What is the best energy-delivery system for hand-held stope drilling and associated equipment in narrow-reef hard rock mines?

by P.J. Petit* and P.D. Fraser†

Synopsis

Changing mining conditions, legislative issues, rising costs, and the constrained supply of skills and electricity in South Africa, have been some of the criteria forcing mine operators and engineers to review the traditional use of compressed air to power underground hand-held drilling operations in narrow-stope, hard-rock mines. In answering the question, '*What is the best way to power this mine*?', they have resorted to trade-off studies with results of limited usefulness, because they are site-specific, and use only a few comparative parameters, based on a small data set.

This paper aims to provide definitive, objective, and quantitative decision-making approaches to evaluating alternative energy-delivery systems for stoping in narrow-reef hard rock mines, based on primary and relevant criteria. These include quantifiable criteria such as capital expenditure, operating costs, resulting financial returns, energy and water usage, production performance, life-of-mine, etc. Other important criteria with qualitative aspects are integrated. These are safety, health, and environmental concerns, legislative requirements, business risk, technology change, etc.

The paper begins with a review of decision-making processes available, and proposes the use of the analytical hierarchy process (AHP) method as a multiple-criteria decision-making tool and the decision tree based on milestone-driven uncertainties, to validate the selection of the energy delivery system. The results of a multiple-criteria questionnaire completed by a variety of industry experts and professionals, such as production and operation managers, consultants, suppliers, and techno-financial analysts, are discussed.

The evaluation indicates the potential for hydropower to be the best solution for narrow-reef hard rock mines, based on current information, mine design layout and production.

Keywords

hand-held stope drilling, energy delivery system, multiple-criteria decision-making (MCDM), analytical hierarchical process (AHP), valuation, sensitivities, scenarios, decision-tree analysis.

Introduction

Mining is an uncertain activity with both technical and economic challenges. The decision-makers are confronted with multiple primary and derived criteria that involve multiple scenarios with disproportionate amounts of detail. In such situations, mostly as a result of time constraints, the tendency is generally to revert back to 'engineering judgement', biased towards satisfying the perceived dominant criteria at that point in time.

The solution for the question posed in this study lies in assigning realistic and numeric ratings to explicit criteria for multi-criteria decision-making, across various energy delivery systems, to obtain a holistic and optimized outcome. This is because no single criterion can be viewed in isolation, due to direct or indirect relationships that exist between criteria.

The objective of this paper is to examine the techno-economic and practical criteria pertaining to the decision, and the selection of an energy delivery system for hand-held stope drilling and associated equipment in narrow-reef hard rock mines. This is based on current information on available technologies for a conventional mine layout and feasible production profile derived from responses of a survey group composed of mining industry experts and professionals.

Decision-making criteria

The evaluation of alternative energy-delivery systems is based on the set of criteria that influence decision-making, shown in Table I. Certainty depends on the quality of the information base, and its quantification, both of which can facilitate decision-making. Controllable criteria allow decisions to be enumerated more easily, unlike criteria susceptible to external influence factors. An increase in uncertainty across criteria, with fluctuations between the extremes of control and levels of certainty, makes decision-making complex, and results in multiple outcomes based on scenarios.

* *Independent Consultant.*

† *HPE (Innovation)*

Table I

Analysis of decision-making criteria

Control (top) / No Control (bottom); Uncertainty (left) / Certainty (right)

Life of Mine operating requirements		Production performance	Training and skills
Technology	Penetration rate		Implementation and Management
	Recovery	Electricity consumption	
Financial returns	Commodity pricing	Operating and production expenditure	Opex and Capex
Stakeholder expectations	RDO's	Safety and health regulations	
	Community	Environmental policies	
	Legislative	Electricity costing	
	Business	Business, risk and strategy	Energy availability
			Eskom buy-back

The focus of the tabulation is to rank the energy-delivery systems by determining the relative importance of all the criteria under consideration, based on multiple-criteria decision-making (MCDM). Each criterion has a relative degree of importance in the overall decision, since they are all risks. However, these criteria are often of conflicting interest. Therefore, the best energy-delivery system based on an independent criterion may not be the optimal solution for a number of co-dependent criteria.

