

Technical operating flexibility in the analysis of mine layouts and schedules

C. MUSINGWINI*, R.C.A. MINNITT*, and M. WOODHALL†

*School of Mining Engineering, University of Witwatersrand, Johannesburg

†GijimaAst, Johannesburg

An often overlooked factor in the analysis of mine layouts and schedules is technical operating flexibility, mainly due to its nebulous nature. If one glosses over technical operating flexibility the resultant mine layouts and schedules tend to be sub-optimal. The need to incorporate technical operating flexibility into the analysis and comparison of mine layouts and schedules is increasing in importance. This paper illustrates the nature of technical operating flexibility, reviews previous work on valuing operating flexibility and proposes how technical operating flexibility can be quantified for tabular reef mines by using a platinum reef deposit as a case study. Once technical operating flexibility is quantified it becomes possible to explore its incorporation into the analysis of mine layouts and schedules and subsequent optimization processes. The work described in this paper is part of a current PhD study at the University of the Witwatersrand.

Keywords: mine plans, layouts, schedules, technical operating flexibility, ore availability.

Introduction

Mining layouts and schedules or, alternatively, mine plans have often been analysed, compared and optimized on the basis of their performance against an array of directly measurable and quantifiable parameters, such as cost per tonne and net present value (NPV). Examples of typical analyses done in recent years are listed in Table I. Some of the analyses take no account of flexibility, while some that refer to flexibility in evaluating mine plans do not consider it in the final analysis. As a consequence, most previous studies have underplayed the importance of flexibility in mine plans.

Woodhall (2002) was among the first to quantify the impact and influence of flexibility in mining operations in a study of the mining life cycle and its importance in mineral resource management in deep level South African gold mines. In a later study on planning for flexibility in underground mine production systems, Kazakidis and Scoble (2003) noted that operating flexibility and strategic adaptability are now increasingly being recognized as critical to long-term corporate success. The importance of flexibility in mine plans was also highlighted at the First International Seminar on Strategic versus Tactical Approaches in Mining held in 2005 in South Africa, where eight of the twenty-four papers presented made reference to and recognized the importance of flexibility in contemporary mine plans. Elkington, Barrett and Elkington (2006) noted that uncertainty is intrinsic to all mining projects and should be planned for by providing operating and strategic flexibility. The need for flexibility in any mining plan is the recognition that the plan should accommodate financial, technical and social changes that have become a reality in the dynamic modern operating business environment. Mining projects with little or no flexibility are unable to change and survive when economic or technical conditions turn sour and have little chance of benefiting from sustained improvements in mineral prices.

Thus flexibility, the planned capacity to accommodate change and an in-built ability to take tactical advantage of situations that arise in a mining environment, introduces an element of strength that is here referred to as robustness.

This paper discusses the definition and importance of technical operating flexibility and proposes a metric for measuring the flexibility. The concept is then applied to analysing flexibility in a case study of a tabular platinum reef deposit on the Bushveld Complex in South Africa. The work reported in this paper is part of an ongoing PhD research study at the University of the Witwatersrand.

Operating flexibility in layouts and schedules

A mine layout is a graphical illustration of the relative location of primary access development workings, secondary access development workings, production areas and any other service excavations such as pump chambers in an underground mine. A mine schedule shows the sequential timing of the excavation of each of the mine workings and the sequence of ore reserve extraction to be followed. Scheduling may also be graphically represented in the form of a Gantt chart generated from software such as Earthworks Production Scheduler (EPS®). A mine plan is the integration of a layout and a schedule. Mine plans may be strategic plans, whose scope encompasses the medium-to long-term life-of-mine planning or tactical plans that typically address immediate to short-term mine planning.

