Quantified Value-created Process (QVP) – A value-based process for mine design and operating decisions

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Synopsis

This paper introduces the Quantified Value-created Process (QVP), a decision-making process for use in mine design and operation. The implementation of the QVP is founded on a ten-step rock engineering design process and a ten-step strategic planning process. The potential of this approach is demonstrated by examples of value created as a result of good research, design, and planning. The QVP is divided into two parts, namely, a 'planning the process' section and an 'implementing the process' section, and can be considered to be an extension of the risk approach. All costs, direct and indirect, associated with a significant mining decision (design, operational, investment) must be quantified in advance of committing to that decision, to determine the value that will be created in the short, medium, and long terms. Ethical values, associated with health, safety, the environment, public perception, and social aspects, may be difficult to quantify in economic terms, but must nevertheless also be considered. In contrast with a traditional risk approach, the QVP will identify the upside, and allow executives to make more informed strategic decisions. In this context it is essential to actively engage upper management in the decision process.

Keywords

Quantified Value-created Process, decision-making, value creation.

Introduction

Mining is recognized as a risky business, which is why risk assessment is a routine activity in many mining processes. Financial risk is associated with any mining investment, with the possibility that the actual return on an investment will be different from that expected. Hadjigeorgiou (2020) noted that in addition to traditional financial risks, which include credit, liquidity, market, foreign exchange, interest, and commodity prices, mining companies have to tackle environmental, community, political, and reputational risks in an interconnected global economy. Mining companies are therefore faced with the task of developing winning strategies for a business unit, a particular asset, or a specific project. Ilbury and Sunter (2005) recognized that different people within an organization have different wishes, opinions, strengths, and weaknesses, and consequently perceptions of what 'winning' is. They postulated that the objective should not be 'seeking alignment of everyone's meaning of winning, but a balance between their meanings'. The case is made in this paper that traditional, narrowly focused risk analyses may miss the opportunity to provide a winning strategy or increased value that balances various objectives. This is brought to perspective with reference to environmental, social, and governance issues.

Environmental, social, and governance (ESG) compliance is now an integral requirement for all mining companies. ESG in effect represents risks and opportunities that will impact a company's ability to create long-term value. This includes traditional environmental issues, social issues like labour practices such as health and safety, and governance matters. The issues covered by ESG are not new and arguably are what was understood as being a good corporate citizen. The major change, however, is that failure to demonstrate compliance with ESG requirements could potentially harm a company's valuation, access to capital, or its brand reputation in the market. In fact, many institutional investors will shun any company that does not comply with ESG best practices (Glass Lewis, 2021).

Geotechnical engineering provides several examples of focused risk analysis approaches. For example, evaluation of the risk associated with the stability of open pit mine slopes is frequently undertaken (Terbrugge *et al.*, 2006; Contreras, 2015; Read and Stacey, 2009). Furthermore, risk has been proposed as a criterion for design in rock engineering (Stacey, Terbrugge, and Wesseloo, 2007). However, such risk evaluations are usually associated with the downside, and ignore the upside potential. Experience at many mine sites suggests that decisions are often made based on short-term considerations, often cost-cutting exercises, which may result in 'quick fixes'. The short-term consequences may provide immediate value, but the longer-term consequences of these actions may often lead to much greater value destruction. The practical implication is that frequently experienced problems, such as rehabilitation of rock support, clearing blockages of orepasses, clearing slope failure material from haul roads and pit bottom, *etc*., will often be the subject of provisions in the operating budget of a mine. Once such a budget has been established, mine management will usually be satisfied if the operation meets its budget forecasts and see these problems as the cost of doing business. However, this approach ignores the potential upside, which is the additional value that could have been realized in the longer term if these problems could have been prevented. Furthermore, budget provisions usually only cover the direct costs of the consequences, and do not take into account what is frequently the most important cost, that of the loss of production.

The proposed Quantified Value-created Process (QVP) can be considered an extension of the risk approach. All costs, direct and indirect, associated with a significant mining decision (design, operational, investment) must be quantified in advance of committing to that decision, to determine the value that will be created in the short, medium, and long terms. Ethical values, associated with health, safety, the environment, public perception, and social aspects, may be difficult to quantify in economic terms, but cannot be ignored. Thus, in contrast with a risk approach, the QVP approach will identify the upside, and allow executives to make appropriate strategic decisions. For example, it might be shown that a proposed decision will result in short-term value destruction, but that medium and longer term value will be substantial, thus promoting a positive decision. Value created in the short term, but not in the longer term, should result in a negative executive decision. To implement the process, executives need to demand quantification of all relevant direct and indirect costs from their mine management and operational staff to assist in making their decision. Mining company executives have managerial and financial expertise, but may be non-technical, which means that they are unlikely to understand fully all the technical issues associated with proposed mining developments. This phenomenon has been described as an 'asymmetry in knowledge' between the different levels of management within a mining company (Hadjigeorgiou, 2020). Traditionally, executives have to base their decisions on the confidence they have in the information supplied to them by mine management. In contrast, with this approach, using the QVP, executives will have a comprehensive involvement in the overall development and thus be able to make the most meaningful decisions for the short, medium, and long terms with knowledge and confidence.

In the following sections, examples will be given of value creation achieved in numerous mining projects. This will be followed by a suggested ten-step QVP, which is aimed at ensuring a logical implementation of the process.

Examples of value creation in mining

In this section, information extracted from published material is presented to illustrate that all significant mine design and operational decisions should be based on the quantified value that will be created by those decisions, taking into account the short, medium, and long term. Although the selected examples are mostly geotechnical in nature, the same concepts can be applied to other fields. The published information generally relates to after-the-event evaluations, to illustrate the magnitude of the value that can be created. However, the thesis of the paper is that such value should be quantified in advance so that appropriate decisions can be taken to realize optimum value in line with the company's goals.

Health and safety

Safety is of prime importance in mining, and a safe mine represents great ethical value for the mining company. Poor design and operation, leading to unsafe situations and accidents, often have serious economic consequences. It is possible to quantify the financial implications of accidents or potential accidents, although this does not appear to be commonplace. Preis and Webber-Youngman (2021) suggest that financial costs relating to mining incidents can be split into direct and indirect costs, with indirect costs being substantially greater. Quantifying health and safety costs is complex and in many cases made more difficult as the costs are incurred at different time periods following a mining incident.

Mine policy in preventing health and safety incidents is usually very bland and although the overarching objective is zero harm, in practice rules or guidelines are often arguably bent, against policy, so that short-term production targets can be met. This highlights the need for both accountability and responsibility repercussions of full enforcement of safety guidelines.

