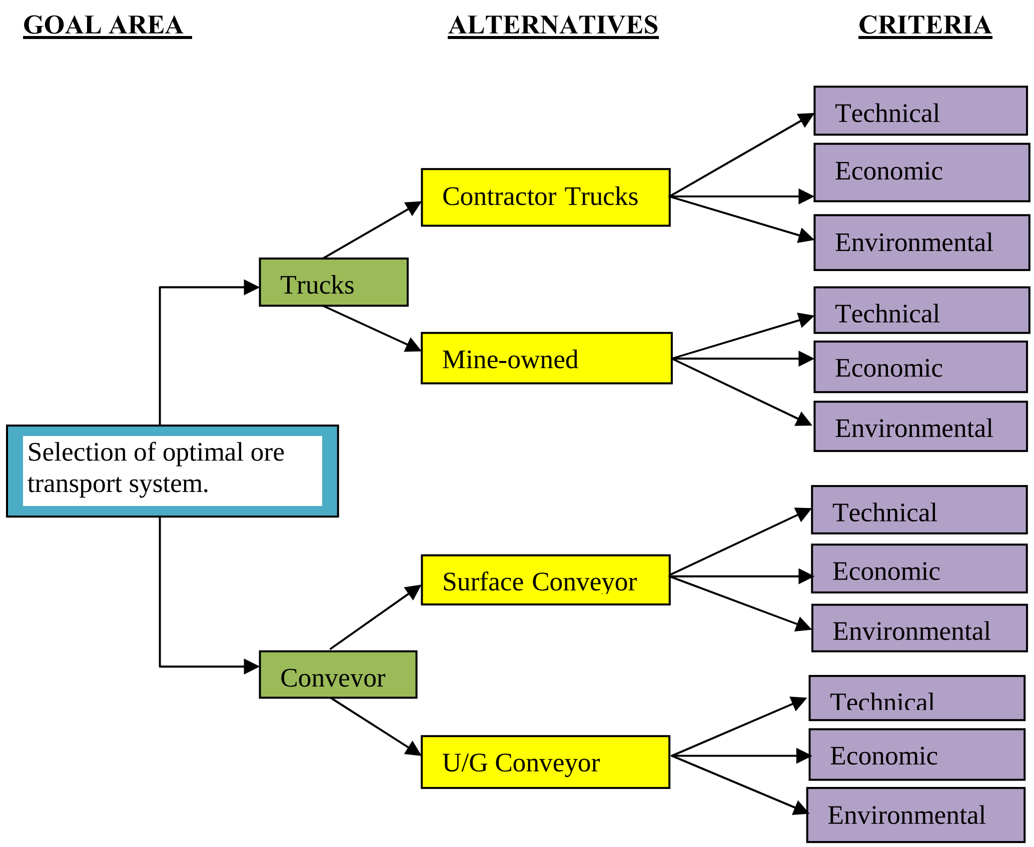

Figure 5.1 AHP Hierarchy for Obuasi ore transfer system

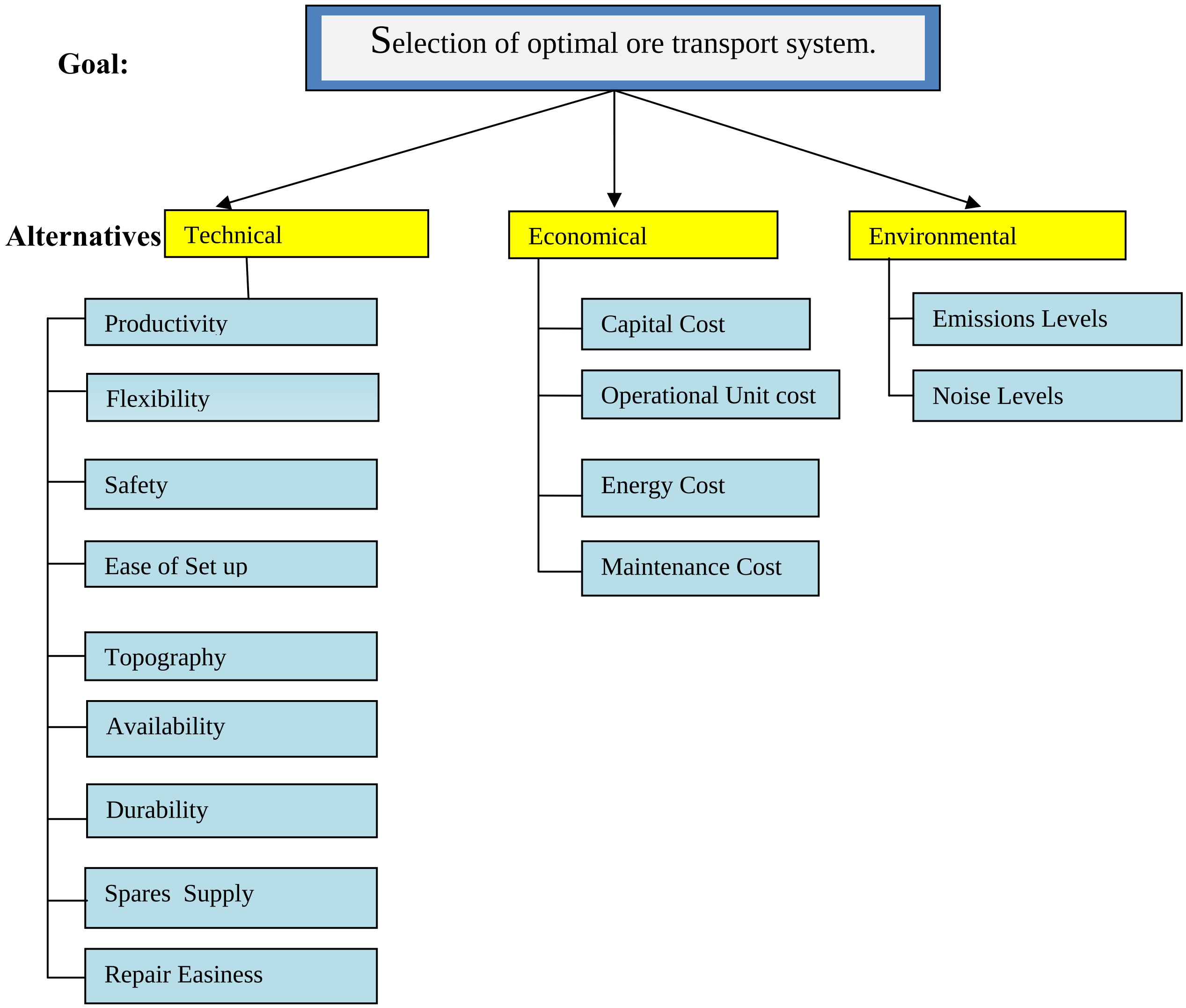

Figure 5.2 AHP model for optimal ore transport system selection

Based on the research that was conducted, a significant amount of information was gathered on the alternatives. The information was divided into three main areas, which formed the main criteria for comparing the ore transport systems. The three major areas are technical parameters, economic and environmental factors as shown by Figures 5.1 and 5.2.

