Technical operating flexibility in the analysis of mine layouts and schedules

by C. Musingwini*, R.C.A. Minnitt*, and M. Woodhall†

Transaction Paper

Synopsis

An often overlooked factor in the analysis of mine layouts and schedules is technical operating flexibility (or tactical flexibility), mainly due to its nebulous nature. By glossing over technical operating flexibility the resultant mine layouts and schedules may be suboptimal. The need to incorporate technical operating flexibility into the analysis and comparison of mine layouts and schedules is increasing in importance. The nature of technical operating flexibility is illustrated, previous work on valuing of operating flexibility reviewed, and a proposal made on 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 has been quantified it becomes possible to explore its incorporation into the analysis of mine layouts and schedules and subsequent optimization processes. This paper is a revised version of a paper presented in the Proceedings of the Second International Platinum Conference, 'Platinum Surges Ahead' in 2006. 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/tactical 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 on 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 are a reality in the dynamic modern business operating 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 (or tactical 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. This paper

* *School of Mining Engineering, University of Witwatersrand, Johannesburg.*
† *GijimaAst, Johannesburg.*

Table I

Examples of studies on evaluation of layouts and schedules

Study	Objective	Evaluation Criteria used	Reference to Flexibility
Egerton (2004)	Comparison of conventional, hybrid and mechanised mining of UG2 reef on the Bushveld Complex.	Dilution; extraction ratio; shaft head grade; capital cost (R//t); Total cost (R/t); On-mine cash cost (R/t).	None
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 Rmil, tonnes 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 tonnes; PGM head grade; m^2/employee; tonnes/employee; fatality accident rate per million man hours.	None
Carter (1999)	Description of mining methods at Tshepong Mine, Matjhabeng Mine, Harmony Mine and Great Noligwa 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 mechanised 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; tonnes mined per worker; m^2 mined per stope employee.	None

Key: LSP—longwall with stabilizing pillars; SGM—sequential grid mining; SDD—sequential down-dip mining; CSDP—closely spaced dip pillar mining system; XLP—extra low profile; LP—low profile; NPV—net present value; IRR—internal rate of return; LOM—life of mine; PGM—platinum group metals

is a revised version of the paper presented in the Proceedings of the Second International Platinum Conference 'Platinum Surges Ahead' held in 2006 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. The layout is dependent on the mining method or technology selected to exploit the mineral deposit. 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 (LOM) 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 'adaptability, adjustability, elasticity, responsiveness,' which can be interpreted to mean the ability to adapt, adjust or respond to changes. This definition is fundamental in understanding operating flexibility in mining. Mines operate in a business environment characterized by several uncertainties of a financial, technical or social nature such as fluctuating exchange rates, cyclical mineral prices, rising wage costs, 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 Sparks, 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 swiftly to move the mining operations to different production faces when issues of grade control or unpredicted geological structures require it. In this way, production risks are minimized. 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 argued 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 that are created 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 required mine layouts with more 'flexible' geometries that offer a higher degree of operational flexibility. Kazakidis and Scoble (2003, p. 34) emphazised 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 can be observed indirectly in that a more flexible operation potentially has little variation between actual and planned production efficiencies and is likely experience shorter production shortfall periods. The small production variation can be achieved only if alternative 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. Two schools of thought by Woodhall (2002) and Kazakidis and Scoble (2003) were considered in developing a metric for technical operating flexibility.

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 defined it as shown in Equation [1].

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

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 generated flexibility. 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.

It can be observed that the definition by Woodhall (2002) is a logistical construct while that by Kazakidis and Scoble (2003) is a value construct, although both constructs are indicative of issues surrounding the measurement of operating flexibility. By considering these two proposals, a metric in the form of a flexibility index, FI, can be defined as shown in Equation [2].

$$FI = \frac{\textit{Available fully equipped alternative stopes } (m^2) + \textit{Stopes already in production } (m^2)}{m^2 \textit{ of production stopes reqired to meet planned production rate}} \quad [2]$$