Design and operation of orepasses

Design decisions regarding orepasses involve the definition of pass location (including proximity to production excavations, shafts, crusher chambers, *etc*.), orientation (inclination and orientation relative to geological strata), size, shape, length, method of excavation, lining and installed support, system geometry, and operating principles. Storage capacity and required operating life may also be important. In high-stress environments, pass cross-sections may 'grow' during use due to stress-induced failure of the rock and/or the geological structure. From an operating point of view, it is most efficient to locate passes as close as possible to the sources of ore and shafts so as to optimize the load-haul-dump or other transfer efficiencies. However, in a deeper sub-level caving environment, for example, stress concentration in the solid around the base of the caved area, which is where passes are located, may lead to rock failure in the pass if it is too close to the orebody. Thus a 'close' pass would provide short-term operational benefits, but in the medium to longer term a 'more distant' pass may avoid such rock failure and associated loss of production and rehabilitation costs, and therefore contribute much greater economic value to the mine. In a deep-level gold mining environment. passes with an initial diameter of 2.4 m have been reported to have opened up under stress to a span of up to ten times the original diameter. Minney (1990) describes a case in a deep-level gold mine in which pass breakout failure occurred to such an extent that the 'extended' pass affected the stability of the shaft with which it was associated. The impact on the efficiency of the pass would have been significant, indicating the longer term economic benefit and value that could have been realized with improved orepass design.

Because orepasses rarely involve safety risks, it appears that they are usually given no more than scant detailed design considerations (Hadjigeorgiou and Stacey, 2013), and there rarely appears to be any strategy in planning, designing, and operating orepass systems. A likely explanation is that the comprehensive costs of the absence of strategies have not been apparent. Mines can usually quantify satisfactorily the routine construction, operational, and maintenance costs, but they commonly do not have cost data on hangup clearance, blast damage repair, and rehabilitation. All of these unexpected occurrences impact on production and can result in major costs of loss of production, which is often the single most important economic factor for a mine. A review of orepass design practice in the deep gold mining industry, involving 200 individual passes in eight mines (Joughin and Stacey, 2004) revealed minimal quantitative information: what information there was, was often undocumented, but communicated by word of mouth from shaft personnel; and very few cases existed in which geological information, such as from borehole logs, was available for passes. This confirms the widespread absence of strategy associated with planning, design, and operation of orepasses (Hadjigeorgiou and Stacey, 2013). The practical implication of not collecting adequate geotechnical data has been demonstrated in a benchmarking study of ten Canadian mines. There was no incidence of uncontrolled failure in any orepass section developed in competent rock mass conditions (*i.e.* Q value greater than 5, see Table I).

In massive mining operations, from an operational efficiency point of view, it is an advantage to locate orepasses as close to the orebody as possible such that tramming times are minimized and production rates maximized. However, as mining progresses, the stresses around the orebody will change and this might lead to stress concentrations in the orepass and resulting instability. As a result, the orepass may become inoperable, and therefore it will be necessary to transport ore to adjacent orepasses, at much lower efficiencies and greater costs. In such cases value is destroyed. Therefore, such potential occurrences should be taken into account in the design location of the passes to optimize value.

Blasting in open pit mines

The quality of blasting determines the amount of damage induced in the rock mass. The extent of this damage effectively determines the stable slope angles that can be adopted in open pit mines. In addition, the fragmentation is determined by the blasting, and the particle size distribution has a major influence on the efficiency of loading, hauling, and milling. Research conducted by Bye (2003) established the desired particle size distributions in both ore and waste rock at an open pit mine. The research involved over 200 trial blasts to define those blast designs that would deliver the required fragmentation. The result was a significant improvement of 18% in the average plant milling rate, 16% in the autogenous milling rate, 13% in the average instantaneous loading rate for ore and waste, and 11% in the average instantaneous loading rate for ore. An additional revenue of over $2 million a month was realized in the plant alone (Little, Bye, and Stacey, 2007).

Table I

Performance of orepass sections in ten underground mines (after Lessard and Hadjigeorgiou, 2006)

Q rating	No. of sections	Non-supported	
		Total	Failed
> 5 (fair)	47	4	0
< 5 (poor)	53	3	3
Total	100	7	3

Further blasting research was carried out to investigate the value of implementing electronic delay detonators (EDDs). This demonstrated that EDDs would consistently provide uniform fragmentation. The implementation of EDDs involved an extra blasting cost, but the fragmentation surpassed expectations and therefore the blast patterns could be expanded, reducing the overall drilling and explosive costs. The result was then in fact not a cost, but a cost benefit attributable to the EDDs.

While conventional mine thinking might have argued that the costs of trial blasts would not be justified, that EDDs would be too costly, and that blasting costs should be minimized, the research and subsequent implementation resulted in substantial value creation for the mine. This demonstrated the importance of a focus on longer term value creation rather than on short-term costs. In addition to the blasting benefits, EDDs also play an important part in the management of slope stability. EDDs improve the quality of wall control blasting, thus providing the indirect benefit of enhanced wall stability and hence steeper slopes that result in further economic benefits. Slope optimization is dealt with in a later section.

Good blast design and practice is also relevant in underground excavations. In tunnels, for example, poor quality blasting causes damage and instability in the rock mass, which then requires more support to ensure stability. Spending more on good blast designs is likely to improve safety and save substantially on rock support costs, thus creating value for the operation.

Preconditioning of stope faces in gold mines

Preconditioning of deep-level gold mine stope faces is now common practice in South Africa to reduce, and in most cases prevent, the occurrence of stope face rockbursts. Research carried out by Toper (2003) demonstrated very considerable safety benefits as a result of preconditioning: the area mined per accident increased by 347% for updip mining, 260% for diagonal mining, and 254% for combined mining.

In addition, despite the additional amount of drilling, with the expectation of increased direct costs as well as higher costs of labour for the additional drilling, blast-hole drilling penetration rates actually increased, and total drilling time reduced. An increase of up to 50% in the stope face advance per blast was achieved, and there was a significant improvement in the condition and stability of the hangingwall. With the finer fragmentation – about 30% smaller particles and more uniform particle size distribution (Toper *et al.*, 2000) – the result was greater efficiency in ore handling.

This research proved that preconditioning of gold mine stope faces contributes to improved safety, productivity, and profit, creating huge safety and economic value for the mines, amounting to many millions of dollars. However, this value would have been even greater, and the safety record better, had a QVP been contemplated 50 years earlier. In-mine trials in the 1950s (Roux, Leeman, and Denkhaus, 1957) indicated the potential of preconditioning to reduce rockbursts. These trials demonstrated that the number of severe rockbursts was reduced by 73%, and occurrences of on-shift rockbursts were rare. Unfortunately, despite the success of the trials, preconditioning became a routine operation only some 40 years later, in the late 1990s.