Subsequent to the above, a questionnaire (Appendix 1, p57) was developed to obtain mine practitioners opinions in ranking and weighting the criteria and sub-criteria that would be used in comparing the ore transfer systems. One part dealt specifically with the weighting while the second dealt with the ranking. This questionnaire was then issued to practitioners. The practitioners team was composed of five members who are often involved in equipment selection on the mine. Of these five practitioners, two are Mine Planning Engineers from the Technical Department. Each one of them has more than ten years of experience in mine planning. Two practitioners are Production Managers from the Mining department. The last practitioner is the Engineering Manager of the mine. Thus, they have sufficient experience in equipment selection and are qualified to assign pair-wise comparison judgments for the proposed AHP model. The opinions expressed by them in their judgments are considered to be representative of the company in evaluating the equipment selection criteria and the selection requirements. The data obtained from responses to the questionnaires was put into a spreadsheet and the geometric average response was obtained.

Table 5.1 and Table 5.2 show the list of sub-criteria and alternative ore transfers and their codes:

Table 5.1 Criteria names and codes

CODE CRIT	**E RIA**
C1	Production
C2	Flexibility
C3	Safety
C4	Ease of setup
C5	Topography
C6	Availability
C7	Spares supply
C8	Repair Easiness
C9	Durability
C10	Capital cost
C11	Energy cost
C12	Maintenance cost
C13	Operational unit cost
C14	Emissions levels
C15	Noise levels

In order to rate the alternatives Saaty (1978a; 1978b) uses a hierarchical pair-wise comparison between attributes and/or objectives and then solves them with eigen vectors of the reciprocal matrices. The scale (Table 5.3) used is the one proposed.

Table 5.2 Ore transfer alternatives codes

Code	Alternatives
CT	Contract Trucking
MT	Mine-owned Trucking
SC	Surface Conveyor
UG	Underground Conveyor

In the hierarchy, the matrix of the upper nodes corresponds to level zero (the comparison of criteria) while the other correspond to level one. The construction of the square reciprocal matrices is performed by asking the decision maker to compare criterion **i** with criterion **j** represented by the value $\mathbf{a_{ij}}$**,** with respect to two particular criteria. The other values are assigned as follows: (a) $\mathbf{a_{ji}} = 1/\mathbf{a_{ij}}$; (b) $\mathbf{a_{ii}} = 1$. For this report, Saaty's reciprocal matrices are as shown in Table 5.4.

Table 5.3 Relative judgement scale

Relative Importance	Value[1]
Equal importance/quality	1
Somewhat more important/better	3
Definitely more important/better	5
Much more important/better	7
Very much more important/better	9

The maximum eigen value and eigen vector was used to solve the reciprocal matrices (Tables 5.4 and 5.5). The eigen vector corresponding to the maximum eigen value is a cardinal ratio scale for the elements compared. The eigen vectors are then normalised to ensure consistency. After obtaining the normalized eigen vectors for each matrix, the vectors of the upper level became the members of the

[1] The numbers 2, 4, 6, and 8 are half way positions between the values in the table.

full matrix of weights of alternatives for each criterion (Table 5.6). This last matrix of vectors is then multiplied by the matrix of weights of the criteria comparison (the eigenvector of the criteria comparison) Table 5.7. The intermediate results are as shown:

Table 5.4 Sub-criteria comparison matrix for the weights (for matrix B)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	1	6	1/9	5	1	1/3	1/3	1	1/3	1/9	3	3	2	1	1
C2	1/6	1	1/9	4	2	1/3	1/3	1	1/3	1/6	1	1/7	1/3	1/4	1/6
C3	9	9	1	9	9	6	6	9	9	8	9	7	5	6	8
C4	1/5	1/4	1/9	1	2	1/5	1/2	½	1/3	1/6	1/2	1/4	1/5	1/5	1/6
C5	1	1/2	1/9	1/2	1	1/5	1/5	¼	1/6	1/8	1/4	1/5	1/6	1/5	1/6
C6	3	3	1/6	5	5	1	3	4	2	1/2	3	2	1	1/2	1/6
C7	3	3	1/6	2	5	1/3	1	2	1	1/6	2	1	1	1/6	1/4
C8	1	1	1/9	2	4	1/4	1/2	1	1/4	1/6	1/3	1/4	1/6	1/5	1/6
C9	3	3	1/9	3	6	1/2	1	4	1	1/6	2	1/2	1/4	1/4	1/4
C10	9	6	1/8	6	8	2	6	6	6	1	5	4	3	1/2	1/2
C11	1/5	1/2	1/9	2	6	1/2	2	4	1/2	1/2	1	1/2	1/3	1/2	1/2
C12	1/5	1/2	1/9	4	5	1/6	1	4	1	1/3	2	1	3	1/4	1/4
C13	1/6	1	1/7	2	5	1/4	1	4	1/3	1/4	1	2	1	1/6	1/4
C14	1	4	1/6	5	5	2	6	5	4	2	4	3	2	1	1/4
C15	1	6	1/8	6	6	6	4	6	4	2	4	3	2	4	1

Table 5.5 Matrix tables for criterion and alternatives comparison (for matrix A)

Productivity				
	CT	MT	SC	UG
CT	1	4	1/6	1/3
MT	1/4	1	1/6	1/4
SC	6	6	1	2
UG	3	1/4	1/2	1

Flexibility				
	CT	MT	SC	UG
CT	1	1/4	5	6
MT	4	1	6	8
SC	1/6	1/6	1	2
UG	1/6	1/6	1/2	1