Definition of operating flexibility

The *New Collins Dictionary and Thesaurus* (1989, p. 382) defines flexibility as 'the ability to adapt' or 'adaptability, adjustability, elasticity, responsiveness'. This definition is fundamental in understanding operational flexibility in mining. Mines operate in a business environment characterized by several uncertainties including fluctuating exchange rates, cyclical mineral prices, rising wage costs,

Table I
Examples of studies on evaluation of layouts and schedules

Study	Objective	Evaluation parameters used	Reference to flexibility
Vieira (2004)	Analysis and comparison of four different mining methods to mine ultra-deep tabular gold reefs. The four methods considered are LSP, SGM, SDD and CSDP.	Economics (payback, NPV, IRR); ventilation (incl. cooling & refrigeration); rock engineering stability; logistics; LOM.	SGM has great flexibility for negotiating geological features and allows for selective mining. LSP not flexible for negotiating geological features and managing grade variability. Dip pillar mining systems offer a higher degree of operational flexibility.
Harrison (2004)	Comparison of XLP trackless mining, LP trackless mining and conventional mining for platinum reefs.	Stoping height in m, initial investment in Rm, tons milled per month, production cost in R/t milled, total cost in R/platinum oz.	None
Ackerman and Jameson (2001)	Description of mining method at Impala Platinum and its performance over 5 years.	Production tons; PGM head grade; m ² /employee; tons/employee; fatality accident rate per million man hours.	None
Carter (1999)	Description of mining methods at Tshepong Mine, Matjhabeng Mine, Harmony Mine and Great Nologwa Mine.	Cash cost per oz; m ² mined per month; m ² /employee; stoping cost in R/m ² ; stope width mined cm; m ² mined/m developed ratio.	None
Knock (1994)	Comparison of mechanized and labour-intensive mining of a tabular platinum reef at RPM Union Section.	Total cost in R/t; total stoping costs in R/t; labour cost/t mined; tons mined per worker; m ² mined per stope employee.	None

changing geological conditions and changing government fiscal policies. Mining plans have to be adjusted or adapted quite often over the life of the operation to cope with these changes. The ability of mining plans to adjust, adapt or respond to changes is operational flexibility. A flexible mining plan is therefore a robust mining plan because it can adapt to changes in the operating environment.

Operating flexibility in a mining operation is a nebulous concept, difficult to define and measure, because it means different things to different people. However, two different kinds of operating flexibility can be identified at the different levels of mining operations. At a strategic or corporate level, operating flexibility is the ability to meet the required shareholders' return on investment at an acceptable level of risk. This type of flexibility is obtained by structuring the company's portfolio of operations to be able to divest from unprofitable operations, take on board new operations able to generate the minimum required levels of profitability and schedule when greenfield projects can be brought on stream. Strategic operating flexibility has been referred to as managerial flexibility in real options analysis (Kajner and Gordon, 1992; Samis and Poulin, 1998; Davis, 1998; Dapena and Fidalgo, 2003; Kazakidis and Scoble, 2003). Flexibility at a tactical or operating level is the ability to swiftly move the mining operations to different production faces when issues of grade control or unpredicted geological structures require it. This type of flexibility is referred to in this paper as technical operating flexibility.

Importance of operating flexibility in layouts and schedules

The importance of operating flexibility in enhancing project profitability or project value is highlighted in a number of articles. Macfarlane (2005, p. 187) underscores the importance of flexibility in mine plans by arguing that 'where flexibility to deal with changing economic cycles has not been created (as a value-adding decision), reactive planning has to be undertaken, which is value-destroying'.

Macfarlane (2005) further argues that ideal optimal planning profiles should be ones that create value early in the life of a mining project, and part of this value should then be reinvested into building flexibility in the operation. In this way, an optimal path of extraction can be created through the removal of operating constraints, provided the flexibility options are exercised. Steffen and Rigby (2005) argue that flexibility to ensure an optimum production profile from known reserves over the life of the mine is so important that it should warrant executive directive because it involves risk acceptability and directly affects corporate balance sheet capacity. Vieira (2004) argues that an optimal overall strategy of mining requires mine layouts with more 'flexible' geometries that offer a higher degree of operational flexibility. Kazakidis and Scoble (2003, p. 34) emphasized the importance of flexibility in mine plans because 'the ultimate level of profitability of a mining project is enhanced by flexibility in the mine plan'. Woodhall (2002, p. 43) also highlights the need for an 'appropriate level of mining flexibility to manage profitability over time'.