Another typical mining example of co-dependence is the transportation of personnel underground. There are several safety, technical, operational, and financial requirements to be fulfilled simultaneously, rendering the selection of options such as a chairlift *versus* man carriers difficult. The selection of a chairlift introduces increased safety at the expense of high capital cost and mine planning, while man carriers bring flexibility but augment ventilation requirements.

Valuation and decision methodologies

Project valuations range from deterministic to probabilistic, and thus range from simple spreadsheet models to sophisticated and dynamic models involving advanced skills. These include:

- Discounted cash flow to determine the NPV, IRR, and earnings ratios
- Sensitivity analyses to investigate the stability of the solution with respect to changing one key criterion at a time, thus determining key drivers
- Scenarios involving listing a series of criteria and changing the value of each criterion for each scenario:
  - Analytical hierarchical process (AHP), expressing the relative values of a set of criteria of different parametric units within a matrix, to rank or eliminate scenarios
- Monte Carlo simulation to calculate a statistical forecast of variability for the scenario
- Decision tree analysis to identify possible outcomes of scenarios in sequence, where one criterion results in a set of outcomes, subject to probability. The result is the optimal combination of a series of sequential decisions based on the possible future outcomes and the highest probability of each outcome occurring
- Option pricing considers management flexibility by using different inputs to produce the same output as appropriate.

However, each of the valuation and decision methodologies entails a series of benefits and drawbacks, as suggested in Table II.

Energy delivery systems

The hand-held drilling technologies utilized in platinum and gold mines and considered in this comparative are illustrated in Figures 1–4.

Assumptions

The following assumptions are made to define the study:

- Stope drilling occurs in rock with suitable mechanical properties, such as the rock mass rating (RMR), and other rock characteristics
- Blasting is considered successful in each conventional mining cycle

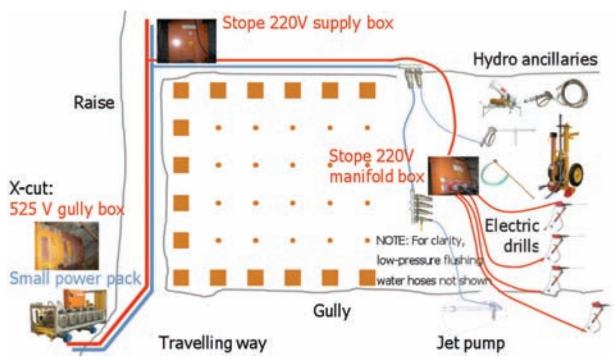

Figure 1—Electric drilling and equipping within the conventional panel

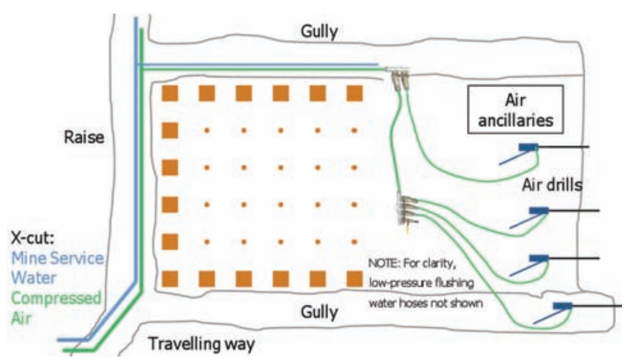

Figure 2—Pneumatic drilling with compressed air generated and piped from surface

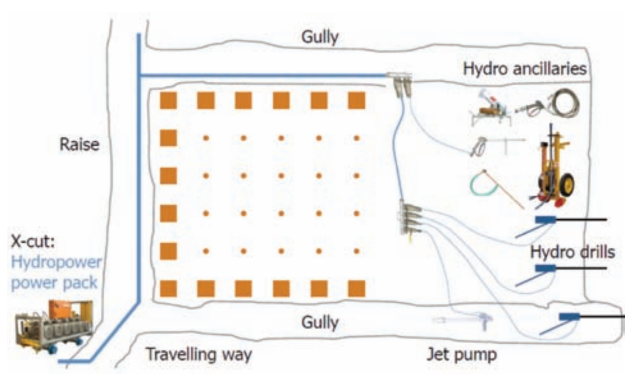

Figure 3—Hydropower (open-circuit) drilling with powerpacks in the crosscut and high-pressure pipe reticulation in the stope