Safety				
	CT	MT	SC	UG
CT	1	1/2	1/5	1/3
MT	2	1	1/5	1/3
SC	5	5	1	8
UG	3	3	1/8	1

Ease of setup				
	CT	MT	SC	UG
CT	1	3	6	8
MT	1/3	1	5	7
SC	1/6	1/5	1	2
UG	1/6	1/6	1/8	1

Topography				
	CT	MT	SC	UG
CT	1	1	1/5	1/8
MT	1	1	1/5	1/8
SC	1/2	1/2	1	1/2
UG	8	5	1	1

Availability				
	CT	MT	SC	UG
CT	1	4	1/5	1/4
MT	1/4	1	1/4	1/4
SC	5	4	1	3
UG	4	4	1/3	1

Spares supply				
	CT	MT	SC	UG
CT	1	2	1/4	1/2
MT	1/2	1	1/2	1
SC	4	2	1	2
UG	2	1	1/2	1

Repair Easiness				
	CT	MT	SC	UG
CT	1	2	1/4	1
MT	1/2	1	1/3	1
SC	4	3	1	3
UG	1	1	1/3	1

Durability				
	CT	MT	SC	UG
CT	1	2	1/3	1/2
MT	1/2	1	1/3	1/3
SC	3	3	1	2
UG	2	3	1/2	1

Capital cost				
	CT	MT	SC	UG
CT	1	6	6	6
MT	1/6	1	3	6
SC	1/6	1/3	1	2
UG	1/6	1/6	1/2	1

Energy cost				
	CT	MT	SC	UG
CT	1	1	1/4	1/2
MT	1	1	1/2	1/2
SC	4	2	1	3
UG	2	2	1/3	1

Maintenance cost				
	CT	MT	SC	UG
CT	1	4	1/4	1
MT	1/4	1	1/6	1/2
SC	4	6	1	3
UG	1	2	1/3	1

Operating unit cost				
	CT	MT	SC	UG
CT	1	3	1/6	1/4
MT	1/3	1	1/6	1/4
SC	6	6	1	3
UG	4	4	1/3	1

Emissions levels				
	CT	MT	SC	UG
CT	1	2	1/8	1/8
MT	1/2	1	1/8	1/8
SC	8	8	1	1/2
UG	8	8	2	1

Noise levels				
	CT	MT	SC	UG
CT	1	1	1/2	1/8
MT	1	1	1/2	1/8
SC	2	2	1	1/5
UG	8	8	5	1

The final result is obtained by considering the normalised vectors for criteria comparisons, for each alternative (level 1 of hierarchy-**MATRIX A, Table 5.6**) as belonging to the same matrix and then multiplying it by the criterion weights (level zero of hierarchy –**MATRIX B, Table 5.7**), which are given by the criteria comparison normalised vector (Table 5.8) .

Table 5.6 Criteria-alternative comparison weights (Matrix A)

Criteria comparison for each alternative (Matrix B)

	Prod	Flex	Safety	Ease	Topo	Avail	Spares	Repair	Dura	Capital	Energy	Maint	Unit	Emiss	Noise
CT	14	28	8	56	7	14	17	18	17	61	13	20	11	7	8
MT	6	59	11	31	7	7	17	14	11	23	16	8	7	5	8
SC	52	9	61	8	31	51	44	52	44	10	48	55	56	37	15
UGC	28	5	19	5	56	28	22	16	28	6	24	17	27	52	68

Table 5.7 Criteria comparison weights (Matrix B)

Technical									Economics				Environmental	
Prod	Flex	Safety	Ease	Topo	Avail	Spares	Repair	Dura	Capital	Energy	Maint	Unit	Emiss	Noise
5	2	28	1	1	6	4	2	2	13	3	4	3	9	12
5.836									6.025				10.599	

Table 5.8 Criteria alternative comparison weights (Matrix A x B)

Matrix A X B

	Prod	Flex	Safety	Ease	Topo	Avail	Spares	Repair	Dura	Capital	Energy	Maint	Unit	Emiss	Noise
CT	72	57	218	78	8	90	71	37	33	791	45	84	39	64	96
MT	33	121	319	43	8	47	70	28	22	302	55	32	22	45	96
SC	273	18	1723	12	39	317	181	104	90	125	167	235	188	343	182
UGC	145	11	545	7	69	174	90	32	57	80	82	73	90	482	812

Table 5.9 Criteria alternative comparison–overall results

OVERALL RESULTS								
	TECHNICAL	%	ECONOMIC	%	ENVIRONMENTAL	%	OVERALL	%
CT	663	13%	959	40%	160	8%	1782	18%
MT	690	13%	411	17%	141	7%	1242	13%
SC	2757	53%	715	30%	526	25%	3997	41%
UGC	1131	22%	325	13%	1294	61%	2750	28%
	5,241		2,410		2,120		9,771	

5.1 Summary Results

The results (Table 5.9) show that Alternative **SC,** with 41%, has the highest value and is thus the most optimal ore transfer system between KMS and the processing plant according to the experts ranking. The next is the **UGC**, with 29%, while **CT** and **MT** follow with 17% and 12% respectively. Thus Alternative **SC** is the best choice. A summary table of all the AHP results showing the various scoring, estimated weights and final ranking is shown below (Table 5.10).

Table 5-10 AHP summary table

		Weight	CT	MT	SC	UG	C.R
Technical	Productivity	5.2	14	6	52	28	0.008
	Flexibility	2.1	28	59	9	5	0.074
	Safety	28.2	8	11	61	19	0.148
	Ease of setup	1.4	56	31	8	5	0.005
	Topography	1.2	7	7	31	56	0.002
	Availability	6.3	14	7	51	28	0.165
	Spares supply	4.1	17	17	44	22	0.095
	Repair easiness	2.0	18	14	52	16	0.036
	Durability	4.2	17	11	44	28	0.026
Technical Score			**699**	**713**	**2,854**	**1,193**	
Economic	Capital cost	13.0	61	23	10	6	0.122
	Energy cost	3.5	13	16	48	24	0.044
	Maintenance cost	4.2	20	8	55	17	0.036
	Operating unit cost	3.4	11	7	56	27	0.083
Economic Score			**959**	**411**	**715**	**325**	
Environmental	Emissions levels	9.3	7	5	37	52	0.046
	Noise levels	11.9	8	8	15	68	0.002
Environmental Score			**160**	**141**	**526**	**1,294**	
Overall Score			**1,818**	**1,265**	**4,094**	**2,812**	**0.102**
			18%	**13%**	**41%**	**28%**	

The summary above gives the overall process ranking and weighting and the final results using the Canadian Conservation Institute (CCI) AHP Matrix Model and steps in the “Requirement Prioritisation study (Mead, 2006; appendix II). The Consistency Ratio (CR) of 0.102 is on the borderline and is acceptable. The CR for the individual criterion also ranges from 0.002 to 0.165. This confirms a high degree of consistency in the analysis. The CR values were obtained from Canadian Conservation Institute (CCI) AHP Matrix Model using values from the reciprocal matrix Tables 5.4 and 5.5.

