The application of the analytical hierarchical process in complex mining engineering design problems

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Synopsis

Mining engineers frequently encounter complex design problems for which the critical components of the design are difficult to quantify or compare. Teams of people typically work on these designs and human perceptions and judgments play a strong role. To assist with this process, the analytical hierarchical process (AHP) as a decisionmaking tool is described in this paper. Although the technique is used in many other disciplines, it is currently not widely used in mining engineering in South Africa. To use the AHP process, the problem should be treated as a hierarchy that defines the goal, the alternatives to reach it, and the criteria for evaluation of these alternatives. Pairwise comparisons are conducted on the criteria of the hierarchy to establish priorities. The value of the technique is that it is simple to test for consistency amongst the pairwise comparisons to ensure that the answer obtained is better than that provided by a random selection. To illustrate the technique, the use of a backfill support system in a platinum mining project was investigated. Ten design parameters, which will be impacted by the use of backfill, were identified and weighted according to their relative importance. The result of the AHP evaluation was that the use of a backfill support system should be preferred to a conventional support system at the mine.

Keywords

analytical hierarchical process, backfill, mine design

Introduction

Mining engineers are frequently faced with problems where a number of alternative designs need to be evaluated. Some of the typical problems faced by these engineers are deciding on the best option to access the orebody, location of the shafts, the choice of mining method (e.g. trackless or conventional mining), what the optimum layout should be, and what support to use. A large amount of data is typically collected to assist with this design process, but the evaluation and integration of the available information is difficult. In many cases, more than one solution to a particular problem is possible and choosing the 'best' option can be a daunting task. The final designs are frequently based solely on subjective decisions and previous experience of mining engineers. As this is not entirely satisfactory, methodologies to assist with this process will greatly increase the confidence that can be placed in the option eventually selected.

This paper describes the analytical hierarchical process (AHP) as a decisionmaking tool in mining engineering with specific reference to the use of backfill in a platinum project. Although the technique is used in many other disciplines, it is currently not widely used in mining engineering in South Africa. Some earlier references to the use of this technique in mining engineering can be found in papers published by Acaroglu[1] and Ataei *et al.*[2]. Musingwini and Minnitt[3] used AHP to rank conventional, mechanized and hybrid mining methods in the South African platinum mining industry. From this study, conventional mining was found to be the most efficient method. In a subsequent study, Musingwini[4] used AHP to optimize the level and raise spacing for a typical Bushveld Complex platinum mine. Optimizing level and raise spacing in inclined narrow reef mining has been a subject of controversy for decades and some form of multi-criteria decision analysis (MCDA) process is required. AHP was found to be the most appropriate technique for this study. By examining an orebody based on real geological data, the derived optimal range of vertical level spacing was 30 m to 50 m and the raise spacing was 180 m to 220 m.

As described by Bushan and Rai[5], AHP is particularly valuable when teams of people work on complex problems, especially those with high stakes, involving human perceptions and judgments, whose resolutions have long-term repercussions. It has significant benefits

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when critical components of the design are difficult to quantify or compare. These attributes are typical of large mining engineering projects. As a further illustration of the technique, a case study on the use of backfill as support in a new platinum project is described in this paper.

Overview of the analytical hierarchical process

AHP was developed by Saaty[6]. Forman and Gass[7] gave an interesting overview of the development of the technique. In the late 1960s Thomas Saaty was managing the research programme for the Arms Control and Disarmament Agency at the US State Department. In spite of working with some of the world's leading economists and game and utility theorists, Saaty was disappointed with the results and the inability of the team to come up with practical and sharp answers. He also noted some years later at the Wharton Business School that that there were communication difficulties between scientists and lawyers and that there was no systematic approach used for decisionmaking. Based on these observations, he was motivated to develop a simple method to help ordinary people make complex decisions and this resulted in the AHP. AHP methodology is taught in many universities and is used extensively by organizations such as the Central Intelligence Agency. Saaty has published 11 books on its use and application and the biennial International Symposium on AHP (ISAHP) is testament to its value and wide acceptance. According to Sun[8], nearly a hundred Chinese universities offer courses on this method, over 900 papers have been published on this topic in China, and there is a journal dedicated exclusively to AHP.

The procedure for using AHP is well described in many textbooks and websites on the internet. The process essentially entails the following components:

➤ Describe the problem as a hierarchy that contains the goal, the alternatives to reach it, and the criteria for evaluation of these alternatives
➤ Conduct pairwise comparisons of the elements of the hierarchy to establish priorities amongst these elements
➤ Synthesize the pairwise comparisons into a set of overall priorities for the hierarchy
➤ Test for consistency amongst the pairwise comparisons
➤ Make a decision based on the results.