Table II

Advantages and disadvantages of valuation methods

Valuation method	Advantages	Disadvantages
NPV	Shows real value added to the project	Cost of capital must be determined for single business plan
	Takes account of time value of money	Provides no comparative measure of profitability
	Provides a cash equivalent which can be used as an index for comparison at a given time	Assumes all parameters carry same risk and all variables are optimal, thus no flexibility
	Applied to any type of cash flow	Assumes conditions of low uncertainty
IRR	Relates returns only to the capital not recovered	Based on hurdle rate. Reinvestment rates must be considered
	IRR is presented as an 'interest rate'	Delays do not affect IRR, hencemay give a misleading answer
	Independent of the cost of capital	Multiple root problems exist
Sensitivity (incl. AHP)	Uncertainties can be defined in a range of values, instead of a singular value	Ranking of cash flows and NPV not easy, since capital expenditure must be similar. Constancy assumed on parameters not analysed
	Relative importance of separate input measures can be ascertained	Positive reciprocal matrix format required
	Ability to rank choices in the order of their effectiveness in meeting conflicting objectives	Scale range of the weightings (larger range required for nebulous cases)
	Ability to detect inconsistent judgments	Constancy assumed on parameters not analysed
Scenario	Analyses risk on single and multiple criteria simultaneously	No management flexibility
Monte Carlo	Correlations and other interdependencies can be included	Must be an accurate representation of the system investigated
	Eliminates bias towards a certain criterion	Ignores new information available over time
	Includes randomness (assesses risk)	Management flexibility
Decision tree	Suited for uncertainties in parameters	Depend on reliable information
	Provides a comprehensive overview for the alternative scenarios of a decision	Examines only a single criteria at any node
	Management flexibility	Changing of sequence of decision can alter final outcome
Option pricing	Management impact considered	Dependent on stock and strike values of shares
	Multiple outcomes as business conditions evolve	Timeframe is important

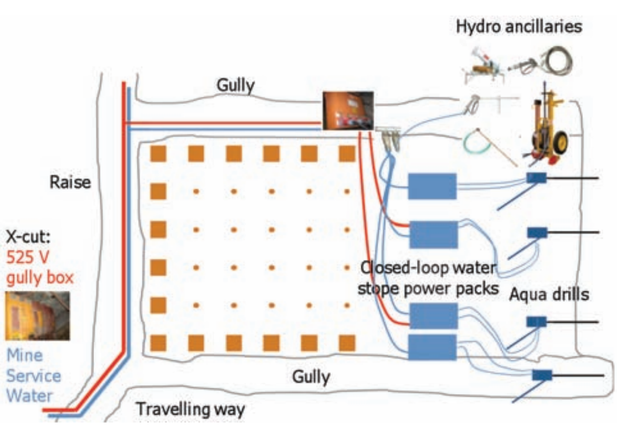

Figure 4—Aquapower (closed circuit) drilling with powerpack in the stope, one per drill, and the drilling water re-circulated back to the powerpack

- ➤ The production profile and life of mine utilized in the study are not altered across the energy-delivery system methods
- ➤ Open-circuit hydropower is modular (localized), and not centralized
- ➤ Trackless and hybrid mining are not considered, and any requirements, such as supply of compressed air to the refuge chambers in the production areas, are also supplied and paid for by conventional mining.

Analytic Hierarchical Process (AHP)

The analytical hierarchical process uses a multi-level hierarchical structure containing independent objectives, criteria, sub-criteria, and alternatives. These are paired and configured in a matrix for comparison. The comparisons are weighed and then ranked as a function of the relative performance measures of the alternatives, known as the relative values (RV). The methodology is briefly outlined in the Appendix.