Thus the subjective evaluation of the selection of an optimal ore transfer system as conducted is seen as slightly inconsistent as the CR is above the threshold of 0.10. However, according to (Saaty, 1980), consistency up to 0.20 could be tolerated. In summary therefore this approach is quite consistent, structured and intuitive.

CHAPTER 6

DISCUSSION

6.1 Introduction

Analysis of the results indicated that many of the ore transfer options obtained high points with respect to the environment criterion. Historically, environmental issues have not been something of great concern at Obuasi mine, however with the current global environmental and climate-change awareness, the experts have attached greater importance to it.

Table 5.7 showed that the weighting assigned for the three main criteria by the various experts. As can be seen, the environmental criterion was considered to be more important than the other two criteria. The economic criterion was considered second highest in terms of importance while the technical criterion was considered to be the least important.

In Table 5.6, the average weights of the sub-criteria are shown. From the average weighting table, it can be clearly seen that quite a few of the sub-criteria obtained relatively high values. These included safety, capital cost, and noise. The availability of the transfer options and the rate of production or productivity followed closely behind with one less point between them. These issues represent the areas of greatest concern for the experts, or stated differently, are the most important issues for the experts. This is followed by durability and spares availability. The latter is also very important since even though being very safe and cost effective, the lack of spares could cripple the entire transfer arrangement selected. Environment has the highest weighting compared to economic and technical criteria in the weighting and this importance is carried through into the overall results.

6.2 Technical

Starting at the top with the technical criterion which has an average weighting of **5.836**, it is to be noted that the nine sub-criteria have a relatively even distribution with the exception of safety. This indicates that the elements in the sub-criteria are considered relatively of equal importance in comparison to each other. Safety of the transfer system has the highest weighting in the sub-criterion suggesting that it is more important than the others. The next streams of sub-criteria which are fairly equally ranked are availability, productivity and durability in their order of importance. Apart from these, the others following at the lower end of the weighting appear to be of equal importance.

With respect to the first sub-criteria, safety of the system as was expected, was assigned the highest score. Conveyors in this regard were highly rated over trucks, with surface conveyors being the best of the options (Table 5.8).

The next highest technical sub-criterion was availability. Again conveyors far outweighed trucks, with surface conveyors obtaining the highest score. This assertion as observed by the experts is confirmed in many reference manuals. The next technical sub-criterion is the production rate or productivity. This is a very important issue for Obuasi Mine as the strategic direction is to increase production and also decrease cost. The scoring reflects the need for this change if the improved production is to be achieved. Conveyors were given generally higher scores than trucks.
Generally trucking has not fared well at Obuasi Mine leading to regular model changes as could be observed with contracting fleets and even the few mine-owned trucks. The concern borders on durability, which is the next higher scoring on the technical list. This fact was expressed in the experts scoring where conveyors received a very high score while trucking generally received significantly lower scores.

The issue of spares availability and ease of repair are thought to be very essential, considering that manufacturing centers are far from the mine site and received a lower weight ranking. On the sub-criteria, the scoring by the experts on transfer options were fairly average, yet surface conveyors had the highest.

The scoring for the sub-criterion flexibility is very interesting as it came out lower than generally expected. This is supposed to be the highest scoring points of any type of trucking system and a very key issue. However based on the fact that the disposal points and receiving points are fixed, flexibility was rated lower as the fifth in the technical weighting. Trucking as expected received the highest scoring and for the first time in the analysis mine trucking was above contract trucking. This may be due to the experts observation of the other uses which mine trucking could be put to when not in use for ore delivery.

The next two final technical sub-criteria are repair easiness and topography, with the later being the least weighted. These follow similar and expected trend with conveyors being the best favoured in terms of easiness of repairs and surface conveyors having a slight edge. On topography the scores from the experts did not follow the normal line of thinking expected. The alternatives were basically ranked the same with conveyors in a marginal lead. Underground conveyors were rather the highest with the view that they could be developed amidst any type of terrain. The general assertion that favours conveyors is their ability to transport material along uneven slopes that exceed the dynamic stability of the transported material. This should have earned the conveyor system a relatively higher score.

6.3 Economic

The economic criterion should have been considered significantly more important than the technical criterion, however the margin of ranking was minimal. In looking at the individual sub-criteria, it can be seen that some of the sub-criteria, especially capital, have the highest overall weighting. The general expectation is that the overall values in the economic sub-criteria should in some respect be of more significant importance than technical. However, this does not seem to be the case according to ranking by the 5 experts. They are almost equally ranked. The highest in the economic sub-criteria is capital. This also ranks as the second highest in the 15 listed sub-criteria.

The issue of capital has been the bane of the failure/success of most major projects at Obuasi as in any other business entity. Huge initial capital demands become draw backs on most projects, whereas stage by stage or stepwise capital expense profile attracts favourable support. This is one of the stark differences between financing trucks and conveyors. With the rather tight capital structure on the mine, the trucking option had a higher scoring. This view is supported by the experts. The scoring is more than double that of the conveyor options, with the contract truck haulage highly favoured in the experts' scoring.

On the contrary, the other sub-criteria within the economic criteria are showing a higher scoring for the conveyor options. These are basically within the operational realm, which include energy cost, maintenance cost, and total unit operating cost. The scoring for the alternatives favoured the conveyors, showing almost a double. The highest rating was still the surface conveyor in the analysis. According to (Schmidt, 2001) the ton-kilometer cost of transport by belt conveyor may be as low as one-tenth the cost by haul truck.