The definition assumes that the fully equipped alternative stopes have already been developed, ledged and equipped, and are in close proximity to the working stopes so that no shift is lost in relocating production crews to the alternative working places, should such a need arise. A simple guide on face length requirement, as practised by Anglo Platinum Ltd., is that it is prudent for planners to ensure that the minimum alternative equipped panels are not less than the estimated geological loss percentage in order to sustain planned production levels (Smith and Vermeulen, 2006). They give an example where 200 m of face length are required to meet planned production and an estimated geological loss of 17% is expected. A minimum of 234 m (200 × 1.17) of face are required, representing a minimum alternative equipped face requirement of 34 m. In this way, inherent flexibility is built into the mine plan but will be relative depending on the factors considered important by the mine planner.

From Equation [2], if FI<1, then for the period under consideration the operation is inadequately developed for production and has no flexibility at all since there are fewer stopes available than are required to meet the planned production rate. If FI=1 the operation is temporarily inflexible because any unforeseen loss of panels causes the operation to slip back into a situation of no flexibility at all. If FI>1, then the operation is flexible. 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 any given 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 that the operation was inadequately developed for production in that particular year. Accordingly, the development has to be stepped up to bring the operation to an acceptable level of operating flexibility. The behaviour of the flexibility index is explored in a platinum reef case study later in this paper.

Technical operating flexibility and ore availability

As indicated in Equation [2], technical operating flexibility is created by making available additional fully equipped stopes over and above those required for planned production. The starting point in creating technical operating flexibility is having development in advance of stoping operations. Other critical mining activities and/or factors that are interrelated, then determine the success of the conversion of the developed areas into fully equipped stopes that become available as alternative face. These activities include ledging, ground support, and equipping. Factors such as geological structural disturbances, falls of ground and change in economic circumstances, such as a drop in mineral price, directly lead to non-conversion or temporary loss of conversion of a developed area as alternative mining face. In some cases development laid out well ahead of stoping may not necessarily be in the correct or optimal areas, again leading to a loss of mining face. Figure 1 is an illustration of the sequence of typical mining phases in the build-up to technical operating flexibility, starting from the time a raiseline has holed. A change or delay in a mining phase directly affects subsequent phases and ultimately technical operating flexibility. Therefore, it can be argued that developing well ahead of stoping operations does not necessarily create flexibility. Technical operating flexibility and the timing of development ahead of stoping are therefore two interrelated concepts in the planning of tabular reef mines linked together by the concept of ore availability.

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. Ore availability could also be expressed as m^2 of available mining face. Although it is debatable what counts as ore availability, 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) refer to this parameter as an 'apparent ore reserve life' and indicated 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 backlenghts and notices 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.

Low ore availability implies reduced technical operating flexibility and high ore availability implies increased technical operating flexibility. This relationship allows the measurement of technical operating flexibility by varying the levels of ore availability. Ore availability was therefore used as a proxy for technical operating flexibility in the platinum reef case study, assuming a 100% success rate at every mining phase in converting developed areas into alternative mining face.

Case study

The geological data used for the case study constituted proprietary data and were masked to protect its real identity. Firstly, data for the case study orebody model were selected as a subset from a larger data set for the entire orebody, but were carefully chosen so that the global geological characteristics of the entire orebody were not lost. Secondly, the data set was pseudo-named Orebody 1 (OB1). Figure 2 illustrates the structural geology of OB1.

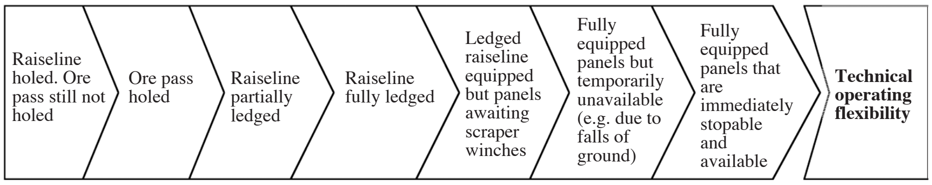

Figure 1—Sequence of mining phases building up to technical operating flexibility