AHP for energy delivery systems

Several co-dependent techno-economic criteria are required to formulate a decision beyond financial indicators. Since the life-of-mine (LOM) cost is determined on expenditure for a single business plan, and assumes all criteria carry same risk and are optimal, the decision is biased on the lowest LOM cost only. The influence and sensitivity of certain criteria can result in the selection of an alternative energy-delivery system, compared to the option with the lowest LOM cost only. Hence, the AHP decision matrix of all criteria provides a method to corroborate or contradict the initial decision.

The decision matrix in Table III lists pertinent and clustered criteria across various categories. The lower value in each row indicates less importance, while the highest score specifies the greatest importance. For example, penetration rate is more important than SHE, implementation and management, and business risk, but of equal importance to legislative aspects, electricity consumption, operating expenditure, capital expenditure, and electricity cost.

Table III

Overall preference matrix (OPM)

Criteria	Legislative	SHE	Implementation and management	Business risk	Technical penetration rate	Electricity consumption	Opex	Capex	Electricity cost
Legislative	1.000	0.182	0.667	0.333	1.000	1.000	1.000	1.000	1.000
SHE	5.500	1.000	3.667	1.833	5.500	5.500	5.500	5.500	5.500
Implementation and management	1.500	0.273	1.000	0.500	1.500	1.500	1.500	1.500	1.500
Business risk	3.000	0.545	2.000	1.000	3.000	3.000	3.000	3.000	3.000
Penetration rate	1.000	0.182	0.667	0.333	1.000	1.000	1.000	1.000	1.000
Electricity consumption	1.000	0.182	0.667	0.333	1.000	1.000	1.000	1.000	1.000
Opex	1.000	0.182	0.667	0.333	1.000	1.000	1.000	1.000	1.000
Capex	1.000	0.182	0.667	0.333	1.000	1.000	1.000	1.000	1.000
Electricity cost	1.000	0.182	0.667	0.333	1.000	1.000	1.000	1.000	1.000
Maximum negative cashflow	1.000	0.182	0.667	0.333	1.000	1.000	1.000	1.000	1.000

Table IV

Option performance matrix and ranking

	Electric drilling	Pneumatic drilling	Hydropower drilling	Aquapower drilling
Legislative	0.364	0.092	0.280	0.265
SHE	0.258	0.217	0.290	0.235
Implementation and management	0.205	0.415	0.208	0.173
Business risk	0.258	0.261	0.274	0.207
Penetration rate	0.158	0.180	0.374	0.287
Electricity consumption	0.339	0.093	0.280	0.288
Opex	0.253	0.274	0.289	0.184
Capex	0.290	0.278	0.278	0.153
Electricity cost	0.273	0.218	0.282	0.227
Maximum negative cashflow	0.257	0.246	0.283	0.215
VFM	0.261	0.234	0.282	0.223

In Table IV, the results of the survey of a variety of expert professionals ranging from production and operation managers, consultants, suppliers, and techno-financial analysts are utilized. The AHP is yet again applied to the four energy-delivery systems for each of the criteria in Table III. The final ranking by score indicates that open-circuit hydropower yields the best solution, based on the overall preference matrix (OPM) and relative value (RV). The value for money (VFM) indicates the relative merits of the energy delivery systems based on the requirements and performance across the criteria listing.

In Table IV, the hydropower drilling option is noted to be the preferred solution overall. The legislative aspects pertaining to noise levels and energy asset management, and the high electricity consumption of the compressed air delivery to the pneumatic drills are severe drawbacks of pneumatic energy delivery. However, pneumatic operations are well established, and implementation and management are habitual.

Other evaluation methods were applied to verify and justify the result with the AHP methodology.

Sensitivity analysis for energy delivery systems

The AHP uses the relevant values of identified criteria to minimize uncertainty and control risk when formulating a strategy. The sensitivity of these criteria is then analysed with a 10 per cent range for each criterion, and the effect on the LOM cost is calculated.