Open pit slope optimization

In addition to the blasting investigations by Bye (2003), described above, further research was carried out into the design of open pit slopes, evaluation of slope stability, and slope optimization, monitoring, and management. The required geotechnical information for slope design includes properties of the rock types present, information on geological structures and their properties, details of the groundwater status, and the boundary conditions (*in-situ* stress conditions). The geometry of the orebody dictates the design configuration of the open pit. Consequently, the extent and shape of the orebody must be well defined and captured in a block model. Bye (2003, 2005a) developed a geotechnical block model of the mine in Datamine. Each 15 m^3 block was assigned appropriate information on the rock type, its compressive strength, the RQD, and Laubscher's Mining Rock Mass Rating (Laubscher, 1990). Interpolation involved geostatistical evaluation of borehole and face mapping information. Using this block model, predictions of blasting costs were made using the blastability index (Lilly, 1986) and the modified Cunningham (1986) fragmentation equation. Inter-ramp slope angles were also determined in the block model using a rock mass classification approach (Haines and Terbrugge, 1991). This allowed the possibility of steepening of planned slopes to be ascertained, and where slope flattening was required. Comprehensive numerical slope stability analyses were carried out. The result of the process was a steepening of the overall slope angle. The strategic and tactical value created was assessed by Bye, Little, and Mossop (2005). The following is a quote from the conclusions to Bye's research (Bye, 2003).

> *'The development of the slope design model provided the opportunity to move away from one design process for the entire pit, and customization of slope design and configurations were developed to cater for local variations in the rock mass conditions. The availability of the geotechnical information in 3D and the improved level of confidence of that data resulted in a slope optimization of the final pit ... the final walls were optimized by three degrees, resulting in revenue increase for the mine in excess of [$120 million] ...'*

It is also worth mentioning the value to the mine of databasing geotechnical and monitoring information (Little, 2006a, 2006b) – this meant that good design information was readily available when required.

Slope optimization initiatives at Sishen mine in South Africa have unlocked significant value. The research carried out for this project involved the development of synthetic rock mass (SRM) models for banded iron formation and shale units, on which the economics of the large iron ore mine depend (Bester, 2019; Bester *et al.*, 2019). The research introduced a 'concept level' SRM for early-stage projects wherein certain informed assumptions may be made based on existing knowledge. SRM models rely on geotechnical data, which can be provided by quality structural mapping of benches. This information is not commonly available in the early stages of a project but can be gathered during the mining process by physical mapping and, when physical access is not available, by remote methods such as laser mapping (Russell and Stacey, 2019). This allows models to be iteratively tested and improved as new geotechnical data becomes available. The slope optimization methodology applied utilized input from SRM modelling to identify the spatial variation in parameters, by highlighting possible areas (of any size or shape) that show unfavourable interactions with slope geometries in early-stage projects, current operations, and future pushbacks. This approach exploited the integration of modern, smooth, implicitly built, radial basis function-derived surfaces and solids in geological/structural geological modelling as critical inputs to slope design, based on maps that show the continuous variation of certain parameters throughout the volume of interest. This slope design methodology can be accommodated from early-stage projects through to revised planning cycles in operating mines. A risk-based approach is followed, which includes focused data acquisition, rigorous stability analysis, and risk assessment in areas of concern, and risk mitigation from early project stages to operating mines. The approach therefore deals with the common fact that slope instability is one of the major sources of risk in open pit mining. This is mainly due to data uncertainties. The development of a geotechnical block model as the main output of the geotechnical engineering function is essential to support the iterative process that will facilitate a dynamic model that can be continuously updated with new information.

The value that was created in the slope optimization process was reported in the company's 2018 Annual Report (Anglo American, 2019):

> *'Reserve life increased to 14 years (from 13 years in 2017), as a result of the optimised pit slope designs built into the updated LoM [Life of Mine] plan life and productivity improvements.*
> *'Most of the annual increase can be attributed to a steepening of the pit slopes of the Sishen pit design resulting in a 50.8Mt increase in Ore Reserves, based on advances made in the spatial geotechnical modelling field enabling a better spatial understanding of pit slope failure mechanisms, allowing for optimisation of pit slope designs.*
> *'Sishen – in 2018 a slope optimisation project was completed which resulted in a reduction in the LoM stripping ratio from 3.89:1 in 2017 to 3.4:1 in 2018.)*

The increase in NPV achieved, mainly due to the slope optimization, was approximately $700 million.

Ground support

The process for selection of ground support for underground mines is well established and follows engineering guidelines. It is relatively straightforward to determine the unit costs and installation costs for ground support. When these are combined with time studies then the decision-makers can make informed choices that meet the technical requirements and are cost-effective. In order to quantify the true value of these choices, however, it is necessary to address the long-term performance of ground support. In practice a significant degradation of ground support over time may require rehabilitation, *i.e.*, additional ground support or replacement of existing support. In this context, what originally may have been considered as both meeting the technical requirements and reducing costs may not be appropriate.

In the mining environment, rock engineering has significant safety implications, but it is often regarded as a cost. Mercier-Langevin (2019) reports that ground support, depending on the prevailing ground conditions, can make up a sizeable portion of the operating budget of an underground mine. For example, ground support material costs at the LaRonde mine, which manages severe squeezing ground and significant seismic risk, were triple those at Goldex mine, which did not have to cope with the same level of geotechnical problems. If one also considers the related development costs it can be seen that the choice of ground support has a significant impact on the profitability of an operation. A further challenge is defining the success of any ground support strategies based on the objectives. For example, in squeezing ground, the objective of ground support is to manage deformation and keep the excavation safe for workers for its service life (Mercier-Langevin and Hadjigeorgiou, 2011). In seismically active ground, the objective of support is to withstand the amount of energy that an event of a given magnitude is expected to generate in order to contain rock ejection. It is now standard practice to use yielding or energy-absorbing ground support elements for both extreme squeezing and seismically active or rockburst-prone conditions.

It is remarkable that, although rockbursts are recognized as major safety hazards, which may result in significant disruptions, and consequent negative effects on the economics of mining and tunnelling, the industry was slow to introduce yielding support. Ortlepp (Cook and Ortlepp, 1968; Ortlepp, 1969) was probably the first to develop a yielding rockbolt for rockburst-prone ground. Testing of this bolt under dynamic loading conditions showed that it had great potential for containing rockburst damage, but it was never commercialized. The conebolt, developed in South Africa in the 1990s (Jager, 1992), was proven to be very effective in dynamic loading conditions (Ortlepp, 1994) but was not installed in South African mines in large numbers, probably due to short-term economic considerations. Modified conebolts were used extensively in Canada and have been successful in limiting rockburst damage (Simser, Joughin, and Otlepp, 2002). Most seismically active mines now use dynamic or enhanced ground support. For example, Creighton mine in Canada has demonstrated that modifications to its ground control strategies and the use of yielding support had a significant impact the evolution of the frequency and severity of rockbursts (Figure 1).