The first step of AHP is to decompose the problem into a hierarchy of smaller problems or elements. Once the hierarchy is built, the various elements are systematically evaluated by comparing them, two at a time. It is acceptable that human judgments, and not just underlying information, can be used in performing the evaluations[9]. AHP converts this process to numerical values that can be processed and compared. By attaching weights to each element of the hierarchy, it allows for the comparison of elements in a rational way. To conclude the process, numerical priorities are calculated for the alternative decisions. Regarding the mathematical principles of the technique, the essence is to construct a matrix expressing the relative values of a set of attributes. The technique is best understood by working through a practical example, and the next sections describe the example of choosing between conventional or backfill support for a platinum project. It should be noted that a team of experts should typically be used to obtain the weighting of

each criterion. As the focus of this paper was mostly to illustrate the AHP technique, the weightings are based on the judgments made by one individual. The conclusion that backfill is preferred to conventional support should therefore be considered in this light.

Choosing between backfill and conventional support

The principal author was involved in a study for a new platinum project, and the mining engineering team was faced with the complex decision to choose between backfill and the more conventional panel support as used in the majority of platinum mines. This is an important decision as the choice of support will affect the mine design process on many levels, and AHP was well suited to assist with this problem. With the exception of Northam Platinum Mine (as shown in Figure 1), backfill is currently not used in any of the platinum mines in South Africa. It was the intention of this study to ascertain whether the integration of a backfill support system into the mine design process from an early design stage onwards can increase the benefits derived from this support type. This is of particular interest in cases where the middling between the UG2 and Merensky reefs is small and the planned multi-reef extraction will create high-stress zones. The rock engineering aspects of backfill have been extensively researched in the past, and the reader is referred to the many references available on this topic[10,11,12]. A further key issue related to backfill is the improved ventilation in mines using this support type. Examples of these studies can be found in Bluhm and Biffi[13], Spearing and Wilson[14], and Pothas[15]. Although many papers on the rock engineering and ventilation aspects of backfill can be found, little is available on the impact of backfill on aspects such as overall mine planning, scheduling, and layout. This makes the decision process during the mine planning phase difficult and highlights the value of a tool such as AHP.

Building the AHP hierarchy

The objective of the study was to choose between backfill and conventional support, and this forms the 'goal' of the AHP hierarchy as shown below. Regarding criteria, it was

Figure 1—An example of the use of backfill in a platinum mine

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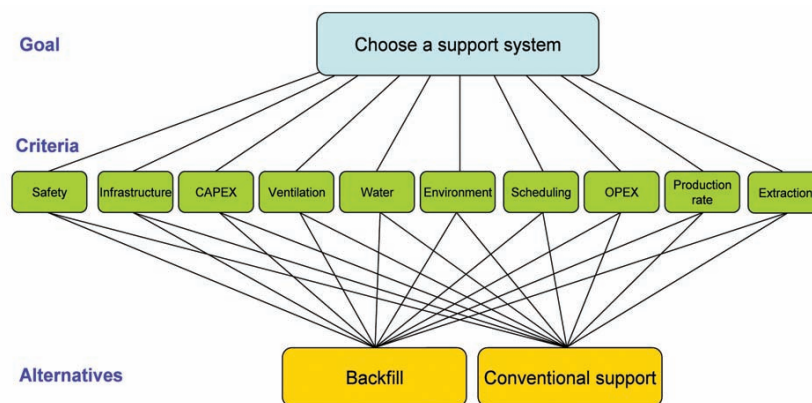

Figure 2—Components of the AHP hierarchy

Table I

Weightings of the criteria by pairwise comparison

	Safety	OPEX	CAPEX	Ventilation	Water	Mine plan	Enviroment	Infrastructure	Production	Extraction
Safety	1.000	3.000	5.000	4.000	9.000	4.000	3.000	7.000	4.000	7.000
OPEX	0.333	1.000	3.000	1.000	6.000	1.000	4.000	5.000	3.000	5.000
CAPEX	0.200	0.333	1.000	3.000	3.000	0.500	3.000	1.000	1.000	3.000
Ventilation	0.250	1.000	1.000	1.000	3.000	0.333	1.000	0.333	1.000	3.000
Water	0.111	0.167	0.333	0.333	1.000	0.167	0.333	0.200	0.333	1.000
Mine plan	0.250	1.000	2.000	3.000	6.000	1.000	3.000	2.000	0.500	4.000
Environment	0.333	0.250	0.333	1.000	3.000	0.333	1.000	0.333	1.000	3.000
Infrastructure	0.143	0.200	1.000	3.000	5.000	0.500	3.000	1.000	1.000	5.000
Production	0.250	0.333	1.000	1.000	3.000	2.000	1.000	1.000	1.000	3.000
Extraction	0.143	0.200	0.333	0.333	1.000	0.250	0.333	0.200	0.333	1.000

determined that a backfill support system will have an influence on ten distinctly different parameters[16]. These parameters are listed below:

1. Safety and other rock engineering considerations
2. Equipment and infrastructure
3. Capital expenditure
4. Ventilation
5. Mine water flow
6. Environmental considerations
7. Mine planning and sequencing
8. Operating expenditure
9. Production rate
10. Reserve extraction

Based on this information, the AHP hierarchy as shown in Figure 2 could be built.

Pairwise comparisons of the criteria and computation of the relative value vector

The second step is to conduct a pairwise comparison of all the criteria based on the information available (see Coyle[17]). A typical question posed will be: what is the relative importance of safety as opposed to capital expenditure? The comparisons are conducted using the preference weights as provided by Von Waveren[18]. These weights are illustrated in Figure 3. To illustrate the use of these ratings, if criterion A is 'extremely preferred' to criterion B, it is rated 9. Criterion B is therefore not preferred at all compared to criterion A and is rated 1/9. This value of 1/9 must be used to describe the importance of

B relative to A as the technique works only if so-called positive reciprocal matrices can be created (see the section below).

The results of the relative weighting analysis performed on the decision criteria for the backfill problem are summarized in Table I. The table shows, for instance, that it is believed that safety scores a 5 (suggesting that it is 'strongly preferred') when compared to capital expenditure (CAPEX).

Figure 3—Ratings used for the pairwise comparison (after Von Waveren[18])

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To generalize the technique, mathematically, it can be described that we compare n criteria $C_1 \ldots C_n$ where n = 10 for the specific case of the backfill problem. The relative weight of C_i compared to C_j is denoted by a_{ij}. This forms a square matrix A as shown in Table I:

$$A = [a_{ij}] \qquad [1]$$

The constraints imposed on matrix A are such that $a_{ij} = 1$ if $i = j$ and $a_{ij} = \frac{1}{a_{ij}}$ for $i \neq j$. This forms a reciprocal matrix. For this matrix, an eigenvector ω of order n can be found so that:

$$A\omega = \lambda\omega \qquad [2]$$

where λ is an eigenvalue. For a matrix in which the weights are consistent, it follows that $\lambda = n$. The weights are consistent if $a_{ik} = a_{ij}a_{jk}$ for all i, j and k. As there is human judgment involved in the setting up the matrix in Table I, the weights may not be consistent, and in this case:

$$A\omega = \lambda_{max}\omega \qquad [3]$$

and $\lambda_{max} \geq n$. In Table II, an approximation of the eigenvector is obtained by multiplying together the entries in each row and then taking the nth root of that product. The nth roots are summed and this value is used to normalize the eigenvector. $A\omega$ can subsequently be calculated by the necessary matrix multiplication. Ten estimates of λ_{max} can be obtained by dividing each component of $A\omega$ by the corresponding eigenvector. The average of these values, 11.037, is the estimate for λ_{max}.

This eigenvector ω gives a good reflection of the relative values of the different criteria that are used to compare the support options. It is therefore also known as the relative value vector (RVV). It gives an indication that, for instance, safety is rated far higher than water or ventilation.

Consistency index and consistency ratio

In order to test whether the data in the matrix show consistency, the consistency ratio (CR) can be calculated. Saaty[6] suggested that this check is an essential part of AHP as a matrix may approach randomness if no consistency is applied in the allocation of weightings. This may lead to results that are as valueless as the throwing of a dice. Imagine a scenario where OPEX is given a weighting of 9 when compared to CAPEX (suggesting that it to be extremely preferred), then CAPEX is given a weighting of 9 when compared to water and finally water is given a weighting of 9 when compared to OPEX. The result of this weighting allocation would be meaningless, as it would not be clear which criteria should be preferred over the others. In order to check for these inconsistencies and to verify whether the results are meaningful, the consistency index (CI) and CR should be calculated.