6.3 Environmental

The environmental criterion, as was commented earlier, has the highest weighting of the three criteria. The environmental impacts of mining operations have become more important in recent times. Accordingly, these impacts are gradually becoming an important factor in the choice of equipment for mining operations. In material handling operations in mines, belt conveyor systems are generally considered to be more environmentally friendly than off-highway truck systems. The highest score in the sub-criteria were within the environmental area. The highest weighed sub-criterion is noise followed by the only other environmental sub-criterion, emission levels. These are almost equally ranked with capital. Unfortunately only two sub-criteria could be considered though there were other sub-criteria such as aesthetic / visual, but as indicated earlier the Canadian Conservation Institute AHP Matrix Model (CCI AHP) that was used limited the matrices to only 15 sub-criteria.

The noise and emissions sub-criteria received an almost twice as large a score as from the experts for both underground and surface conveyors over contract and mine-owned trucks. The latter alternatives scoring were fairly similar on the lower scale. The highest scoring from the experts was underground conveyors. This is logical and follows conventional expectations.

6.5 Overall Assessment

Table 5.9 and Table 5.10 detail the compiled results of the AHP. In terms of the technical criteria, the maximum score for this is 5,241 with an average weight of 582. It is clear that surface conveyors scored the highest at 53%. This is followed by underground conveyors, at 22%. The trucking alternatives under technical have the same scoring by the experts at 13%.

In the economic section, it can be seen that the transfer system with the highest economic score is contract trucking. This is followed by surface conveyors. At the tail end are mine-owned trucks and underground conveyors which closely obtained identical economic scores. The leading transfer system for the economic criterion, contract trucking, obtained high scores for its low initial capital, however, it received lower scores for operational cost.

In the environmental criteria, there was a wide disparity in the weighted response over the two major alternatives. Trucking had the least scoring. This was less than 10% while conveyors were high at above 20%. The major contributory factor is the peculiar location of Obuasi mine. About 25% of the KMS shaft to the Processing plant access route links up with the community roads. This has both safety and environmental risks. The surface conveyors would however be installed either over land or on stilts. Because of the obvious topographical advantage it could circumvent the high intervening slopes to link the KMS shaft to the plant. The underground conveyor would not encounter any of such challenges. Besides, its transfer would be the shortest in terms of distance between the two points. These benefits could have augmented the environmental scoring for the underground conveyors by the experts to a highest score of 61%.

The move for change is seemingly obvious with the analysis so far, barring any contingencies in the mine set-up and current strategic thinking. Besides plans to increase production from underground, discussions are underway to reduce the current mine footprint. This would further limit the number of active hoisting shafts to effectively two, which are KMS and KRS. The KMS shaft which is the one being used for the current research would subsequently have to improve in efficiency if the mine is to match the increase in production from current capacity of 175,000 tpm to above 220,000 tpm. KMS shaft would then have to hoist about 5,000 tpd. Technically, this is slightly below the economic limit required for conveyor installation. The minimum daily production tonnage is 5,000 tpd for conveyors (Fernie, 1996). On the contrary, haulage distance from the shaft to the plant is 2.8 km. This is also more than the 1 km minimum economic requirement to change from truck or rail haulage to conveyor system (Altoff, 1996).

In support of this research, financial assessments made gave the following results. The current contract haulage trucking system at a rate of $1.26 per tonne and a projected 5% annual increment resulted in a cumulative haulage cost of $22.0 million in nine years. However, estimated project cost for conventional overhead conveyor is about $12.32 million. This gives a payback between 9 to 10 years. A ground level conveyor is estimated to cost $8.95 million also with a payback 6 to 7 years.

The availability of capital continues to be a major issue at Obuasi mine and this tends to stifle growth and initiation of such turn-around projects. This obviously makes truck haulage the panacea for the short term but is strategically not cost effective. Mine-owned trucking system has also been tried but lack of appropriate maintenance regime, overhead cost and labour issues do not make it a desirable choice either.

For effective implementation of the conveyor system, appropriate financing arrangement would be required or alternatively a Build, Operate and Transfer (BOT) system could be considered to facilitate this initiative.

Finally, an observation made was that in terms of the number of sub-criteria, the technical criterion had nine sub-criteria; the economic criterion had four while the environmental criterion had two sub-criteria. It is believed these differences could have affected the results. In hindsight, it is realized that under these circumstances, the criteria and sub-criteria could be kept relatively even to avoid double accounting for the weight of a criterion.

6.6 Summary

The overall observation by the experts under the technical criterion favoured surface conveyors. The high point scoring areas were safety, production rate, availability, spare supply and repair easiness, and durability. Thus close to 70% of the nine sub-criteria favoured the surface conveyor, and the underground as the next favourite. In terms of economic criteria, the experts chose the contract trucking system. This is quite in line as the financial strain is very low and labour issues, maintenance, and availability are more of external factors to the mine management. The difference in scoring was however minimal as it lost ground in the areas of operating cost, which was expected.

Environmental issues also favoured underground conveyors with a very wide margin. Overall though the scoring for the three criteria favoured different alternatives, the final choice as per the analysis is surface conveyors.

CHAPTER 7

CONCLUSION

7.0 Conclusion

Obuasi Mine underground production of 6,000 tpd is considered to be within the small to medium capacity range. The current strategy is to increase production as part of the cost management process to ensure growth and future share holder value. Key to this is an efficient surface ore transfer system from the shaft to the plant. This has been the objective of this research report. The AHP methodology used is quite consistent, structured and intuitive and helped to identify the strengths and weakness of each alternative under the three main criteria and the 15 sub-criteria. The overall observation by the experts favoured surface conveyors, however, the issue of capital in the present regime of the Obuasi mine, makes it difficult to encourage management approval within the immediate future. On the contrary with the current Turn-Around-Project (TAP) and transformation exercise on-going it is hoped that the company would be able to generate sufficient profits to self-fund these worthwhile investments. Alternatively as the surface conveyor has the potential to make adequate returns, from the financial analysis showing a six to ten year payback period in a mining environment, other forms of finance could be considered to undertake the project. Alternatively, the trucking system could be considered as the second best option but with the introduction of additional haulage contractors to induce competition, improve availability and possibly reduce cost. However, the issue of colluding among the contractors could also be an issue.