In retrospect, the reluctance to introduce what is arguably a more effective ground support strategy for extreme conditions is surprising. The reason is probably that yielding bolts are somewhat more expensive than conventional bolts. However, using mine costing data for all aspects of bolt installation (bolt, grout, drilling, labour), it was shown that by increasing conebolt spacing by only 5 cm, the overall cost of the installed yielding support was identical to that of conventional rockbolt support (Ortlepp and Stacey, 1995). The most important aspect of this comparison was, however, that the energy absorption capacities of the yielding bolts were approximately 15 times greater than those of the conventional bolts. If rockburst-resistant support had been implemented substantially, it is probable that much of the rockburst damage, associated direct and indirect costs, and accidents could have been reduced. The resulting value to the mines would have been very significant (Stacey, 2016). Recent research has been carried out (Moganedi, 2018) to estimate the economic value that could have been created by the use of rockburst-resistant support. In this research, 13 rockburst case studies were analysed. Two of these case studies were evaluated to demonstrate the value that could be created by installing appropriate rockburst support systems (Moganedi and Stacey, 2019). This indicated that such dynamic support of an access tunnel could obviate a $20 850 daily loss in revenue, as well as prevent negative consequences such as accidents, injuries, and equipment damage. The installed rock support consisted of rigid elements, as was the case in all except one of the rockbursts evaluated. In contrast, value will be created by energy-absorbing support, which will prevent, or at least reduce, damage. Many yielding support systems are now available in the market, including rockbolts, very strong mesh, and tendon straps.

An example of increased value from the selection of ground support has been observed at the LaRonde mine in Canada. Owing to a combination of high stresses and foliation in the rock mass, the mine is subject to some of the more challenging squeezing ground conditions and high convergence rates. In cases when wall stability is compromised, or if equipment clearance is insufficient, an 8-yard scoop-tram is used to 'purge' the walls, *i.e.* to remove excess material. The resulting drift dimensions require the installation of secondary back support, such as cable bolts, in order to stabilize the greater spans created by scaling of the sidewalls. LaRonde demonstrated that introducing a relatively more expensive rockbolt (the hybrid bolt) in the support system resulted in a significant reduction of 'purging' of drifts that display excessive squeezing (Figure 2). This is another example of increased value following a greater investment in ground support.

Value creation in a deep level open stoping mining environment

This case deals with gold mining at a depth of greater than 2000m, using an open stoping mining method. Instability in the stopes caused equipment damage, as well as ore dilution (le Roux, 2015). There were no safety concerns, since remotely operated LHDs were used for extraction of ore. Owing to dilution resulting from the instability, the recovered ore grade reduced from 5.5 to 4.5 g/t, and the associated loss was some $1.8 million per month

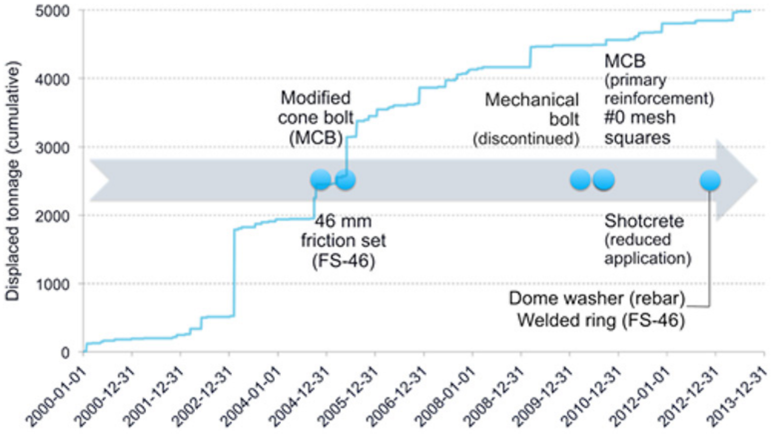

Figure 1—Correlation between the evolution of ground support systems and the frequency and severity of rockbursts at Creighton mine (**after Morissette *et al.***, 2017)

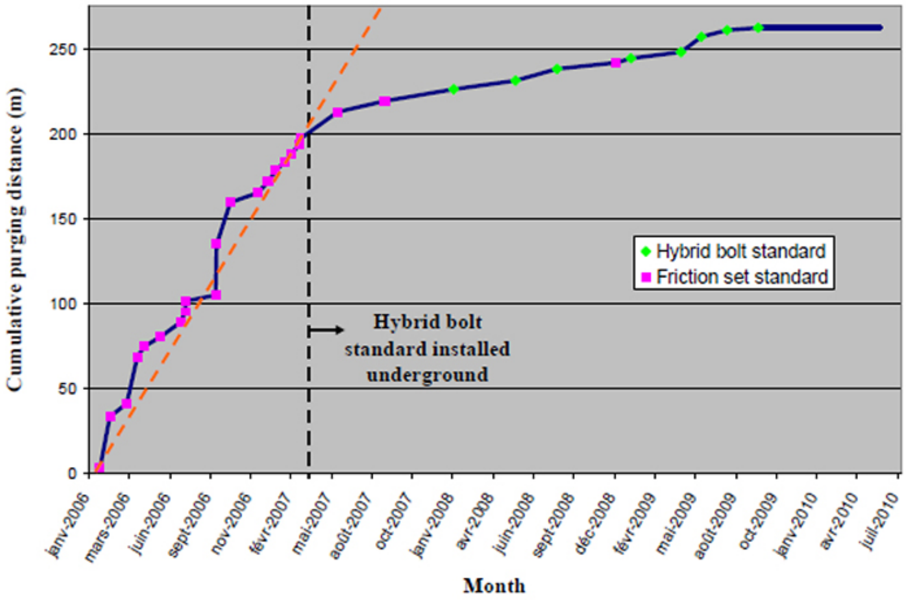

Figure 2—Reduction in cumulative distance purged under the 215 level, related to the introduction of the hybrid bolt as part of the ground support standard for squeezing rock conditions at LaRonde (after Turcotte, 2010)

(based on a gold price of $20 000 per kg). The cost of damage to trackless equipment (illustrated in Figure 3) was also significant, and in addition there were costs for standing time. A $40 million cost was estimated for a 10-year period at the mine. Other costs, associated with milling and plant treatment, secondary blasting, transport, and hoisting amounted to about $24 million. The calculated total opportunity loss was $65 million over a 10 year period. These costs indicate the significance of 'accurate' open stope design that will prevent, or at least reduce, costs due to falls of ground.