A good initial sanity check is to ensure that the average value of λ_{max} is larger than n (or 10 in this case). The CI is given by:

$$CI = \frac{(\lambda_{max} - n)}{n - 1} \qquad [4]$$

The average value of λ_{max} is 11.037 from Table II, and the value of CI is therefore 0.115

Table III illustrates Saaty's indicative table for CR calculation. The top row shows the order of the matrix (10 in the example described above), while the bottom number gives a CI value that would indicate randomness in a matrix. The CR is computed by dividing the CI from the matrix (0.115) by the number 1.49 from Table III: CR = 0.115/1.49 = 0.077.

Table II

Calculation of the eigenvector

	Safety	OPEX	CAPEX	Ventilation	Water	Mine plan	Environment	Infrastructure	Production	Extraction	nth root of product	Eigenvector$_\omega$	$A\omega$	λ_{max}
Safety	1.000	3.000	5.000	4.000	9.000	4.000	3.000	7.000	4.000	7.000	4.077	0.307	3.395	11.051
OPEX	0.333	1.000	3.000	1.000	6.000	1.000	4.000	5.000	3.000	5.000	2.116	0.159	1.832	11.490
CAPEX	0.200	0.333	1.000	3.000	3.000	0.500	3.000	1.000	1.000	3.000	1.104	0.083	0.921	11.068
Ventilation	0.250	1.000	1.000	1.000	3.000	0.333	1.000	0.333	1.000	3.000	0.871	0.066	0.730	11.125
Water	0.111	0.167	0.333	0.333	1.000	0.167	0.333	0.200	0.333	1.000	0.308	0.023	0.239	10.325
Mine plan	0.250	1.000	2.000	3.000	6.000	1.000	3.000	2.000	0.500	4.000	1.597	0.120	1.326	11.022
Environment	0.333	0.250	0.333	1.000	3.000	0.333	1.000	0.333	1.000	3.000	0.699	0.053	0.580	11.020
Infrastructure	0.143	0.200	1.000	3.000	5.000	0.500	3.000	1.000	1.000	5.000	1.124	0.085	0.979	11.562
Production	0.250	0.333	1.000	1.000	3.000	2.000	1.000	1.000	1.000	3.000	1.041	0.078	0.880	11.221
Extraction	0.143	0.200	0.333	0.333	1.000	0.250	0.333	0.200	0.333	1.000	0.335	0.025	0.265	10.489
											13.272	1.000		11.037

Table III

Values to test for randomness (Saaty[6])

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

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A CR value that is larger than 0.1 indicates that the data should be treated with caution, as it indicates an approach towards randomness. If this is encountered, the ratings of the criteria need to be re-allocated. On the other hand, a value of zero shows perfect consistency, while a value below 0.1 indicates that the matrix is consistent enough to be used with confidence. The CR for this matrix is in the range where it can be used with confidence.

Setting up the option performance matrix

After the RVV is calculated, each of the possible support designs (in this case, backfill support and conventional support) now also need to be evaluated according to the pairwise comparison method for each criterion. To assist with this process, the ten evaluation criteria will now be discussed individually with regards to the impact of the two support systems. This discussion is specific to the feasibility study for a new platinum mine.

Each discussion is concluded with a score for that criterion. For the purposes of this comparison, it is assumed that the backfill and conventional support is placed correctly and timeously. The scores are typically derived through discussion by a team of experts. In this illustrative example, however, the scores were taken from Kluge[16], where they were chosen by one individual. Therefore, the absolute value of the criteria ratings are indicative only and can be altered to reflect additional information or assumptions.

Safety

The dangers arising from rockfall and rockburst related incidents in the narrow tabular mining industry are well known and documented[19]. This was recently confirmed by Handley[20] who stated that 'rock falls and rock bursts continue to dominate the fatality statistics in the underground mines, especially gold and platinum mines, where the combined rock-related incidents are the largest single contributor to injuries.' For the particular platinum project, the safety risk is exacerbated by the mining depth, which extends to 1400 m, and by the interaction of multi-reef mining horizons. Based on expected poor ground conditions, especially in the mining environment with close inter-reef middling distance, the placement of backfill was considered as an important component to improve ground conditions.

The success of backfill in achieving these objectives has been confirmed in the literature and in numerous case studies. The placement of fill 'is providing significant benefits from a rock mechanics point of view', particularly in areas where discipline is maintained in keeping the fill-to-face distance low[21]. The use of backfill in multi-reef environments with closely spaced reefs has been specifically addressed by Spearing and Wilson[14], who stated that 'backfill can play a highly significant role by allowing the middling to settle and 'float' on the backfill'. They further emphasized that the psychological impact of having a hard backfilled wall behind the worker has a positive bearing on worker morale and therefore productivity. Workers are also contented by better ventilation control (discussed in more detail below). These factors will contribute to a safer environment. The regional support benefits derived from backfill placement at Northam Platinum Mine arediscussed by Roberts *et al*.[22]. They illustrated that the unravelling of the hangingwall is avoided with the placement of fill in the Merensky stopes.