A metric for technical operating flexibility

Currently, there is no standard procedure that has been documented or formalized for quantifying or valuing operating flexibility in mine plans, despite its increasing importance (Kazakidis and Scoble, 2003). Instead, flexibility has been or can be observed indirectly in that a more flexible operation has little or no variance between actual production efficiencies and planned production efficiencies. The small variance can be achieved only if spare mining face is available. The mining faces must also have a high degree of independence from each other and where independence is low, as in longwall mining, flexibility will also be low.

At a tactical planning level, Woodhall (2002, p. 40) distils the concept of operating flexibility down to the mining face and defines mining operating flexibility for underground tabular reef gold mines as:

the provision of sufficient equipped mining face to make alternative, profitable work places available to sustain planned production levels... and the only true flexibility in terms of having choice to mine or not mine is therefore equipped panels waiting to be stoped.

Kazakidis and Scoble (2003) propose an index as a metric for measuring managerial flexibility and define it as:

$$\text{Flexibility index, } F(\%) = \frac{\text{Option Value, } OV}{NPV_{\text{passive}}} \times 100, OV > 0 \quad [1]$$

The *OV* is the additional *NPV* over the base case of a project that would be derived from exercising the alternatives made available by the flexibility obtained. However, the flexibility comes at premium that includes capital and/or operating costs. Therefore if the flexible option is not exercised, the *NPV* over the base case will decline, because of the additional costs incurred to acquire the operating flexibility.

The proposals made by Woodhall (2002) and Kazakidis and Scoble (2003) are integrated to form a metric for measuring technical operating flexibility. The metric is a Flexibility Index, *FI*, defined by:

$$FI = \frac{\text{Available fully equipped stopes} + \text{Stopes already in production}}{\text{Production stopes required to meet planned production rate}} \quad [2]$$

If $FI < 1$, then the operation is inflexible for that time period because there are fewer stopes available than are required to meet the planned production rate. If $FI > 1$, then the operation is flexible. An *FI* index of 1 would imply a marginal level of operating flexibility. For example, in the platinum reef case study presented in this paper, a total of 75 production stopes is required per year to meet a production rate of 1 800 000 tpa, assuming a maximum of 5 active production panels per stope at a time, each panel being 30 m in length and advancing at 15 m per month to give about 2 000 t/month per panel. If ledging and equipping are completed on 15 stopes in a particular year when 50 stopes are already under production, then the *FI* is 0.87, implying an inflexible operation for that year. The behaviour of this index is explored in the platinum reef case study.

Ore availability and operating flexibility

Ore availability is a measure of how far development has been kept ahead of stoping operations. It is the amount of ore available for stoping with little or no further development required, expressed in years of production at current rates of production. Although the definition of what constitutes ore availability is open to debate, a logical reasoning is that all stopes with fully ledged raise lines are available ore, stopes with raises that have holed but not yet ledged are not available for stoping, and stopes with partly ledged raiselines are partially available in the proportion of length ledged to length of raise.

A minimum ore availability of 2 years is a typical figure for most narrow tabular reef deposits. A few examples are highlighted to illustrate this point. Storrar (1977, p. 273) refers to this parameter as an 'apparent ore reserve life' and indicates that most tabular reef gold mines on the Witwatersrand Basin considered a figure of 2 years as being a safe value. McCarthy (2002) discusses rules on keeping

development ahead of production and notes that it is usual to keep primary access development two years ahead of production in longhole stoping operations of narrow reefs. In an article on the progress made in extending the life of mine to 18 years at Northam Platinum Mine, Lanham (2004) cites 2 years as an ideal figure for ore availability for the mine due to its geological complexity, but notes that some platinum mines on the Bushveld Complex are comfortable with ore availability of 12 months due to their simpler geologies. Woodhall (2002) analyses statistics for a Witwatersrand Basin tabular reef gold mine that was using scattered mining on 150 m raiselines and 180 m backlengths and noticed that the mine had, between 1994 and 1999, almost consistently achieved a period of 23 months as the time lag between development effort and the subsequent stoping results. This is an important indicator of the ability to change existing levels of operating flexibility should it be considered necessary.

Ore availability is an indicator of short-to medium-term operating flexibility of mining operations. Low ore availability implies reduced flexibility and high ore availability implies increased operating flexibility. This relationship allows the measurement of technical operating flexibility by varying the levels of ore availability. This was the approach adopted in the platinum reef case study.