Le Roux (2015) carried out back-analyses of records of stope instability, which showed that commonly used rock mass failure criteria and empirical approaches were not applicable. Instead, he implemented a strain-based design criterion, which resulted in reliable prediction of stability of the open stopes. Very significant reductions in equipment damage and dilution (Figure 4) resulted from the revised stope designs. It was estimated that the loss of income would probably have been greater than $250 million without the strain-based design criterion, confirming the value created for the mining operation (le Roux and Stacey, 2016).

Figure 3—Equipment damage due to rockfalls in open stopes (after le Roux, 2015)

Improved design confidence due to collection of additional geotechnical data

In the early stages of mining there is commonly a deficit in the geotechnical data available for mine design. The result is likely

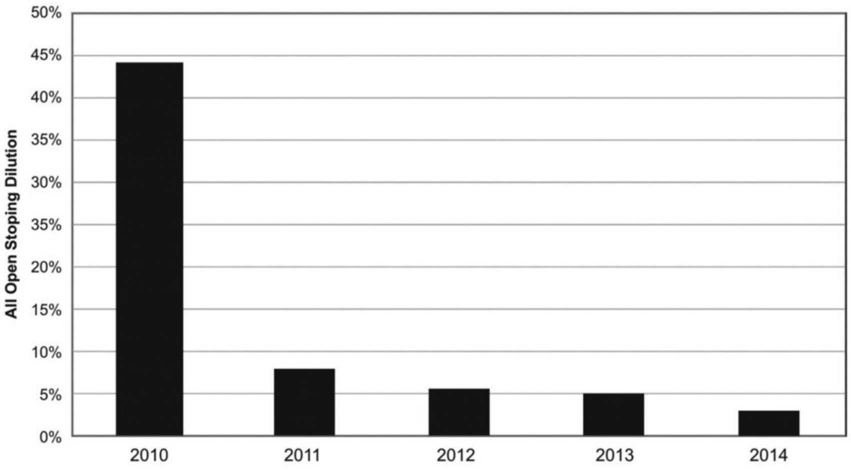

Figure 4—Annual dilution associated with deep level open stope mining (after le Roux, 2015)

to be a more conservative design to allow for the ’unknown’ conditions. As mining progresses and more rock surfaces are exposed, there is the possibility of obtaining additional geotechnical information and thus improving the design. There is also the possibility, due to the creation of the mining excavations, of new locations for borehole drilling, also to gain more information on the rock mass. However, such additional work involves extra costs which mining companies are often loath to incur. It is not unusual to find that preliminary or incomplete data from the feasibility stage is still the basis of important decisions.

To address the value of additional investigations, Fillion and Hadjigeorgiou (2016, 2017; 2019) carried out research to quantify the improvement in confidence in geotechnical data This work demonstrated that committing funds to additional geotechnical investigations and rock testing provided value through the increased confidence in the data that could then be used for design revisions. Although this research did not quantify actual financial values created, it did clearly show, for example, that the new information would allow open pit slopes to be steepened. In a deep open pit, the value created by steepening of slopes by as little as 1° or 2° could run to hundreds of thousands of dollars. This would clearly justify the additional expenditure on further geotechnical investigations and revised mine design work.

Having established that there is value in additional information, it is possible to establish an informed strategy. Figure 5 illustrates the resulting confidence intervals for uniaxial compressive strength tests for different tock types at the same mining operation. It clearly demonstrates that the number of tests required to attain the same confidence interval differs according to rock type. As the sampling and laboratory costs are independent of rock type it is possible to quantify the increased value, *i.e.*, greater confidence in the design parameters, of additional tests for each rock type.

Suggested QVP implementation

In this section, a logical process for the implementation of the QVP will be described. This work is inspired by the engineering design process developed by Bieniawski (1988, 1992, 1993), whereby ‘mine design is a process based on empiricism and practical experience that does not qualify as engineering design’. The lack of a thorough engineering design process in mining is sometimes attributed to significant variability and geological complexity in the rock masses that host the mining. However, a more likely explanation is the attitude of many mining personnel, for example – ‘Our mine is different, and therefore what applies elsewhere, does not apply here.’ This is further compromised by a perception that the economics of the project do not justify the additional costs. Such attitudes do not facilitate the implementation of a thorough design process and are difficult to justify.

Bieniawski (1992) defined six design principles, which expanded into a ten-step design methodology or process. Owing to the close correspondence between this process and a circular ten-step strategic planning process (Ilbury and Sunter, 2005), Bieniawski’s process was cast into a circular format, referred to as the ‘wheel of design’ (Stacey, 2009). This circular format has been adopted for the proposed QVP. Basing the QVP on an engineering design process and a strategic planning process are considered to be completely justified, since it is essential that a decision-making process in mining must take into account both engineering design issues as well as short-, medium-, and long-term strategic planning issues. Figure 6 shows a recommended QVP wheel, with its ten steps: the different colours indicate the different levels of responsibility for carrying out the step. There is significant responsibility indicated for the executive level (directors) since they determine the policies and expectations for the company. Lower level personnel will be required to supply the quantified information that is essential to enable senior personnel to make appropriate, well-informed decisions. The following are the suggested ten steps of the QVP.

1. *Clear definition of the objectives of the decision process*
   This is an extremely important step in which directors and senior management must define the overall aims, for example ‘world-class block caving operation’, ‘safe mine’; ‘no long-term environmental damage’, ‘company policies’ or acceptable risk.
2. *Constraints: restrictions that may affect the decision process*
   Constraints may be related to the mining company itself, for example, accommodation and availability of personnel, equipment maintenance facilities, *etc*., and/or the country, for example, the country’s laws, rail capacity, harbour capacity, electricity supply, water supply.

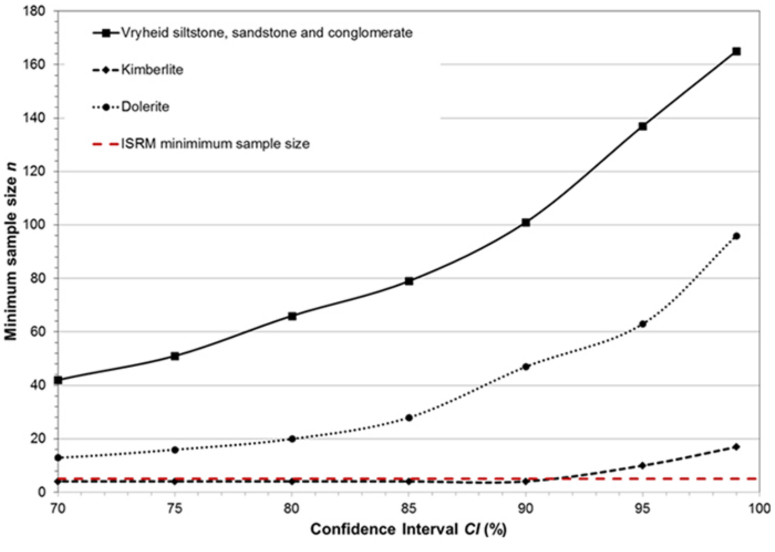

Figure 5—Minimum number of specimens required for a given confidence interval for UCS (**after Fillion and Hadjigeorgiou, 2017**)