The additional water that a backfill system adds to the mining process increases the potential risk of mud rushes in orepasses. However, in this particular project, fissure water inflows from the rock are comparatively large and the additional mud rush risk resulting from the placement of backfill is therefore relatively low.

Based on the confirmation of the advantages of backfill as described in the literature, it is expected that the ground conditions and the safety conditions will be much improved with the use of backfill support in the planned platinum project. It is expected that the frequency and severity of rockfalls will be reduced. As these are the major contributors to fatalities in the narrow tabular mining environment, a major increase in safety and probably a reduction in fatalities will result from the use of backfill. The only safety disadvantage of backfill is a minor increase to the risk of mud rushes. This assumed increase in safety results in the backfill support scoring a rating of 8 above the conventional support in the pairwise comparison method, which places it between 'very strongly preferred' and 'extremely preferred'.

Equipment and Infrastructure requirements

The use of backfill has a significant effect on the required infrastructure and this has been the Achilles heel of backfill support systems for many years. For the planned platinum project, the items required are the backfill plant, the backfill shaft, and forty backfill pipe ranges which will be used to pump the fill from the plant to all operational raise lines. The use of a committed backfill shaft for the pipe ranges was preferred to the more conventional use of a bratticed portion of an existing shaft owing to the following reasons:

➤ The bratticing of the ventilation shaft would have increased the required shaft diameter. This would have increased the costs and slowed the expected rate of shaft sinking

➤ The installation of the brattice would have slowed down the entire shaft commissioning and production process by at least six months, a delay that would have had a great negative impact on the valuation of the project

➤ The bratticed-off portion in the ventilation shaft would have provided a very confined space in which to maintain or replace potentially damaged backfill pipe ranges

➤ If the pipe ranges were installed in the main shaft, range blockage, failure or maintenance would lead to shaft downtime and a resultant loss of production[23]

➤ The service cage in the shaft will provide an additional safety egress out of the mine and the replacement or maintenance of pipes will be much simplified. Additional flexibility for mine ventilation flow, especially downcast, is also provided through this shaft.

Despite some of the advantages brought about by the backfill infrastructure, the excavation of an additional shaft, the placement of over 100 km of pipes, and the construction of an additional plant brings with it inherent space constraints on surface, project risks (schedule and quality), and costs. Based on these reasons, conventional support receives a score of 7 for infrastructure, which is ranked 'very strongly preferred'.

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Capital expenditure

The backfill system, and in particular the infrastructure surrounding the plant and the pipe system, brings with it an increase in project capital expenditure. Estimates indicate that this is equivalent to 9% of the total project capital expenditure. This significant increase in project capital requirement must be compared against the potential reduction in fatalities that can result from the backfill system implementation.

Handley[20] estimated that the direct cost of fatality in the gold mining industry is equivalent to approximately R1.1 million (this will be far more in 2011). He also stated that at an operating margin of 33%, R3.3 million additional revenue has to be generated to cover the cost of one fatality. Indirect costs resulting from a fatality, such as lost production due to shaft closure and reduction in worker morale, were excluded from the analysis and the true cost of a fatality in the mining industry will be far higher. The true cost benefit of the use of a backfill system can unfortunately not be quantified, as the number of fatalities prevented by the system will not be known.

The large increase in project capital expenditure resulting from the backfill system results in conventional support being allocated a score of 8, which is located on the rating chart between 'very strongly preferred' and 'extremely preferred'.

Ventilation

Owing to the high thermal gradient encountered in the Bushveld Complex, refrigeration will be required at mining depths below 600 m. The maximum depth of 1400 m implies that significant refrigeration is required for the successful extraction of the rock at that depth. Furthermore, the long strike distances will require a strict control of air flow through development ends and old workings. To assist with this control, the use of a backfill support system on the primary reef can provide considerable advantages to the ventilation design and layout. Bluhm and Biffi[13] summarized the ventilation-related advantages of a backfill system as follows:

➤ *Reduced heat flow from surrounding rocks*—the backfill provides an insulating buffer against the heat radiating from the host rock. Backfill, nevertheless, can heat up in time and backfill therefore 'does not obviate the need for in stope cooling'. However, the placement of cooled backfill can be considered under certain circumstances. Most importantly, even with non-cooled backfill, it has been observed in practice that a reduction in stope heat load of up to 50% can be achieved in certain stopes. Overall, if fill is employed mine-wide, a total reduction in ventilation requirement of 30% can be expected[24]. For the platinum project, this implies that the refrigeration requirements and associated costs will be reduced by 15%

➤ *Assisting in the control of air flow in the stope*—the backfilling of mined out areas greatly reduces the occurrence of leakage in the stopes, as the air flow is physically channeled by the solid fill into the desired direction. If a good mining and filling cycle is maintained, the face-to-fill distance will remain low. As a result, 'Air flow velocities are double what they are in conventional mining'[24]. It is well known that better air flow and a cooler face increase worker morale.