The proposed AHP model is generally applicable to any selection process in mining operations. However, using the AHP model, the criteria for equipment selection are clearly identified and the process is structured systematically. This enables decision-makers to examine the strength and weakness of each system using the pair-wise comparison. Moreover, the use of the AHP model can significantly reduce the time and effort in decision making and also has the potential to improve the selection process. The AHP model developed in this paper could be used as a basis for implementing future equipment selection for the mine particularly load-haul-and-dump systems. This is however the first time a more structured approach has been used for equipment selection at Obuasi.

Appendix 1

Questionnaire-Trucks and conveyors.

As part of a research, this questionnaire is to aid in selecting the best way to transfer ore from the KMS shaft to STP mill. The methodology in use is the Analytical Hierarchy Process (AHP) which uses pairwise comparison in making the best choice.

The Subcriteria pairwise comparison is to provide an insight of which criteria e.g. productivity, durability (i.e. A or B) has higher advantage over the other and to what intensity (1-9). Write A or B in the first box depending on which one you think has higher advantage. Write 1, 3, 5, 7 or 9 in the second box showing intensity by using the scale in table one as guide.

The alternatives include:

1. C.T -Contractor trucks
2. M.T -Mine own trucks
3. S.C -Surface conveyors
4. U/G-Underground conveyors

Attributes

Productivity of the system High work output efficiency and effectiveness of the method is desired.
Flexibility of the system A method that can adapt to changes in tonnage is preferred.
Safety in operation Assurance of protection from harmful and dangerous situations
Easiness of set up Proven to be easily made ready for use and requiring less time and technical effort
Topography Ability to maneuver up and down relatively steep or shallow land slopes is required.
Availability of system less breakdowns with higher work efficiency is desired.
Spare parts supply One with readily available spare parts is desired.
Repair easiness A method that is not difficult to repair is preferred.
Durability Strong and long lasting method is necessary.
Capital Cost Lowest capital for purchase is desired.
Energy cost Minimal cost of fuel or electricity is necessary.
Maintenance cost Least cost for repairs and maintenance is desired
Unit cost Least cost per tonne of ore moved is required.
Jobs/labour Least labour cost is desired.
Emissions levels Lowest risk of Harmful emissions and gases to the environment is good.
Noise Levels Least loud and unpleasant sound emitted into the surrounding environment is desired.
Aesthetic/Visuals Least visual impact to the environment is good.

GOAL: selection of optimal transport system for the transfer of ore from KMS to STP.

The fundamental scale of pairwise comparison.		
1	Equal importance	Two elements contribute equally to the objective.
3	Moderate importance	Experience and judgement slightly favour one over the other.
5	Strong importance	Experience and judgement strongly favour one over the other.
7	Very strong importance	One element is favoured very strongly over another; its dominance is demonstrated in practice.
9	Extreme importance	The evidence favouring one element over another is of highest possible order of affirmation.