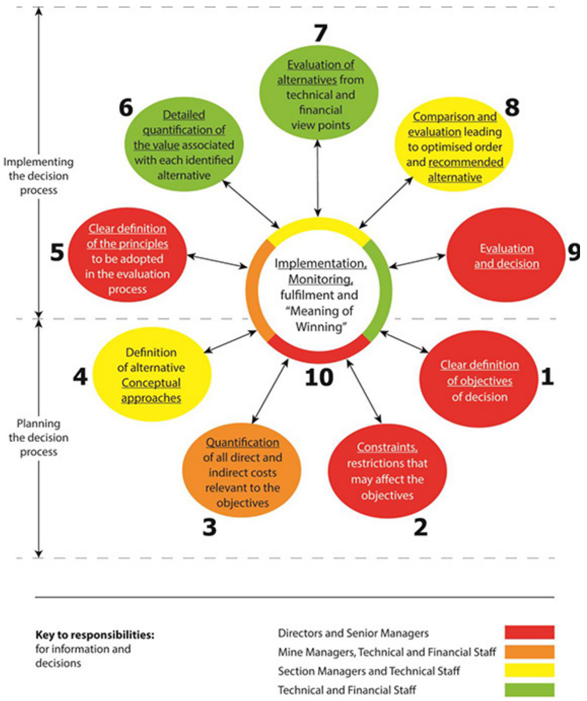

Figure 6—Quantified Value-created Process wheel. The arrows on the spokes of the wheel indicate that, at each step, the requirements of previous steps must continue to be met; in particular, that the objectives defined in step 1 of the process are being addressed

3. *Quantification of all direct and indirect costs relevant to the objectives*
   In this step, a catalogue of costs would be compiled, for example, drilling costs, blasting costs, rock support costs, loading and hauling costs, *etc*., and indirect costs such as costs of falls of ground, costs of rehabilitation of support, costs of accidents, costs of damage to equipment, and (probably most significantly) costs of loss of production due to any of the factors listed (and others). Costs associated with past occurrences on the mine or experienced by the mining company, such as collapses, equipment damage, orepass blockages, shaft instability, *etc.* would be sources of information in compiling the catalogue, which is then available for reference in the considerations in step 4, and is essential for step 6.
4. *Definition of alternative conceptual approaches (to achieve the objectives)*
   In this step, alternative mining methods and layouts that would potentially achieve the objectives would be considered (including excavation methods, excavation sizes, rock support methods, *etc*.), ideally allowing the alternatives to be listed in preferential order for quantification in step 6.

The first four steps of the process involve the planning of the decision process. This stage is extremely important, requiring very clear thinking and definition of objectives, culminating in alternative conceptual approaches to be considered. Significant director-level input is required in this first stage, and in the definition of the principles to be adopted in the evaluation process (step 5).

The following six steps involve the more routine or 'number-crunching' part of the process, to provide the quantification of value on which the ultimate decision will be based. Directors and senior managers will make the final decision in step 9, followed by the actual implementation in step 10.

5. *Clear definition of the principles to be adopted in the evaluation process*
   Non-negotiable company policies will be stated, essentially defining the company's ideals and standards to be used in the evaluation process.
6. *Detailed quantification of value associated with each identified alternative*
   Using the catalogue of costs developed (step 3), the value created in each step 4 alternative must be quantified. Importantly, this should be aimed at avoiding losses rather than minimizing costs. The example referred to in the section 'Design and operation of orepasses' is relevant: locating an orepass close to an open stope may minimize tramming costs, but the pass may become unstable as the stope is mined due to stress concentrations in its vicinity. Costs will then increase substantially owing to loss of production due to non-availability of the pass, or to much greater tramming costs if an alternative, distant orepass has to be used. A second example is the choice of rock support – limiting the amount, type, and capability of the support may apparently reduce costs, but will result in greater potential for instability, rockfalls, possible accidents, and equipment damage, leading to loss of production and the requirement for rehabilitation and re-supporting. The importance of taking into account indirect costs cannot be overemphasized.
7. *Evaluation of value created for each alternative from technical, financial, health and safety, ethical, social, and environmental viewpoints*
   In addition to the quantified value determined in the step above, this step will take into account further aspects such as health and safety, ethical, social, and environmental effects, which may not be fully quantifiable, but which may influence the ultimate decisions.
8. *Comparison and evaluation, leading to optimized order and recommended alternative*

The outputs from steps 6 and 7 must be carefully considered and presented in optimized order of value created, for thorough evaluation by the executives and senior management.

9. *Executive evaluation and decision*
   This is the final executive step of the process, in which the final decision on the method of execution of the project is made.
10. *Implementation, monitoring, fulfilment, and the 'meaning of winning'*
    The decision is implemented, and the progress must be monitored to check that the project is performing as predicted. If there is any deviation from the predicted performance, it may be necessary to intervene in the process (*i.e.*, reconsider appropriate earlier steps) to bring the project back to the desired performance. The ultimate aim is to achieve fulfilment and, as indicated by Ilbury and Sunter (2005) in their strategic planning process, the 'meaning of winning'.

A critical element in the implementation of the QVP is recognizing the role of personnel within the organization in the cession and implementation process. Although there are inherent variations within each organization, it is important that the levels of responsibilities are well defined and well understood. In a discussion on managing risk, Hadjigeorgiou (2020) suggested that the purpose of risk management is the creation and protection of value. In a mining company, risk management responsibilities are shared or assigned to different players. A similar template that would address the QVP could be as follows.

- ➤ The Board of Directors is generally assigned a risk oversight role. Atkins and Ritchie (2019) further suggest that there is need for mining expertise in a board and upper management in order to be able to request the appropriate assurance of mining-specific technical and operational risk.
- ➤ Senior management designs and implements processes that respect the Board's corporate risk strategy and that function as directed. It is the responsibility of senior management to instil a culture of risk-adjusted decision-making throughout the organization and provide guidelines to technical personnel. Finally, senior management informs the Board on the company's most material risks, how these risks interrelate, how they affect the company, and how management addresses them.
- ➤ Mine management is responsible for the day-to-day operation. In a single-asset company there is an overlap between responsibilities of senior corporate and mine management.
- ➤ The main responsibility of the technical engineering group is to design and construct engineering structures and provide oversight to operations. They employ risk analysis tools to identify and quantify geomechanical risk. Finally, they provide input to the company risk policy/strategy.
- ➤ The main emphasis of operations is to implement good practice to ensure the safety of personnel and equipment, and to limit or mitigate risk.