Given the advantages that a backfill support system has for ventilation design and control, it was decided to prefer the backfill support by a score of 9 compared to conventional support. This is equivalent to a rating of 'extremely preferred'.

Mine water flow

As the pumped backfill can easily harden in the pipe ranges, it is essential that the pipes are always flushed with water within 30 minutes of the deposition of the fill material. The flushing requirements are approximately 30 m³ of water per range, which is equivalent to 1000 m³ or 1 Mℓ of water per day for pipe flushing. In addition, approximately 30% of the volume of the placed hydraulic backfill will bleed out as water, and some additional water is flushed though the backfill ranges before use to determine whether the pipe used leads to the correct stope. It is estimated that water from these two sources will also be approximately 1000 m³/day.The resultant 2 Ml of water added to the mine water system per day can be compared to a typical non-backfill daily mine water flow of 42.3 mℓ. Despite the fact that the flush and bleed water will put significant demands on the settling facilities, it is assumed that the existing settling and pumping capacity is sufficient to accommodate this additional water. Backfill water will therefore impact only on the electricity consumption of the main pumps. As the pumping costs are less than 5% of total operating cost, the total impact on operating cost will be an increase of approximately 0.2%. The placement of backfill leads to slight improvement in mine water control as water reports more readily to the drain holes and/or pump stations[14].

The minimal increase in pumping costs is mostly offset by the improvement in mine water control. Based on the pairwise comparison between conventional support and backfill, the conventional support was allocated a score of 6, which is equivalent to a rating of between 'strongly preferred' and 'very strongly preferred'.

Environmental

It is one of the requirements of the Department of Mineral Resources (DMR) and the Department of Environmental Affairs (DEA) during the Environmental Management Plan (EMP) application process that methods of reducing the surface impact of a mining operation are stated. The use of backfill underground will reduce the environmental problem of tailings on surface[25]. As all the primary reef is backfilled with plant tailings in this project, approximately 40 Mt of plant tailings (50% of the mined material) will be returned underground during the life of mine. The chemically reactive plant tailings are rendered inert when combined with the cementitious binder material underground and the underground backfill material will no longer constitute an environmental hazard. An additional benefit of backfilling is that the tailings dams on surface, which require significant and long-term environmental management, are reduced in size. The removal of 40 Mt from the surface tailings dams will reduce the surface footprint of the dams by 6.5 ha (at an average dam height of 20 m).

Based on the clear environmental benefits brought about by the use of backfill, it was decided to allocate backfill a score of 7 ('very strongly preferred') over the use of conventional support.

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Mine scheduling and planning

The Merensky Reef is more profitable than the UG2 Reef. Not only is the grade per ton of rock approximately 25–30% higher in the Merensky Reef, but the higher base metal content adds additional by-products to the mix. The plant recoveries achieved for Merensky Reef in the concentrator are also better. The general approach of mine planning in a platinum mine is therefore to mine the Merensky Reef as early as possible and exploit the UG2 Reef later.

This objective is easily achieved in mining areas with a large middling between the two reefs. In these cases the Merensky Reef is extracted as the primary reef on every half level until the maximum strike distance is reached. For the new project in areas where the middling is large, the mine design has provided for long crosscuts that access both reef horizons simultaneously. This reduces the amount of development required to open up either of the two orebodies. These same crosscuts are then used to extract the UG2 Reef on a retreat basis, back towards the shaft infrastructure.

A mine scheduling problem occurs in areas where the middling is very small and the extraction of the Merensky Reef leaves zones of high stress concentration on the UG2 Reef horizon. If the Merensky Reef is mined first in this area, possible large-scale sterilization of the UG2 Reef will occur. This problem is reduced with the primary extraction of the UG2 Reef and subsequent placement of backfill, which leads to a de-stressed mining environment for the secondary mining of the Merensky Reef.