Case study

The geological data used for the case study constituted proprietary data and was masked to protect its real identity. Firstly, data for the case study orebody model was selected as a subset from a larger data set for the entire orebody, but was carefully chosen so that the global geological characteristics of the entire orebody were not missed. Secondly, the data set was pseudo-named Orebody 1 (OB1). Figure 1 illustrates the structural geology of OB1.

OB1 is an outcropping UG2 reef of the Bushveld Complex. The orebody strikes roughly north-south for about 4 km and has an average dip of 9°. The total global geological ore losses for the model came mainly from dykes, faulting and potholing. The depth of oxidation was estimated to extend some 30 m vertically below surface. No mining would take place in the oxidized zone. The average PGE mining grade is about 5.3 g/t over a 1 m stoping width. The grade generally decreases with depth. The total mineable ore resource was estimated at 17.5 million tons.

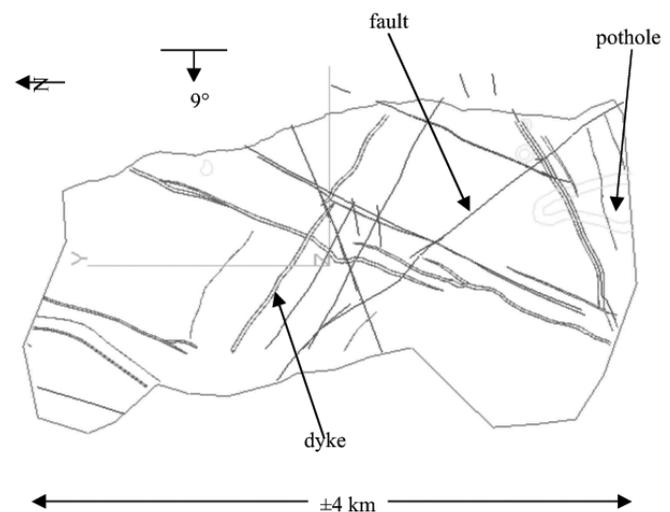


Figure 1. Structural geology of OB1

The orebody was planned be mined on a conventional breast mining layout grid of 200 m raiselines and 200 m backlengths. The layout gave a total of 129 stopes. Access would be by means of an off-reef decline from surface located about mid-way between the northern and southern boundaries. Small potholes would be mined through while large pothole areas would be circumvented. The layouts were done using the rule-based Mine 2-4D® design and planning software. Figure 2 illustrates the mining layout in 3D showing the down-dip ‘V-shaped’ mining front as suggested by Handley (1999) and typical of scattered layouts or their variants. The output from Mine 2-4D® was exported to Earthworks Production Scheduler (EPS®) for scheduling.

Results and discussion

Schedules based on ore availability constraints in steps of 3 months over the range 0–36 months were then developed, so that flexibility could be investigated 12 months on either side of the customary figure of 2 years. For clarity of illustration, some diagrams will show only ore availabilities

which are multiples of 3 months. By delaying the start date for a stope to be scheduled into production, future flexibility is generated. However, this also delays revenue from that stope when costs have been incurred to prepare it for production. As indicated earlier, the longer the delay between completion of stope preparation and production start from that stope, the greater the reduction in project NPV. For each particular ore availability constraint, the corresponding NPV and flexibility index values were computed. The NPV was based on net of development and stoping costs and revenue from production. Figure 3 shows the production profiles for ore availability taken in steps of 6 months. As ore availability is increased, there is a gradual shift of the production profiles to the right. This is expected because as ore availability is increased, the gap between development completion and production start-up widens, thus pushing the production profile more to the right. Figure 4 shows the corresponding stoping PGE grade profile over the project for 0 months and 36 months ore availability. Grade gradually falls with time since, with the down-dip ‘V-shaped’ mining front, the lower grade stopes located further from surface will be mined out towards the end of the operation.