This terminology has been used in the QVP wheel in Figure 6.

Discussion and conclusions

Examples have been illustrated of the major value that can be created in projects by careful attention to engineering design and implementation. The values created in these examples were determined after the event, but they do indicate the enormous value that could be used for justification of planning and design decisions. In most of these cases, although the value created has been quoted in financial terms, it must be recognized that much non-financial value will often be created as well. Examples are health and safety, and social aspects such as extended employment periods, which are of benefit to the employees as well as their dependents and the community. Social value will also be created by careful management of environmental matters.

In contrast with conventional risk evaluation processes, which tend to focus on negative aspects such as costs and potential losses as the basis for decisions, the proposed decision-making process, based on quantitative evaluation of the value that can be created, focuses on the upside or positive aspects. This proposed process is firmly rooted in well-established engineering design and strategic planning principles, which are essential components of mine planning, design, and operation. The logical QVP presented requires significant input from executives, particularly in the early stages, and this will ensure that ethical and responsible decisions are made, and that short-, medium-, and long-term strategic considerations are taken into account. Quantification of the inputs to the process, as required by the executives, will be supplied by mine management personnel and mine technical specialists, who have access to the appropriate costing information and to records of past performance on the mine, including accidents, damage, collapses, dilution, loss of production *etc*., and associated costs. This will allow the benefits of additional investment to be quantified. For example, the value created by installing better, but more costly, rock support; the value of improved monitoring for advanced indication of any instability, with the potential of then avoiding the instability, and with the associated safety value; and of course ensuring that any loss of production is minimized. The ultimate decision on the implementation of chosen option is again the responsibility of the executives, based on the quantified value-created data. All steps involved in the process should be monitored to ensure that the objectives defined in step 1 of the QVP are met. Any deviation from these objectives may require intervention (such as returning to an earlier step) to bring the process back on track.

It is suggested that the proposed QVP is a logical decision-making system that will result in decisions that will be of great benefit in the planning and operation of mines.

References

Atkins, A.C. and Ritchie, M. 2019. Improving board assurance of technical and operational risks in mining. *Proceedings of the First International Conference on Mining Geomechanical Risk*. Australian Centre for Geomechanics, Perth. pp. 97-110.

Bester, M. 2019. A risk based methodology to improve the definition of geotechnical design sectors in slope design. PhD thesis, University of the Witwatersrand. 214 pp.

Bester, M., Stacey, T.R., Basson, I., Koegelenberg, C., Creus, P., Lorig, L., and Cabrera, A. 2019. A risk-based methodology to improve the definition of geotechnical design sectors in slope design. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 119. pp 1027-1038.

Bieniawski, Z.T. 1988. Towards a creative design process in mining. *Mining Engineering*, vol. 40. pp. 1040-1044.

Bieniawski, Z.T. 1992. Invited Paper: Principles of engineering design for rock mechanics. *Rock Mechanics*. Tillerson, J.R and Wawersik, W.R. (eds). Balkema, Rotterdam. pp. 1031-1040.

Bieniawski, Z.T. 1993. Principles and methodology of design for excavations in geologic media. *Research in Engineering Design*, vol. 5. pp.49-58.

Bye, A. 2003. The development and application of a 3D geotechnical model for mining optimisation, Sandsloot open pit platinum mine, South Africa, PhD thesis, University of Natal. 203 pp.

Bye, A. 2005a. The strategic and tactical value of a 3D geotechnical model for mining optimisation, Anglo Platinum, Sandsloot open pit. *Proceedings of the 1st International Symposium on Strategic vs. Tactical Approaches in Mining*. South African Institute of Mining and Metallurgy, Johannesburg. 13 pp.

Bye, A. 2005b. Unlocking value through the application of EDD's at Anglo Platinum's, PPRust open pit operations. *Proceedings of the 1st International Symposium on Strategic vs. Tactical Approaches in Mining*. South African Institute of Mining and Metallurgy, Johannesburg. 30 pp.

Bye, A., Little, M., and Mossop, D. 2005. The strategic and tactical value of slope stability risk management at Anglo Platinum's Sandsloot open pit. *Proceedings of the 1st International Symposium on Strategic vs. Tactical Approaches in Mining*. South African Institute of Mining and Metallurgy, Johannesburg. 20 pp.

Contreras, L.F. 2015. An economic risk evaluation approach for pit slope optimization. *Journal of the Southern African Institute of Mining and Metallurgy*, vol 115. pp. 607-622.

Cook, N.G.W. and Ortlepp, W.D. 1968. A yielding rockbolt. *Bulletin of the Chamber of Mines of South Africa*, no. 14. pp 6-8.

Cunningham, C.V.B. 1986. The Kuz-Ram model for prediction of fragmentation from blasting. *Proceedings of the 1st International Symposium on Rock Fragmentation by Blasting*, Luleå University of Technology, Sweden, 23-26 August 1983. Luleå University of Technology. pp. 439-452.

Fillion, M-H. and Hadjigeorgiou, J. 2016. Implications of collecting additional data for slope design in an open pit operation. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 116. pp. 357-366.

Fillion, M-H. and Hadjigeorgiou, J. 2017. Quantifying the impact of additional laboratory tests on the quality of a geomechanical model. *Rock Mechanics. and Rock Engineering*, vol. 50. pp. 1097-1121.

Fillion, M-H. and Hadjigeorgiou, J. 2019 Quantifying influence of drilling additional boreholes on quality of geological model. *Canadian Geotechnology Journal*, vol. 56. pp. 347-363.

Glass Lewis. 2021. An overview of the Glass Lewis approach to proxy advice. Proxy paper™ Guidelines. San Francisco, CA. 47 pp.

Hadjigeorgiou, J. 2020. Understanding, managing and communicating geomechanical mining risk. *Mining Technology*, vol. 129, no. 3. pp. 159–173.

Hadjigeorgiou, J. and Stacey, T.R. 2013. The absence of strategy in ore-pass planning, design and management. *Journal of the Southern African Institute of Mining and Metallurgy*, vol 113, no. 10. pp. 795-801.

Haines, A. and Terbrugge, P.J. 1991. Preliminary estimation of rock slope stability using rock mass classification systems. *Proceedings of the 7th International Congress of the International Society of Rock Mechanics*, Aachen. Balkema, Rotterdam, vol. 2. pp 887-892.

Ilbury, C. and Sunter, C. 2005. The Games Foxes Play – Planning for Extraordinary Times. Human and Rousseau Tafelberg. 180 pp.