As the primary extraction of UG2 Reef is less profitable than the mining of Merensky Reef, a co-extraction sequence was developed. It is planned that the UG2 Reef will be mined two raise lines ahead of the Merensky Reef. This will allow sufficient time for underground exploration and identification of the Merensky Reef to occur from the UG2 stopes. In areas, where the Pothole Merensky Reef (PHR) is geologically consistent, the secondary raise is immediately developed and mining commenced. The rock handling is performed with the aid of orepasses feeding into the mined UG2 raise.

Despite the challenges posed to half level production, output control, and ventilation by this co-extraction mining method, the ability to mine the Merensky Reef in these areas as soon as possible adds significant value to the overall project. Co-extraction is made possible only by the use of backfill, which minimizes the effect of Merensky remnants on the middling and underlying UG2 Reef excavations.

The enhancement in profitability brought about by co-extraction, which is made possible by a backfill system, implies that the backfill support system is 'very strongly preferred' to the conventional support system and it scores 7 on the pairwise comparison scale.

Operating cost

The increase in operating cost is often touted as the single biggest concern around the use of a backfill support system. This is not surprising, given the fact that most financial mine evaluation models show a far higher sensitivity to operating costs than to capital expenditure. The cost of backfilling is estimated to be between 10–20% of total underground costs, with the binder cost alone constituting 75% of total backfill material costs[25].

The feasibility study conducted in 2007 for this particular platinum project included a component in which the operating costs were derived from first principles. This was benchmarked against other operations in the mining group. It was estimated that the use of backfill in the primary reef horizon would lead to an increase of only 7.5% in operating costs. Since the completion of the feasibility study, the cost of binder has increased dramatically and the advent of ISA milling at the adjacent plant has led to an increased requirement for binder material in the backfill slurry. It is therefore now estimated that backfill will increase the shaft head mining costs by 10%, which is in line with the lower range estimate in the literature. The cost contribution of 75% from binder material also proves to be accurate. If it is assumed that the support costs for timber and support packs to be used in the stopes would have added 2% to the operating costs, the actual cost increase resulting from the use of backfill is 8%.

Given this significant increase in operating cost, conventional support is allocated a score of 7, which is indicative of the category 'very strongly preferred' in the pairwise comparison table.

Production rate

Experience in the gold mining industry has shown that the operation of a backfill system has tended to reduce production rate on the levels where it is being used. These reduced production rates are due to a number of operational factors such as interference of backfill operations with face cleaning and material hauling operations, but a detailed discussion of these is outside the scope of this paper.

If the decision is made to use a backfill system in the early design phase of a new mining complex, then it can be assumed that many of these operational issues can be overcome, as half levels, haulages, raises, and panels are all designed and excavated specifically with backfill infrastructure in mind. Furthermore, as the production teams will take part in an operation that uses a backfill system from the outset, efficient mining cycles, which include cleaning and filling on wider panels, can be expected to be optimized at this new operation from the beginning. A time and motion simulation including backfill, men, material, and rock for this new planned operation was conducted during the feasibility study. It was found that the production rate would not be materially impacted by the backfill operation.

Despite the fact that this incorporation of backfill into mine design and planning from the outset is expected to negate the possible reduction in production rate, current operating history at backfill operations suggests otherwise. For this reason a conventional support system was chosen to be 'strongly preferred', which is equivalent to a score of 5 on the AHP criteria.

Reserve extraction

The use of a backfill support system eliminates the requirement for crush pillars to be left between the mining panels and some regional support pillars. This increases the reef extraction in the stopes, which leads to reduced development costs per ton of reef mined. Increasing

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extraction is fully in line with the DMR's mandate that mines are to maximize ore body extraction to the best of their ability in order to sustainably mine South Africa's mineral wealth.

An estimate in the literature stipulated that percentage extraction in narrow tabular gold mines is increased from approximately 85% to 90% with the placement of backfill[11]. For this platinum project using conventional support, the panel length between crush pillar lines would not have exceeded 20 m. The extraction on the primary reef would have been 12% less compared to a layout using backfill. This is equivalent to an overall increase of project reserves of approximately 5%.

The addition of mineable reserve extends the life of the operation, adding to project sustainability and slightly increasing project NPV. For this reason the backfill support system was scored an 8, which is situated between 'very strongly preferred' and 'extremely preferred' on the AHP scale.

Setting up the option performance matrix

The scores allocated for each of the evaluation criteria are summarized in Table IV. It can be seen that for five of the ten comparison criteria, the backfill support design was preferred, while the conventional support was preferred in the other five criteria. In order to determine the actual result of this evaluation, however, the weightings as well as the actual level of preference as determined by the pairwise comparison will need to be calculated. This is illustrated below.