Different parameters are sensitive on the LOM cost for each of the energy sources and drilling options. The most significant changes on the LOM cost are shown in Figures 5–8. The most sensitive parameter for all energy delivery systems is the operating expenditure.

It is to be noted that for pneumatic drilling, the electricity cost is the primary cost component for the operation, and other operating costs are negligible. The least sensitive energy-delivery system across all criteria is hydropower, where SHE is the most sensitive criterion.

Decision tree for energy delivery systems

The decision tree is a strategic planning technique based on the sequential method of eliminating quantifiable criteria that

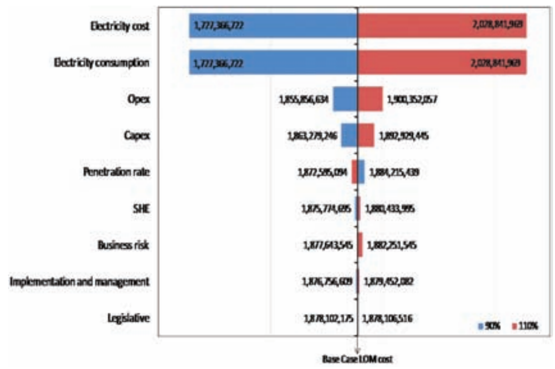

Figure 5—LOM cost scenarios with various sensitivities for electric energy system

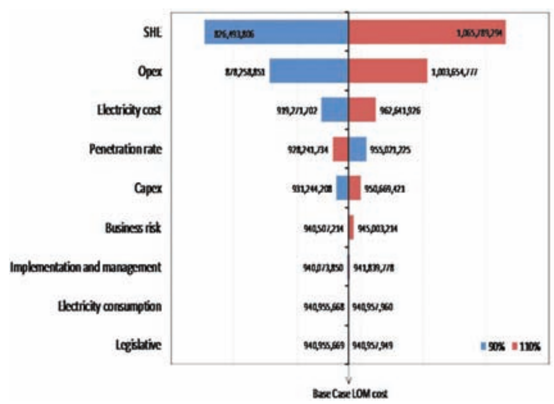

Figure 6—LOM cost scenarios with various sensitivities for pneumatic energy system

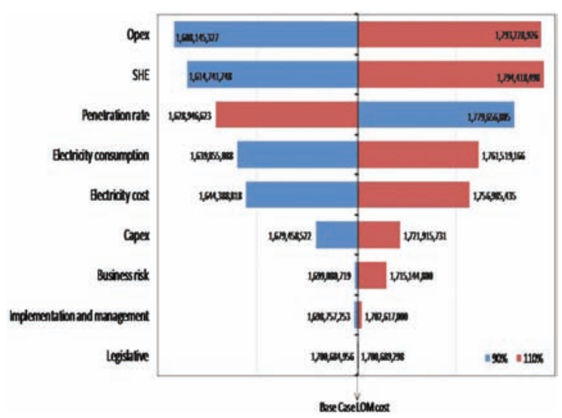

Figure 7—LOM cost scenarios with various sensitivities for hydropower energy system

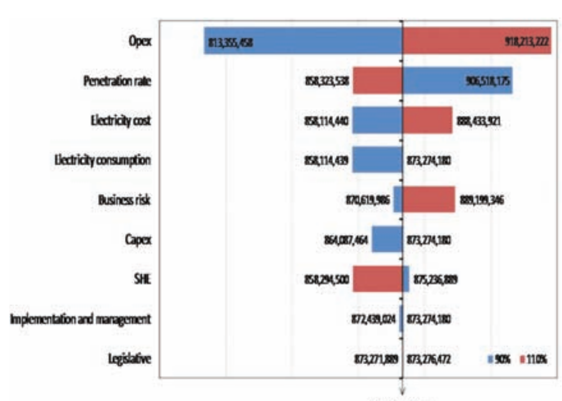

Figure 8—LOM cost scenarios with various sensitivities for aquapower energy system

do not offer the most advantageous solution. Uncertainties increase complexity on account of risk. The operating cost is selected as the criterion because it is a sensitive parameter across all energy-delivery systems, and affects criteria such as capital expenditure, SHE, business risk, and technology change, while it is affected by other criteria namely production performance, electricity consumption, and cost.