SUB-CRITERIA PAIRWISE COMPARISON BY EXPERTS

		EXPERT 1		EXPERT 2		EXPERT 3		EXPERT 4		EXPERT 5		SUMMARY	
A B		**Higher advantage (A or B)**	**Intensity (1,3,5,7 / 9)**	**Higher advantage (A or B)**	**Intensity (1,3,5,7 / 9)**	**Higher advantage (A or B)**	**Intensity (1,3,5,7 / 9)**	**Higher advantage (A or B)**	**Intensity (1,3,5,7 / 9)**	**Higher advantage (A or B)**	**Intensity (1,3,5,7 / 9)**	**Higher advantage (A or B)**	**Intensity (1,3,5,7 / 9)**
Flexibility	Productivity	B	6	A	1	B	6	B	7	B	6	B	6
Safety	Productivity	A	9	A	9	A	9	A	9	A	9	A	1/9
Ease of setup	Productivity	B	5	A	1	B	5	B	5	B	5	B	5
Topography	Productivity	B	1	B	5	B	1	A	5	B	1	B	1
Availability	Productivity	A	3	A	1	A	3	A	5	A	3	A	1/3
Spares supply	Productivity	A	3	A	5	A	3	A	1	A	3	A	1/3
Repair Easiness	Productivity	A	1	A	3	A	1	B	3	A	1	A	1
Durability	Productivity	A	3	A	3	A	3	A	3	A	3	A	1/3
Capital cost	Productivity	A	9	B	7	A	9	A	9	A	9	A	1/9
Energy cost	Productivity	B	3	B	7	B	3	A	3	B	3	B	3
Maintenance cost	Productivity	B	3	B	7	B	3	B	3	B	3	B	3
Unit cost	Productivity	B	2	B	7	B	2	A	1	B	2	B	2
Emissions	Productivity	A	1	A	7	A	1	B	7	A	1	A	1
Noise	Productivity	A	1	A	7	A	1	B	7	A	1	A	1
Safety	Flexibility	A	9	A	9	A	9	A	9	A	9	A	1/9
Ease of setup	Flexibility	B	4	B	5	B	4	A	1	B	4	B	4
Topography	Flexibility	B	2	B	7	B	2	A	5	B	2	B	2
Availability	Flexibility	A	3	A	1	A	3	A	5	A	3	A	1/3
Spares supply	Flexibility	A	3	A	5	A	3	A	1	A	3	A	1/3
Repair Easiness	Flexibility	A	1	A	3	A	1	B	3	A	1	A	1
Durability	Flexibility	A	3	A	3	A	3	A	3	A	3	A	1/3
Capital cost	Flexibility	A	6	B	3	A	6	A	9	A	6	A	1/6
Energy cost	Flexibility	B	1	B	3	B	1	A	1	B	1	B	1
Maintenance cost	Flexibility	B	7	B	3	B	7	A	1	B	7	B	1/7
Unit cost	Flexibility	B	3	B	3	B	3	A	3	B	3	B	1/3
Emissions	Flexibility	A	4	A	7	A	4	B	1	A	4	A	1/4
Noise	Flexibility	A	6	A	7	A	6	B	3	A	6	A	1/6
Ease of setup	Safety	B	9	B	9	B	9	B	1	B	9	B	9
Topography	Safety	B	9	B	9	B	9	B	3	B	9	B	9
Availability	Safety	B	6	B	9	B	6	B	9	B	6	B	6
Spares supply	Safety	B	6	B	9	B	6	B	9	B	6	B	6
Repair Easiness	Safety	B	9	B	9	B	9	B	3	B	9	B	9
Durability	Safety	B	9	B	9	B	9	B	3	B	9	B	9
Capital cost	Safety	B	8	B	9	B	8	B	9	B	8	B	8
Energy cost	Safety	B	9	B	9	B	9	B	9	B	9	B	9
Maintenance cost	Safety	B	7	B	9	B	7	B	7	B	7	B	7
Unit cost	Safety	B	5	B	9	B	5	B	9	B	5	B	5
Emissions	Safety	B	6	B	9	B	6	B	9	B	6	B	6
Noise	Safety	B	8	B	7	B	8	B	5	B	8	B	8
Topography	Ease of setup	A	2	B	7	A	2	A	9	A	2	A	2
Availability	Ease of setup	A	5	A	9	A	5	A	5	A	5	A	1/5
Spares supply	Ease of setup	B	2	A	5	B	2	B	9	B	2	B	1/2
Repair Easiness	Ease of setup	A	2	A	3	A	2	A	9	A	2	A	1/2
Durability	Ease of setup	A	1.3	A	3	A	1.3	A	3	A	1.3	A	1 1/3
Capital cost	Ease of setup	A	6	B	3	A	6	A	7	A	6	A	1/6
Energy cost	Ease of setup	B	2	B	3	B	2	A	1	B	2	B	1/2
Maintenance cost	Ease of setup	B	4	B	3	B	4	A	1	B	4	B	1/4
Unit cost	Ease of setup	B	5	B	3	B	5	A	3	B	5	B	1/5
Emissions	Ease of setup	A	5	A	7	A	5	A	9	A	5	A	1/5
Noise	Ease of setup	A	6	A	7	A	6	A	5	A	6	A	1/6
Availability	Topography	A	5	A	7	A	5	A	7	A	5	A	1/5
Spares supply	Topography	A	5	A	7	A	5	A	5	A	5	A	1/5
Repair Easiness	Topography	A	4	A	7	A	4	A	1	A	4	A	1/4
Durability	Topography	A	6	A	7	A	6	A	3	A	6	A	1/6
Capital cost	Topography	A	8	A	7	A	8	A	5	A	8	A	1/8
Energy cost	Topography	A	4	A	7	A	4	A	3	A	4	A	1/4
Maintenance cost	Topography	A	5	A	7	A	5	A	3	A	5	A	1/5
Unit cost	Topography	A	6	A	7	A	6	A	3	A	6	A	1/6
Emissions	Topography	A	5	A	7	A	5	A	1	A	5	A	1/5
Noise	Topography	A	6	A	7	A	6	A	5	A	6	A	1/6
Spares supply	Availability	B	3	B	1	B	3	B	9	B	3	B	3
Repair Easiness	Availability	B	4	B	3	B	4	B	5	B	4	B	4
Durability	Availability	B	2	B	3	B	2	B	3	B	2	B	2
Capital cost	Availability	B	2	B	5	B	2	A	3	B	2	B	1/2
Energy cost	Availability	B	3	B	5	B	3	A	1	B	3	B	3
Maintenance cost	Availability	B	2	B	5	B	2	B	3	B	2	B	2
Unit cost	Availability	B	1	B	5	B	1	B	5	B	1	B	1
Emissions	Availability	A	2	A	7	A	2	B	1	A	2	A	1/2
Noise	Availability	A	6	A	9	A	6	B	5	A	6	A	1/6
Repair Easiness	Spares supply	B	2	B	3	B	2	B	5	B	2	B	2
Durability	Spares supply	B	1	B	3	B	1	A	1	B	1	B	1
Capital cost	Spares supply	A	6	B	3	A	6	A	7	A	6	A	1/6
Energy cost	Spares supply	B	2	B	3	B	2	A	3	B	2	B	2
Maintenance cost	Spares supply	A	1	B	3	A	1	A	7	A	1	A	1
Unit cost	Spares supply	B	1	B	3	B	1	A	3	B	1	B	1
Emissions	Spares supply	A	6	A	7	A	6	B	1	A	6	A	1/6
Noise	Spares supply	A	4	A	7	A	4	B	5	A	4	A	1/4
Durability	Repair	A	4	A	3	A	4	A	1	A	4	A	1/4
Capital cost	Repair	A	6	B	3	A	6	A	5	A	6	A	1/6
Energy cost	Repair	A	3	A	3	A	3	A	1	A	3	A	1/3
Maintenance cost	Repair	A	4	A	3	A	4	A	3	A	4	A	1/4
Unit cost	Repair	A	6	A	3	A	6	A	9	A	6	A	1/6
Emissions	Repair	A	5	A	7	A	5	A	5	A	5	A	1/5
Noise	Repair	A	6	A	7	A	6	A	3	A	6	A	1/6
Capital cost	Durability	A	6	A	3	A	6	A	3	A	6	A	1/6
Energy cost	Durability	B	2	B	3	B	2	A	3	B	2	B	2
Maintenance cost	Durability	B	2	B	3	B	2	A	1	B	2	B	1/2
Unit cost	Durability	B	4	B	3	B	4	B	1	B	4	B	1/4
Emissions	Durability	A	4	A	7	A	4	B	3	A	4	A	1/4
Noise	Durability	A	4	A	7	A	4	A	3	A	4	A	1/4
Energy cost	Capital cost	B	5	B	1	B	5	B	9	B	5	B	5
Maintenance cost	Capital cost	B	4	B	1	B	4	B	5	B	4	B	4
Unit cost	Capital cost	B	3	A	1	B	3	B	5	B	3	B	3
Emissions	Capital cost	A	2	A	7	A	2	B	5	A	2	A	1/2
Noise	Capital cost	A	2	A	7	A	2	B	1	A	2	A	1/2
Maintenance cost	Energy cost	A	3	A	1	A	3	A	3	A	3	A	1/3
Unit cost	Energy cost	A	2	B	1	A	2	A	5	A	2	A	1/2
Emissions	Energy cost	B	2	A	7	B	2	B	9	B	2	B	1/2
Noise	Energy cost	A	3	A	7	A	3	B	1	A	3	A	1/3
Unit cost	Maintenance	B	2	B	3	B	2	B	3	B	2	B	1/2
Emissions	Maintenance	A	2	A	7	A	2	B	3	A	2	A	1/2
Noise	Maintenance	A	3	A	7	A	3	A	3	A	3	A	3
Emissions	Unit cost	A	4	A	7	A	4	B	3	A	4	A	1/4
Noise	Unit cost	A	4	A	7	A	4	A	1	A	4	A	1/4
Noise	Emissions	A	4	A	7	A	4	A	5	A	4	A	1/4