Jager, A.J. 1992. Two new support units for the control of rockburst damage, *Proceedings of the International Symposium on Rock Support*, Laurentian University, Sudbury, Ontario. Kaiser, P.K. and McCreath, D.R. (eds.). Balkema, Rotterdam. pp. 621-631

Laubscher, D.H. 1990. A geomechanics classification system for the rating of rock mass in mine design. *Journal of the South African Institute of Mining and Metallurgy*, vol. 90. pp. 257-273.

Le Roux, P.J. 2015. Measurement and prediction of dilution in a gold mine operating with open stoping mining methods. PhD thesis, University of the Witwatersrand.

Le Roux, P.J. and Stacey, T.R. 2017. Value creation in a mine operating with open stoping mining methods. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 117, no. 2. pp. 133-142.

Lessard, J.F. and Hadjigeorgiou, J. 2006. Ore pass database: Quebec underground metal mines. *CIM Bulletin*, vol. 99, no. 1093. pp 1-12.

Lilly, P.A. 1986. An empirical method of assessing rock mass blastability. *Proceedings of the Large Open-Pit Mining Conference*, October 1986. Australasian Institute of Mining and Metallurgy, Melbourne. pp. 89-92.

Little, M.J. 2006a. Geotechnical strategy and tactics at Anglo Platinum's PPRUST open pit operation, Limpopo Province, South Africa. MSc dissertation, University of the Witwatersrand. 176 pp.

Little, M.J. 2006b. The benefit to open pit rock slope design of geotechnical databases. *Proceedings of the International Sympoeium on Stability of Rock Slopes*, Cape Town. Southern African Institute of Mining and Metallurgy, Johannesburg. 14 pp. https://www.saimm.co.za/Conferences/RockSlopes/097-116_Little.pdf

Little, M.J., Bye, A.R., and Stacey, T.R. 2007. Safety and financial value created by good slope management strategies and tactics. *Proceedings of the 6th Large Open Pit Mining Conference*, Perth. Australasian Institute of Mining and Metallurgy, Melbourne. pp 77-85.

Mercier-Langevin, F. 2019. Ground support: A mine manager's perspective. *Proceedings of Ground Support 2019*. Hadjigeorgiou, J. and Hudyma, M. (eds). Australian Centre for Geomechanics, Perth. pp. 29-40.

Mercier-Langevin, F. and Hadjigeorgiou, J. 2011. Towards a better understanding of squeezing potential in hard rock mines. *Mining Technology*, vol. 120, no. 1. pp. 36-44.

Minney, D.S. 1990. Damage and remedial action taken to secure the Free State Saaiplaas No 3 Shaft on 1780 Level. *Proceedings of the Symposium on Rock Instability Problems in Mine Shafts*, Potchefstroom, May 1990. South African National Group of the International Society of Rock Mechanics. pp. 65-72.

Moganedi, K.A. 2018. Reducing risks due to rockbursts: Strategic financial considerations. MSc Eng dissertation, University of the Witwatersrand. 143 pp.

Moganedi, K.A. and Stacey, T.R. 2019. Value creation as an approach to the management and control of rockburst damage in tunnels. *Tunnelling and Underground Space Technology*, vol. 83. pp. 545-551.

Morissette, P., Hadjigeorgiou, J., Punkkinen A.R., Sampson-Forsythe, A., and Chinnasane, D.R. 2017. The influence of mining sequence and ground support practice on the frequency and severity of rockbursts in seismically active mines of the Sudbury Basin. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 117. pp. 47-58.

Ortlepp, W.D. 1969. An empirical determination of the effectiveness of rockbolt support under impulse loading. *Proceedings of the International Symposium on Large Permanent Underground Openings*, Oslo, September 1969. Brekke, L. and Jorstad, F.A. (eds). Universitats-forlaget. pp. 197-205.

Ortlepp, W.D. 1994. Grouted rock-studs as rockburst support: A simple design approach and an effective test procedure. *Journal of the South African Institute of Mining and Metallurgy*, vol. 94. pp. 47-63.

Ortlepp, W.D. and Stacey, T.R. 1995. The spacing of support - safety and cost implications. *Journal of the South African Institute of Mining and Metallurgy*, vol. 95. pp. 141-146.

Preis, E.P. and Webber-Youngman, R.C.W. 2021. Identification of cost factors relating to mining incidents. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 121. pp. 39-46.

Read, J. and Stacey, P. (eds). 2009. Guidelines for Open Pit Slope Design. CSIRO Publishing, Collingwood, Victoria. 496 pp.

Roux, A.J.A, Leeman, E.R., and Denkhaus, H.G. 1957. De-stressing: A means of ameliorating rockburst conditions. Part 1 – The concept of de-stressing and the results obtained from its application. *Journal of the South African Institute of Mining and Metallurgy*, vol. 57. pp. 101-119.

Russell, T. and Stacey, T.R. 2019. Using laser scanner face mapping to improve geotechnical data confidence at Sishen Mine. *Journal of the Southern African Institute of Mining and Metallurgy*, vol 119. pp. 11-20.

Simser, B., Joughin, W.C., and Ortlepp, W.D. 2002. The performance of Brunswick Mine's rockburst support system during a severe seismic episode. *Journal of the South African Institute of Mining and Metallurg*, vol. 102. pp 217-224.

Stacey, T.R. 2009. Design – A strategic issue. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 109, no 3. pp. 157-162.

Stacey, T.R. 2016. Addressing the consequences of dynamic rock failure in underground excavations. *Rock Mechanics and Rock Engineering*, vol. 49 , no 10. pp. 4091-4101.

Stacey, T.R., Terbrugge, P.J., and Wesseloo, J. 2007. Risk as a rock engineering design criterion. *Challenges in Deep Level Mining*. Potvin, Y., Hadjigeorgiou, J., and Stacey, T.R. Australian Centre for Geomechanics, Perth. pp. 17-23.

Terbrugge, P.J., Wesseloo, J., Venter, J., and Steffen, O.K.H. 2006. A risk consequence approach to open pit slope design. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 106. pp. 503-511.

Toper, A.Z. 2003. The effect of blasting on the rockmass for designing the most effective preconditioning blasts in deep-level gold mines. PhD thesis, University of the Witwatersrand. 359 pp.

Toper, A.Z., Kabongo, K.K., Stewart, R.D., and Daehnke, A. 2000. The mechanism, optimization and implementation of preconditioning. *Journal of the South African Institute of Mining and Metallurgy*, vol. 100. pp. 7-16.

Turcotte, P. 2010. Field behaviour of hybrid bolt at LaRonde Mine. *Proceedings of the Fifth International Seminar on Deep and High Stress Mining*. Van Sint Jan, M. and Potvin, Y. (eds). Australian Centre for Geomechanics, Perth. pp. 309-320. ◆