The application of the ratings from the survey results compiled for the energy delivery systems and the calculated LOM costs, are utilized to the current operating cost (base case), and the scenario whereby the operating cost is lowered by 5 per cent, for the same criteria ratings (Figure 9). The best expected monetary value (EMV) is achieved with open-circuit hydropower, because the probability of selection from the survey respondents is the highest and the capital expenditure is the lowest, followed closely by the electric counterpart. However, the best percentage improvement for the scenario is the electric energy delivery system (3.55 per cent), closely followed by hydropower (3.45 per cent). This confirms the result of the AHP ranking process and the observation from the sensitivity analysis.

Conclusions

Decision-making under complex conditions requires analyses beyond the static LOM cost and NPV methodology. LOM costs comparing energy delivery systems incorporate the implicit assumption that variables such capital and operating expenses are certain to occur as predicted in this deterministic valuation method.

The selection of an energy delivery system, based on criteria containing uncertainty and varying measures of control, depends greatly on quality of information available, and therefore, is important for multiple-criteria decision-making.

This study concludes that:

1. Pneumatic, electric, and hydropowered drilling methods are well established in the mining industry, and successfully drill holes in conventional mining
2. Aquapower drilling is new to the industry, but has been halted in research and development stage. Respondent to the survey were not all able to quantify criteria for this energy delivery and drilling system
3. Stope drilling comprises not only the drilling activity itself but includes the ancillary stope equipping, which must also be efficient and cost effective
4. Both the future electricity supply and the cost rate are risks to be considered. Energy delivery methods with lower power consumption are preferred. The electricity consumption of pneumatic drilling is substantially greater than for other drilling methods.
5. Pneumatic drilling requires early capital investment in compressors, infrastructure, and large-diameter shaft piping
6. By virtue of the complexity of mining, and the extensive life of mine, the business risk (on-going) is more important than the initial financial risk (capital)
7. Capital cost committed later in the life of mine spread over a longer period of time is preferred, as realized with hydropower. The lease agreement option for electric drilling is most advantageous, especially for a prolonged life of mine
8. Penetration rate, and thus the ability to complete drilling of a stope panel, if delays have occurred during the shift, is important, with hydropower delivering the highest consistent penetration rates
9. The application of the Analytical Hierarchy Process, corroborated by other decision-making and valuation methods, should be applied for multiple-criteria decision-making. Trade-off studies are of limited usefulness, because they are site-specific, and use only a few comparative parameters, based on a small data set.

Acknowledgements

The authors would like to acknowledge the contributions from Hilti, Hydro Power Equipment, Novatek, Peterstow, and Anglo Platinum operations for facilitating access to study data. Gratitude is extended to the operating team of Royal Bafokeng Platinum for their generous assistance during the course of this study.

References

ATAEI, M., JAMSHIDI, M., SERESHKI, F., and JALALI, S.M.E. Mining method selection by AHP approach. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 108, December 2008. pp. 741–749.

BARRICK SEBEDILO. Bankable feasibility study. Executive summary of the high level overview regarding the electric drilling option. Apr. 2008.

COYLE, G. The Analytical Hierarchy Process (AHP). *Open access material.* Pearson Education Ltd, Glasgow, 2004. pp. 1–11. http://www.booksites.net/download/coyle/student_files?AHP_Technique.pdf [Accessed 12 March 2012].

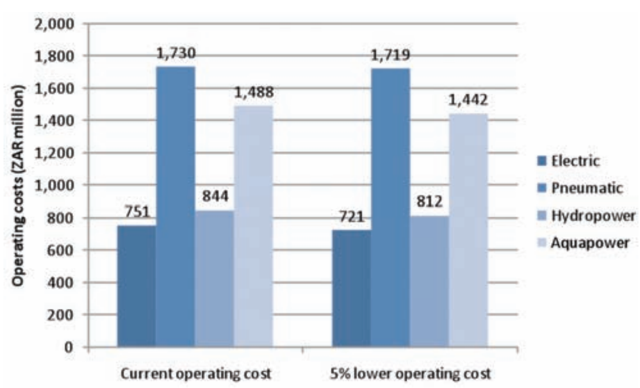

Figure 9—Improvement of the base case with 5% lower operating cost

D'SOUZA, F. Project analysis? Climb the decision tree. President and Fellows of Harvard College. September 2002. http://hbswk.hbs.edu/archive/3090.html [Accessed 21 March 2012].