SUB-CRITERIA COMPARISON MATRIX

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	Scores	Product	Ratio
C1	1	6	1/9	5	1	1/3	1/3	1	1/3	1/9	3	3	2	1	1	5.2%	0.88	16.9172
C2	1/6	1	1/9	4	2	1/3	1/3	1	1/3	1/6	1	1/7	1/3	1/4	1/6	2.1%	0.33	15.8652
C3	9	9	1	9	9	6	6	9	9	6	9	7	5	6	8	28.2%	5.43	19.2726
C4	1/5	1/4	1/9	1	2	1/5	1/2	1/2	1/3	1/6	1/2	1/4	1/5	1/5	1/8	1.4%	0.23	16.6828
C5	1	1/2	1/9	1/2	1	1/5	1/5	1/4	1/6	1/8	1/4	1/5	1/6	1/5	1/6	1.2%	0.22	17.9832
C6	3	3	1/6	5	5	1	3	4	2	1/2	3	2	1	1/2	1/6	6.3%	1.10	17.5835
C7	3	3	1/6	2	5	1/3	1	2	1	1/6	2	1	1	1/6	1/4	4.1%	0.71	17.2976
C8	1	1	1/9	2	4	1/4	1/2	1	1/4	1/6	1/3	1/4	1/6	1/5	1/6	2.0%	0.34	16.7002
C9	3	3	1/9	3	6	1/2	1	4	1	1/6	2	1/2	1/4	1/4	1/4	4.2%	0.74	17.5314
C10	9	6	1/6	6	8	2	6	6	6	1	5	4	3	1/2	2	13.0%	2.43	18.7159
C11	1/5	1/2	1/9	2	6	1/2	2	4	1/2	1/2	1	1/2	1/3	1/2	1/2	3.5%	0.61	17.4063
C12	1/5	1/2	1/9	4	5	1/6	1	4	1	1/3	2	1	3	1/4	1/4	4.2%	0.65	15.4660
C13	1/6	1	1/7	2	5	1/4	1	4	1/3	1/4	1	2	1	1/6	1/4	3.4%	0.54	16.0078
C14	1	4	1/6	5	5	2	6	5	4	2	4	3	2	1	1/4	9.3%	1.67	17.9154
C15	1	6	1/8	8	6	6	4	6	4	1/2	4	3	2	4	1	11.9%	2.12	17.8663
																	CI	0.16
																	CR=CI/RI	0.1025

NORMALISED COMPARISON MATRIX

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0.030	0.134	0.039	0.085	0.014	0.017	0.010	0.019	0.011	0.009	0.079	0.108	0.093	0.066	0.069
C2	0.005	0.022	0.039	0.068	0.029	0.017	0.010	0.019	0.011	0.014	0.026	0.005	0.016	0.016	0.011
C3	0.273	0.201	0.354	0.154	0.129	0.299	0.183	0.174	0.298	0.494	0.236	0.251	0.233	0.395	0.550
C4	0.006	0.006	0.039	0.017	0.029	0.010	0.015	0.010	0.011	0.014	0.013	0.009	0.009	0.013	0.009
C5	0.030	0.011	0.039	0.009	0.014	0.010	0.006	0.005	0.006	0.010	0.007	0.007	0.008	0.013	0.011
C6	0.091	0.067	0.059	0.085	0.071	0.050	0.091	0.077	0.066	0.041	0.079	0.072	0.047	0.033	0.011
C7	0.091	0.067	0.059	0.034	0.071	0.017	0.030	0.039	0.033	0.014	0.053	0.036	0.047	0.011	0.017
C8	0.030	0.022	0.039	0.034	0.057	0.012	0.015	0.019	0.008	0.014	0.009	0.009	0.008	0.013	0.011
C9	0.091	0.067	0.039	0.051	0.086	0.025	0.030	0.077	0.033	0.014	0.053	0.018	0.012	0.016	0.017
C10	0.273	0.134	0.059	0.103	0.114	0.100	0.183	0.116	0.198	0.082	0.131	0.144	0.140	0.033	0.138
C11	0.006	0.011	0.039	0.034	0.086	0.025	0.061	0.077	0.017	0.041	0.026	0.018	0.016	0.033	0.034
C12	0.006	0.011	0.039	0.068	0.071	0.008	0.030	0.077	0.033	0.027	0.053	0.036	0.140	0.016	0.017
C13	0.005	0.022	0.051	0.034	0.071	0.012	0.030	0.077	0.011	0.021	0.026	0.072	0.047	0.011	0.017
C14	0.030	0.089	0.059	0.085	0.071	0.100	0.183	0.097	0.132	0.165	0.105	0.108	0.093	0.066	0.017
C15	0.030	0.134	0.044	0.137	0.086	0.299	0.122	0.116	0.132	0.041	0.105	0.108	0.093	0.263	0.069

First, a summary of five experts pair-wise comparison was obtained by averaging the comparison. This was used in filling the 15x15 matrix table (Table). The data from the table was then averaged by normalized columns to estimate the *eigenvector* of the matrix, which represents the criterion distribution. This was done by computing the sum of the columns in the matrix and divided each value in the matrix by the column sum. The output is the normalized matrix.

To determine the score of each requirement, average the row in the normalized matrix by dividing each row sum by the number of requirements. The score of each requirement is the percentage that the requirement adds to the requirements' total value.

The consistency index/random index (CI/RI) ratio was used to check the consistency of the results To compute the CI/RI ratio, the following steps were taken:[1]

1) Calculate the product of the pair-wise comparison matrix and the vector of scores.
2) Calculate the ratios.
3) Calculate the calculate the consistency index (CI) with the formula "=(average (Y2:Y10) - n) /(n-1)." The value n is the number of requirements or sub-criteria.
4) Calculate the CI/RI score. The RI is the average value of the CI, if the entries in the pair-wise comparison matrix were chosen at random. Because the number of sub-criteria is 15, the RI is 1.59.

[1]Requirements Prioritization Case Study Using AHP Nancy R. Mead, Software Engineering Institute ;Copyright © 2006, 2008 Carnegie Mellon University, 2006-09-23; Updated 2008-09-18

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