Based on the pairwise scores given in Table IV, the eigenvector for each of the criteria can be calculated. Table V illustrates this for the different criteria. Note that the CR values of these matrices are equal to 0, as these 2 x 2 matrices are perfectly consistent.

The calculated eigenvectors are summarized in the option performance matrix in Table IV.

The eigenvectors in this matrix were multiplied with the relative value vector (RVV) to determine the final ratings for comparison. The result is the score for the two support systems in Table VII.

These scores indicate that for the platinum mining project under review, the backfill support system is the preferred support system. It should be emphasised again, however, that

Table IV

Summary of pairwise ratings

	Preferred design	Pairwise score
Safety	Backfill support	8
OPEX	Conventional support	5
CAPEX	Conventional support	8
Ventilation	Backfill support	9
Water	Conventional support	6
Mine plan	Backfill support	7
Environment	Backfill support	7
Infrastructure	Conventional support	7
Production	Conventional support	5
Extraction	Backfill support	8

Table V

Pairwise ratings for the different criteria

	Backfill	Conventional support	nth root of product	Eigenvector
Safety				
Backfill	1.000	8.000	2.828	0.889
Conventional support	0.125	1.000	0.354	0.111
			3.182	
OPEX				
Backfill	1.000	0.143	0.378	0.125
Conventional support	7.000	1.000	2.646	0.875
			3.024	
CAPEX				
Backfill	1.000	0.125	0.354	0.111
Conventional support	8.000	1.000	2.828	0.889
			3.182	
Ventilation				
Backfill	1.000	9.000	3.000	0.900
Conventional support	0.111	1.000	0.333	0.100
			3.333	
Water				
Backfill	1.000	0.167	0.408	0.143
Conventional support	6.000	1.000	2.449	0.857
			2.858	
Mine planning				
Backfill	1.000	7.000	2.646	0.875
Conventional support	0.143	1.000	0.378	0.125
			3.024	
Environment				
Backfill	1.000	7.000	2.646	0.875
Conventional support	0.143	1.000	0.378	0.125
			3.024	
Infrastructure				
Backfill	1.000	0.143	0.378	0.125
Conventional support	7.000	1.000	2.646	0.875
			3.024	
Production				
Backfill	1.000	0.200	0.447	0.167
Conventional support	5.000	1.000	2.236	0.833
			2.683	
Extraction				
Backfill	1.000	8.000	2.828	0.889
Conventional support	0.125	1.000	0.354	0.111
			3.182	

Table VI

Option performance matrix (OPM)

	Safety	OPEX	CAPEX	Ventilation	Water	Mine plan	Environment	Infrastructure	Production	Extraction
Backfill	0.889	0.125	0.111	0.900	0.143	0.875	0.875	0.125	0.167	0.889
Conventional support	0.111	0.875	0.889	0.100	0.857	0.125	0.125	0.875	0.833	0.111

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Table VII	
Final result of the AHP process	
	OPM*RVV
Backfill support	0.56
Conventional support	0.44

the weighting for the individual parameters should typically be derived through discussion by a team of experts. In this illustrative example, the scores were chosen by one individual. Therefore, the absolute values of the criteria ratings (and the final result of backfill being preferred) are indicative only and should be altered for specific projects to reflect additional information or assumptions.

Conclusions

Mining engineers frequently encounter complex design problems for which the critical components of the design are difficult to quantify or compare. Teams of people typically work on these designs and human perceptions and judgments play a strong role. To assist with this process, the analytical hierarchical process (AHP) as a decisionmaking tool is described in this paper. Although the technique is used in many other disciplines, it is currently not widely used in mining engineering in South Africa. To use the AHP process, the problem should be treated as a hierarchy that defines the goal, the alternatives to reach it, and the criteria for evaluation of these alternatives. Pairwise comparisons are conducted on the criteria of the hierarchy to establish priorities.

The value of the technique is that it is simple to test for consistency amongst the pairwise comparisons to ensure that the answer obtained is better than that provided by a random selection. To illustrate the technique, the use of a backfill support system in a platinum mining project was investigated. Ten design parameters, which will be impacted by the use of backfill, were identified and weighted according to their relative importance. The result of the AHP evaluation is that the use of a backfill support system should be preferred to a conventional support system at the mine. It should be noted that a team of experts should typically be used to obtain the weighting of each criterion. As the focus of this paper was mostly to illustrate the AHP technique, the weightings are based on the judgments made by one individual. The conclusion that backfill is preferred to conventional support should therefore be considered in this light.

Acknowledgements

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