ISA, M. (Business Day). New power shortages 'threat to mining'. *Business Day*, Johannesburg, 28 March 2012. p. 1.

KLUGE, P. and MALAN, D.F. The application of the analytical hierarchical process in complex mining engineering design problems. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 111, Dec. 2011. pp. 847–855.

MUSINGWINI, C. and MINNITT, R. Ranking the efficiency of selected platinum mining methods using the analytical hierarchy process (AHP). Third International Platinum Conference 'Platinum in Transformation', Rustenburg. *The Southern African Institute of Mining and Metallurgy, Johannesburg*, 2008. pp. 319 – 326.

TRIANTAPHYLLOU, E. AND MANN, S.H. Using the analytical hierarchy process for decision making in engineering applications: Some challenges. *International Journal of Industrial Engineering: Applications and Practice,* vol. 2, no. 1, 1995. pp. 35–44.

TWP. Comparison for in-stope drilling: hand-held pneumatic drilling, electric or hybrid drilling for Lonmin Saffy shaft pre-feasibility study. TWP, Johannesburg, February 2009.

TWP. Paardekraal 2 Shaft Project Feasibility Study. Electric vs. pneumatic drill trade-off study. TWP, Johannesburg, May 2005.

Appendix

Summary analytic hierarchical process

The pairwise combinations for the analytic hierarchical process (AHP) are established in a judgement matrix, called the overall preference matrix (OPM). The values of the pairwise criteria are assigned, according to the rating scale (see Table V), and are reciprocal (one-on-one mapping). Studies have suggested limiting the number of parameters (order of the matrix) to ten. By using the geometric mean, the nth root factor, and subsequently by normalizing, the relative value vector (RVV), also known as the eigenvector, is then applied to calculate the relative importance of the criteria. The sum of the RVV equate to unity. The eigen value, A_w, is then obtained by the multiplying the RVVs with the matrix. The division of the eigen value by the RVV yields the maximum eigen value λ_{max} for each parameter.

The next step is to determine the consistency of the judgement matrix. A consistency index, CI, is obtained by dividing the average eigen value per parameter by the number of parameters. The consistency ratio (CR) is then determined by dividing the Random Consistency Index, RCI, in Table VI.

If the CR is greater than the threshold ratio of 10%, the ratings in the OPM are untrustworthy, because they are too random, and the OPM should be re-populated. An alternative option in abstruse cases is to increase the scale of the rating. If one option consistently scores favourably with different scales, it is likely to be a convincing choice.

After the RVV is confirmed, each alternative also needs to be evaluated according the pairwise comparison for each criterion. At this stage, certain basic assumptions need to be made. The subsequent scores are derived by a diverse team of mining experts, including engineers, technology suppliers, financial analysts, operational managers, technical services and company executives, increasing the confidence in the ratings since they are subject to disparate, and in some instances, opposing views and priorities.

In instances where alternatives are too close, the exercise can be repeated by including additional criteria to increase the order of the matrix. However, the outcome should not affect the best alternative, but could potentially affect the ranking of the subsequent alternatives by increasing the differential between them. ◆

Table V

Scale of relative importance

Preference weights	Definition	Explanation
1–2	Equal importance	Two factors contribute equally to the objective.
3–4	Somewhat more important	Experience and judgement slightly favour one over the other.
5–6	Much more important	Experience and judgement strongly favour one over the other.
7–8	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9–10	Absolutely more important	The evidence favouring one over the other is of the highest possible validity.

Table VI

RCI values corresponding to the order of the matrix

No. of criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59