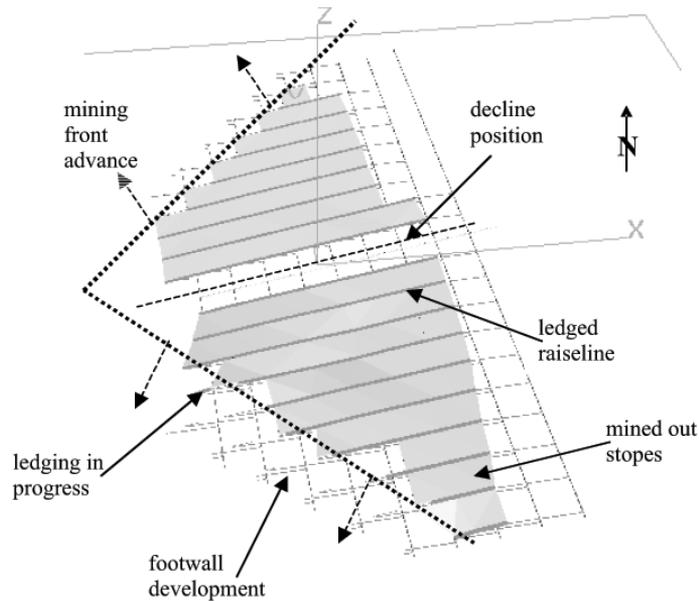


Figure 2. OBI mining layout in 3D showing progression of ‘V-shaped’ mining front

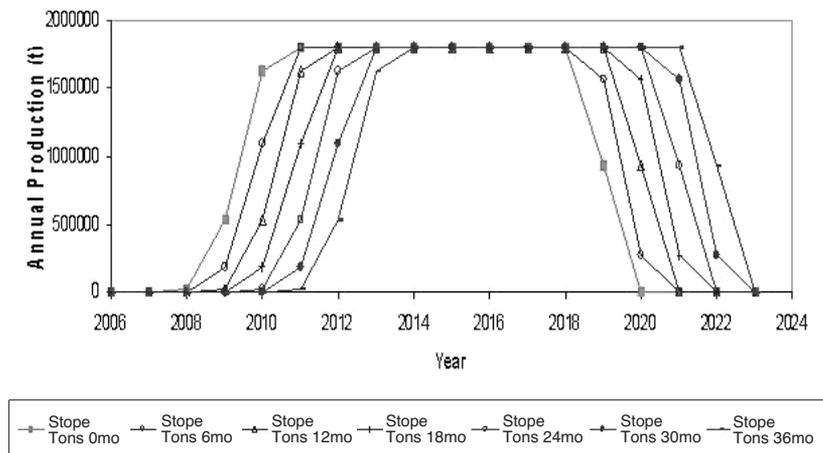


Figure 3. Production profiles for the various ore availability constraints

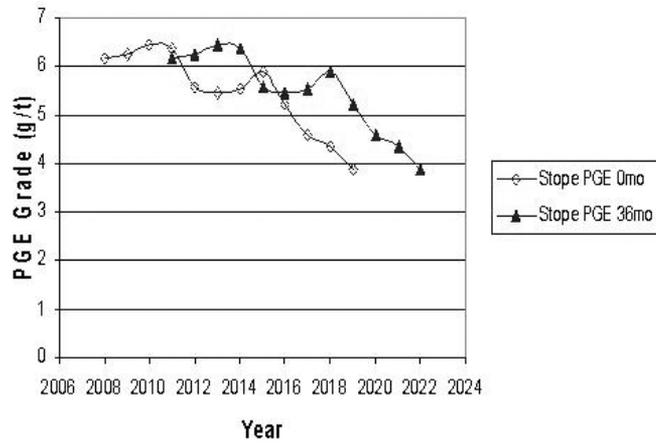


Figure 4. PGE grade profile over life of project

The behaviour of the flexibility index was investigated over the ore availability range of 0-36 months. Figure 5 illustrates the results obtained. From production start-up, the curves steepen with increasing ore availability and the flexibility reaches a peak about halfway through the project life in 2014. This trend shows an increase in technical operating flexibility with increasing ore availability. In the early stages of development, only a few stopes are fully ledged and equipped, but as development progresses, more stopes become available and flexibility increases. Low ore

availability does not give the operation enough time to build up beyond marginal operating flexibility as stopes are mined almost as soon as they are developed. Beyond half of the project life, flexibility starts to decline because there is less development happening and more stoping occurring. Technical operating flexibility of greater than 1.0 is obtained at ore availability of 18 months or more, suggesting that 18 months should be the minimum ore availability for OB1. The flexibility index can therefore be used to determine the minimum ore availability that mines should maintain.