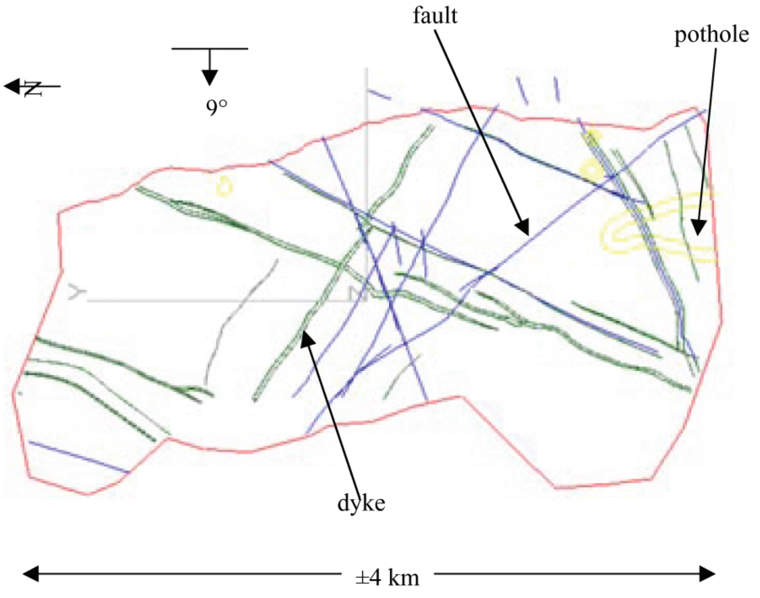

Figure 2—Structural geology of OB1

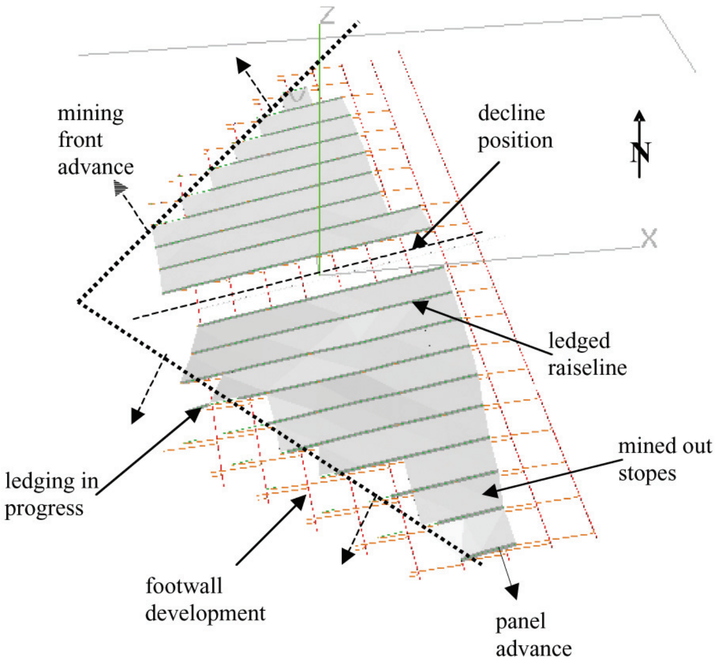

Figure 3—OB1 mining layout showing progression of V-shaped mining front

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 PGE grade refers to ore grade based on the four main platinum group metals namely platinum, palladium, rhodium and gold, which are also known as the 4E elements. The PGE grade for OB1 generally decreases with depth from about 6.5 g/t near surface to 3.9 g/t at the lowest levels. The total mineable ore resource was estimated at 17.5 million tonnes.

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 midway 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 3 illustrates the mining layout in 3D showing the overall 'V-shaped' mining front as suggested by Handley (1999) and typical of scattered layouts or their variants. It can also be seen from Figure 3 that although the overall direction of advance of mining is down along dip and out along strike, the direction of panel advance is only along strike direction. The output from Mine 2-4D® was exported to Earthworks Production Scheduler (EPS®) for scheduling.

Results and discussion

Schedules based on ore availability taken 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 figures 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 level of ore availability 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 4 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 5 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 V-shaped mining front the lower grade stopes located further from surface will be mined out towards the end of the operation. The gradual grade decrease due to the nature of the orebody could possibly mask the effect of flexibility and contribute to the declining NPV trend observed in Figure 7.

