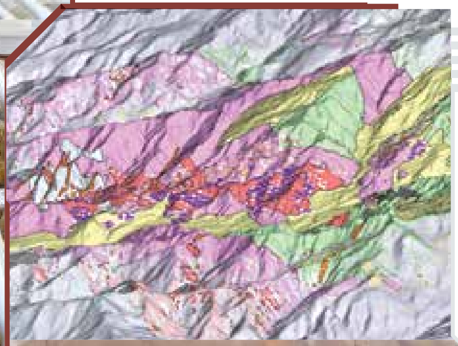

UNDERSTANDING MINE TO MILL

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CRC ORE

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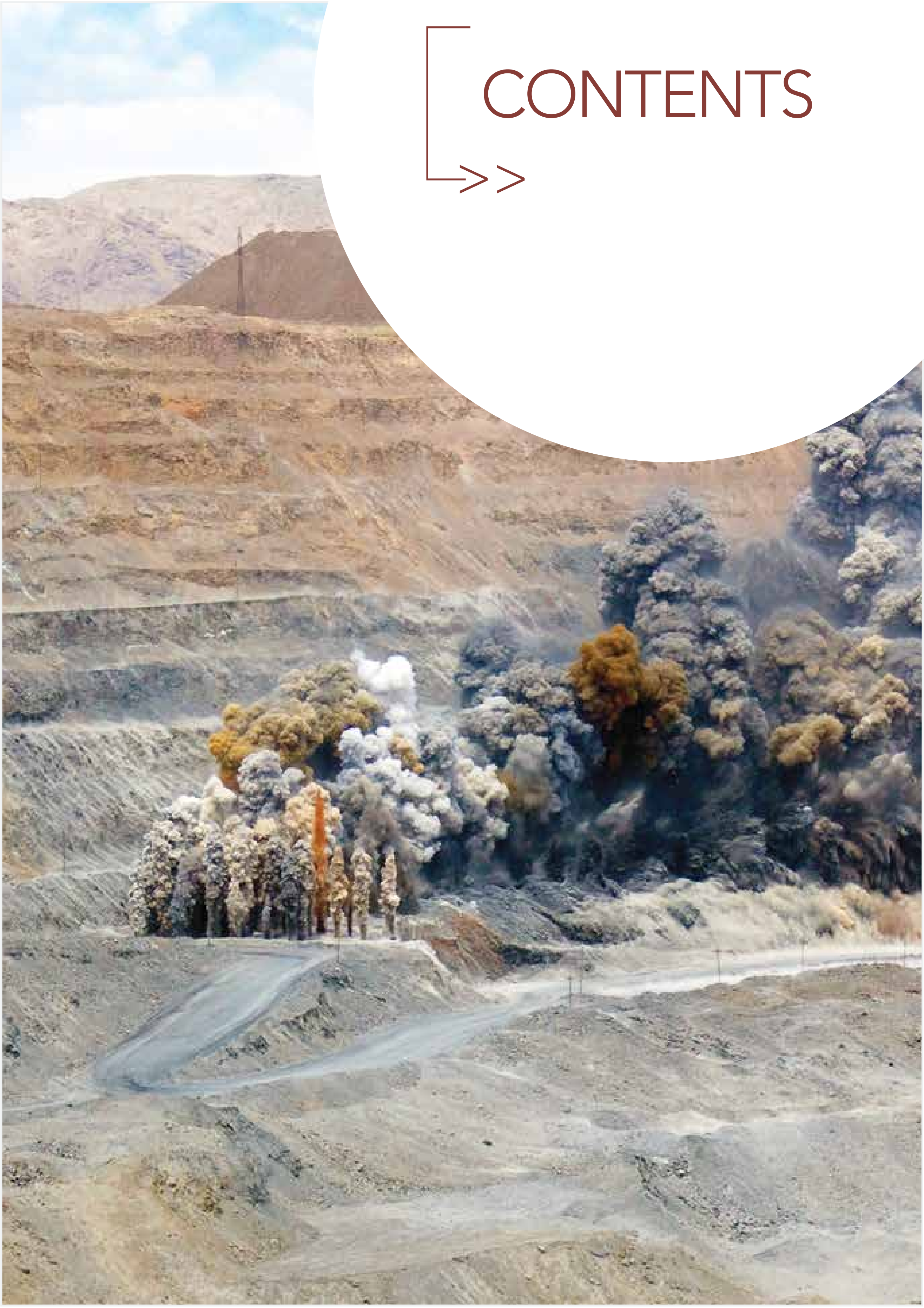

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Foreword

Mine to Mill, which links aspects of mining and mineral processing in order to optimise the combined mining and processing stages, has been under development and use for the last 20 years. Implemented effectively, numerous operations have experienced productivity gains from Mine to Mill in the range of 10-20%.

As is often the case in the mining industry, these gains have been achieved through an effective combination of research and development at mine sites. Since its inception in 2010, the Cooperative Research Centre for Optimising Resource Extraction (CRC ORE) has been involved in research and on-site development to extend established Mine to Mill practice by focusing on optimising metal extraction across the whole value chain. Branded *Grade Engineering™*, this work has a particular focus on gangue rejection at coarse scales, for example blasting, screening and sorting.