Finally, the technical operating flexibility index and project NPV were plotted for the ore availability range of 0-36 months and the results obtained are shown in Figure 6.

It is evident from Figure 6 that technical operating flexibility increases with increasing ore availability while project NPV decreases with increasing ore availability, confirming the earlier argument. The exercise will be repeated on two more geological orebody models to check if a general pattern can be established.

Conclusions

Mine planners are agreed on the need for flexibility in mine layouts and schedules, but there is no consensus on acceptable levels of flexibility because it has not been formally quantified. This paper has defined technical operating flexibility by distilling the concept to the availability of mining face and using an index as a metric for measuring the flexibility. A flexibility index less than

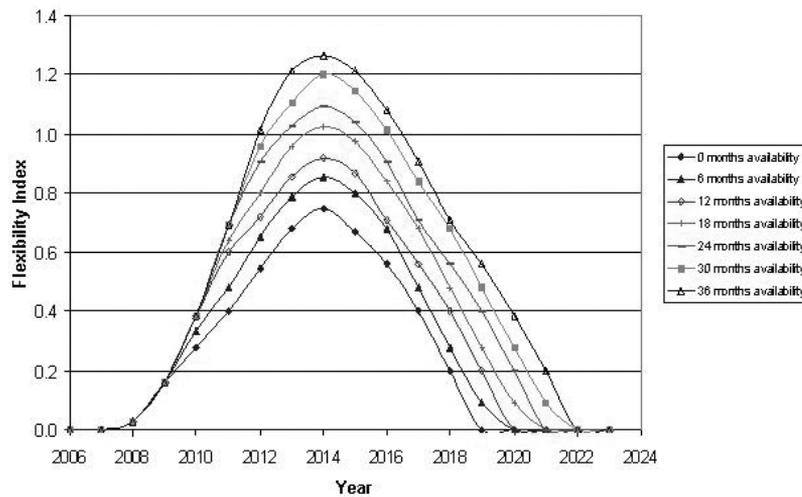


Figure 5. Relationship between Flexibility Index and ore availability

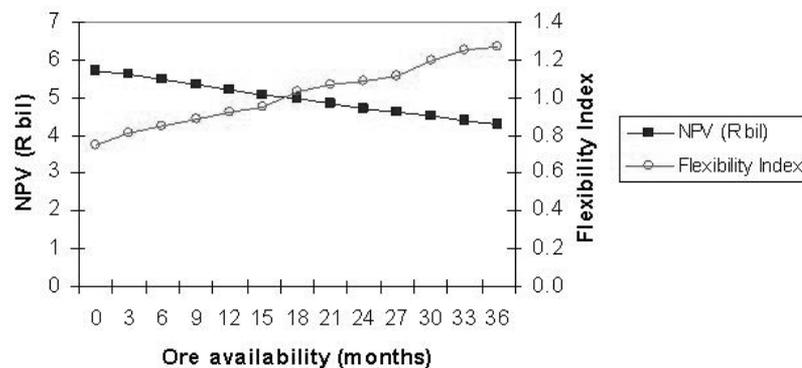


Figure 6. Variation of NPV and Flexibility Index with ore availability

1.0 implies that the operation is inflexible. An index equal to 1.0 suggests marginal operating flexibility, while an index greater than 1.0 suggests a flexible operation. This paper has demonstrated that the flexibility index can be used to determine the minimum ore availability that mines should maintain. For the case study the flexibility index indicated a minimum ore availability of 18 months to be maintained for OB1. Two more geological models have been acquired and will be used to investigate if a general pattern can be established on the behaviour of flexibility with ore availability.

Acknowledgements

The authors would like to acknowledge the assistance received from Mr M. Rogers (Head of Mine Technical Services, Anglo Platinum) for arranging the geological model used in this study and GijimaAst for providing Mine2-4D® and EPS® software.