The behaviour of the flexibility index was investigated over the ore availability range of 0-36 months. Figure 6 illustrates the results obtained from production schedules with varying ore availability. 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

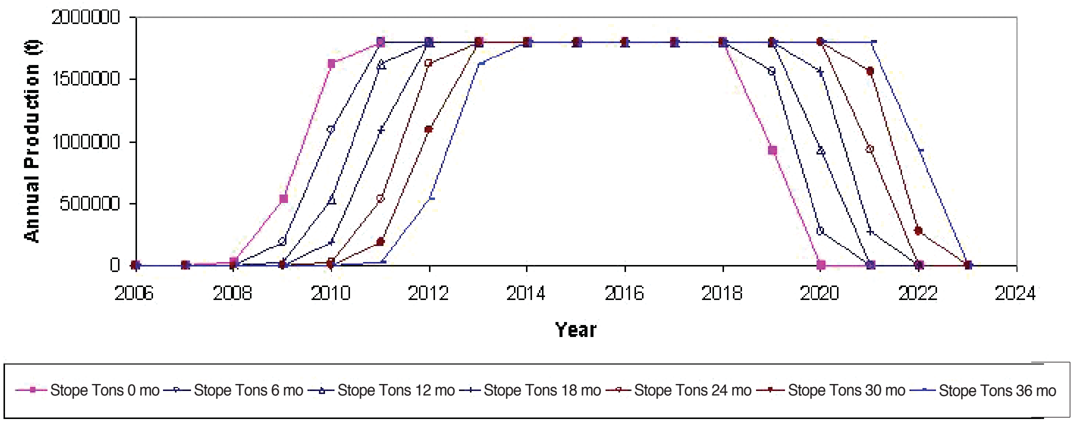

Figure 4—Production profiles for the various levels of ore availability

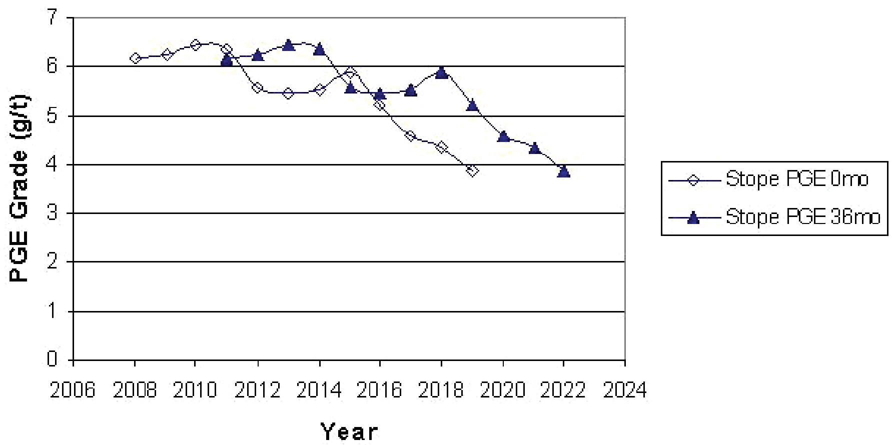

Figure 5—PGE grade profile over life of project

stopes become available and flexibility increases. Low ore availability does not give the operation enough time to build up beyond a flexibility index of 1.0 as stopes are mined almost as soon as they are developed. This trend can be observed for curves representing ore availability less of than 18 months in Figure 6. 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.

When viewed from a risk perspective, two different risk profiles are evident from Figure 6. From start-up to about half of the project life in 2014, there is a higher risk to production because development work is still generating more information about the orebody. Consequently, in this segment of the project, there is a high potential for lost blasts, in turn reducing flexibility build-up, and negatively affecting revenue generation. Beyond 2014, lower risk is expected because most of the development is now complete and there is increased knowledge about the orebody. Most production areas are fully developed, creating the opportunity for fewer lost blasts and increased productivity.