References

- ACKERMAN, G.R. and JAMESON, A.W. Underground mining at Impala Platinum, Ltd., in the Northwest Province of South Africa, *Underground Mining Methods: Engineering Fundamentals and International Case Studies*, Hustrulid, W.A. and Bullock, R.L. (eds.), SME, 2001. pp. 157–163.
- CARTER, P.R. Mining practice for intermediate depth narrow tabular ore bodies with particular reference to the Free State and Klerksdorp Goldfields, *Proceedings of School on Narrow Tabular Orebody Mining*, The South African Institute of Mining and Metallurgy, 21–22 October 1999.
- DAPENA, J.P. and FIDALGO, S. A real options approach to tender offers and acquisitions processes, at URL: <http://www.realoptions.org/papers2003/DapenaDoctrabapproach.pdf>, accessed on 31 March 2006.
- DAVIS, G.A. One project, two discount rates, *Mining Engineering*, April 1998, pp. 70–74.
- ELKINGTON, T., BARRETT, J. and ELKINGTON, J. Practical application of real option concepts to open pit projects, *Proceedings of the 2nd International Seminar on Strategic versus Tactical Approaches in Mining*, Australian Centre for Geomechanics, 8–10 March 2006, Perth, pp. S26.1–S26.12.
- HANDLEY, M.F. A review of Sequential Grid Mining method employed at Elandsrand Gold Mine, *Proceedings of Colloquium on New Mining Methods and Systems for Narrow Reef Mining*, The South African Institute of Mining and Metallurgy, 29 July 1999.
- HARRISON, G.A. Implementation of XLP mining equipment at Anglo Platinum: XLP layouts – alternatives for optimum performance, *Proceedings of Colloquium on Mechanized Mining and Support in the Bushveld Complex*, The South African Institute of Mining and Metallurgy, 12 May 2004.
- KAJNER, L. and SPARKS, G. Quantifying the value of flexibility when conducting stochastic mine investment analysis, *CIM Bulletin*, vol. 85 no. 964, pp. 68–71.
- KAZAKIDIS, V.N. and SCOBLE, M. Planning for flexibility in underground mine production systems, *Mining Engineering*, vol. 55 No.8, October 1992, pp. 33–39.
- KNOCK, A.G.W. Mechanized versus labour-intensive mining of a tabular orebody, *Proceedings of XVth CMMI Congress*, The South African Institute of Mining and Metallurgy, 1994. pp. 75–88.
- LANHAM, A. Northam makes the breakthrough, *Mining Weekly*, vol. 10, no. 43, 5–11 November 2004, pp. 17–20.
- MACFARLANE, A.S. Establishing a new metric for mineral resource management. *Proceedings of First International Seminar on Strategic versus Tactical Approaches in Mining*, The South African Institute of Mining and Metallurgy, 19–21 September 2005, pp. 179–203.
- MCCARTHY, P.L. Production Scheduling, at URL: http://www.amcconsultants.com.au/Members/PDF_Papers/MP/Production_Scheduling.pdf. Accessed on 31 March 2006.
- SAMIS, M. and POULIN, R. Valuing management flexibility: a basis to compare the standard DCF and MAP valuation frameworks, *CIM Bulletin*, vol. 91 no. 1019, April 1998, pp. 69–74.
- STEFFEN, O.K. and RIGBY, N. The value of strategic mine planning, *Proceedings of First International Seminar on Strategic versus Tactical Approaches in Mining*, The South African Institute of Mining and Metallurgy, 19–21 September 2005. pp. 97–120.
- STORRAR, C.D. South African Mine Valuation, Chamber of Mines of South Africa, Johannesburg, 1977.
- The New Collins Dictionary and Thesaurus, William Collins Sons & Co Ltd, Glasgow, 1989, 1173 pp.
- VIEIRA, F.M.C.C. Rock engineering-based evaluation of mining layouts applicable to ultra-deep, gold bearing, tabular deposits. PhD thesis submitted to the University of the Witwatersrand, July 2004.
- WOODHALL, M. Managing the mining life cycle: mineral resource management in deep level gold mining. MSC project research report submitted to the University of the Witwatersrand, October 2002, 84 pp.