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 7. It is evident from Figure 7 that technical operating flexibility increases with increasing ore availability, while project NPV decreases with increasing ore availability, confirming the argument earlier. The observed trend could also be due to a masking of effect of operating flexibility by grade variability as stated earlier on. However, it is expected that NPV would increase with increasing flexibility if the alternative stopes are utilized, for example, to increase production rate or to take advantage of a spike in mineral price. For example, the benefit of meeting planned production levels can be quantified by valuing production loss that would occur if flexibility were absent. The exercise is being repeated on two more geological orebody models to check if a general pattern can be established. The two geological orebody models have grade characteristics different from that of OB1 and could therefore possibly indicate the extent of the masking of the effect of operating flexibility.

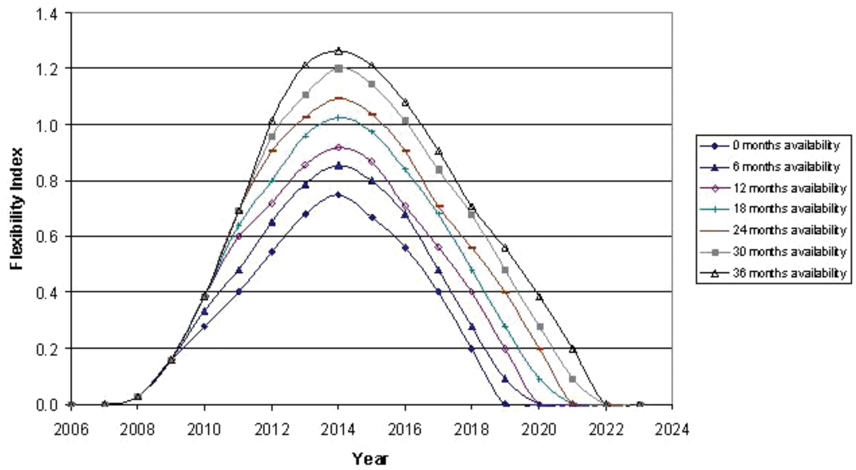

Figure 6—Relationship between flexibility index and ore availability

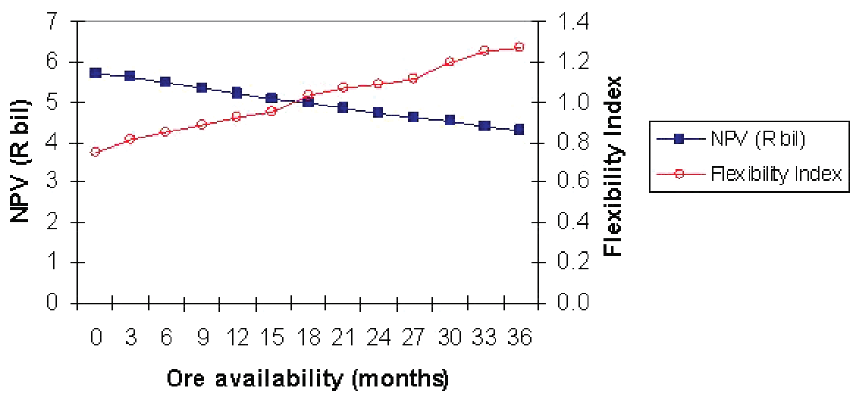

Figure 7—Relationship between NPV and FI at different levels of ore availability

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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. A methodology has been presented in this paper to formally quantify and measure technical operating flexibility (or tactical flexibility). This paper has defined technical operating flexibility by distilling the concept to the availability of alternative mining face and using an index as a metric for measuring the flexibility. A flexibility index less than 1.0 implies that the operation is inadequately developed for production and there is no flexibility at all. An index equal to 1.0 suggests that the operation is temporarily inflexible because any loss of production panels such as due to falls of ground will make the existing development inadequate to generate acceptable levels of operating flexibility. An index greater than 1.0 suggests that the operation is flexible.

This paper has also 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 are currently being investigated to determine if a general pattern can be established on the behaviour of flexibility with ore availability. Additionally, they will also provide a check on the extent to which declining grades with depth as observed in OB1 could have affected the NPV-flexibility index profile.

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