The clear lessons are that Mine to Mill has proven benefits and is simple technically. However, implementing and sustaining Mine to Mill has proved difficult. The capital and operating efficiency of the industry has fallen dramatically in the last ten years as the industry has become addicted to ever greater capital intensity and consumption of power and consumables. Mine to Mill and Grade Engineering™ are concepts which can assist significantly to increase the productivity of the industry. The importance of Mine to Mill and the work of CRC ORE is that they provide solutions which can be applied immediately.

Despite the widespread application of Mine to Mill, there are aspects of the strategy which are not well understood and the range of applications is not fully appreciated. The lessons which have been learned over the last 20 years provide valuable guidance to maximize the success of future Mine to Mill applications.

The purpose of this *Understanding Mine to Mill* publication is to explain in a simple way the elements of Mine to Mill and to summarise the lessons learned and the keys to successful implementation. *Understanding Mine to Mill* does not present a detailed technical examination of Mine to Mill, but rather is designed to inform board members, senior executives and management at a strategic level.

CRC ORE is committed to the effective transfer of technologies to industry. *Understanding Mine to Mill* has been written to lay a foundation of knowledge upon which to build a successful Mine to Mill implementation.

Jonathan Loraine
Chairman - CRC ORE

Summary

Mine to Mill is an operating strategy for mining operations to enhance the performance of mining and downstream processing activities. Correctly implemented, Mine to Mill will provide:

>> True integration of geology, mining and processing functions across an operation with intangible benefits including a more cohesive, satisfied and performance oriented workforce

>> Productivity gains in the 10-20% region while reducing operating costs. This is possible by utilizing effort and cost at the most critical parts of the production chain to achieve overall productivity and cost optimisation

>> Improved predictability and hence consistency of both mining and processing performance by providing performance benchmarks for the range of ore types present in every mining operation. Such predictability allows operations to identify when performance slips below benchmarks and promptly initiate corrective action.

All of the above outcomes are available for a wide variety of open pit coal and metalliferous operations. The opportunity for productivity gains are more limited in underground operations, however gains associated with integration and predictability remain absolutely relevant in these scenarios.

Mine to Mill is a site activity and each operation must determine which of the many Mine to Mill variants fits its needs and has the greatest potential to deliver benefits. The old adage that simple is best is true with Mine to Mill, meaning that a strategy does not have to be unreasonably complex to deliver significant benefits.

The non-technical keys to a successful Mine to Mill application are:

>> Sustained drive and support of the site General Manager, backed by higher level corporate support as appropriate for the organisation and its culture

>> The establishment of a committed team of geologists, mining engineers and metallurgists to plan, develop and implement a suitable Mine to Mill strategy

>> The availability of skilled supervisors and operators to implement the strategy at field level

>> A willingness to change established operating practice in pursuit of a better common goal

>> An organisation structure which supports an integrated operations approach and the development of personal KPIs which stress the performance of the integrated operation rather than individual parts of the operation

>> An effective means of monitoring and reporting production and cost outcomes as the first step in locking in the benefits of the Mine to Mill application

INTRODUCTION

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One of the comments offered when conducting background research on Mine to Mill was the statement, "Mine to Mill is simple". In keeping with this view the objective in presenting the elements of Mine to Mill has been to adopt a logical order of presentation and to avoid complicated detail.

Understanding Mine to Mill is presented in five parts. *Part A – Setting the Scene* provides some definitions of Mine to Mill (M2M) and the historical background. A chronology of Mine to Mill developments is followed by brief descriptions of the very wide range of Mine to Mill applications which have been implemented over the last 15 years.

Part B - Selected Case Studies contains a number of case studies which demonstrate the range of Mine to Mill applications at sites. As far as possible, the format for each case study is similar and ends with a statement of the productivity gains achieved.

Brief details of the tools, both technical and operational, required to implement a Mine to Mill strategy are presented in *Part C – The Building Blocks of Mine to Mill*. The objective here is to discuss the elements in brief and simple terms, citing references to direct the reader to more detailed information.

A great deal of experience has been gained over 15 years of Mine to Mill applications. The views of many of those most intimately involved have been sought and these have been summarised under relevant headings in *Part D – Lessons Learned*. *Understanding Mine to Mill* concludes with *Part E – Delivering the Potential*, where the keys to success are presented on the basis of a great deal of practical experience.

In reading much of the extensive Mine to Mill literature a number of papers were encountered which provided excellent summaries of aspects of Mine to Mill. These papers are reprinted in the Appendix.

SETTING THE SCENE

>> PART A

THE WIDER CONTEXT

The term Mine to Mill (M2M) is now widely used within the mining industry. However, widespread usage does not necessarily equate to a clear understanding of the concept. The purpose of this booklet is to examine the elements which together make up M2M and in doing so:

- >> Provide an understanding of the concept and its applications
- >> Outline the elements which turn M2M from a concept to a broad-based production and operating tool
- >> Summarise the range of associated production applications
- >> Draw lessons from almost 20 years of experience in mining operations
- >> Discuss the keys to successful implementation of M2M

Two other terms are broadly synonymous with M2M. These are Pit to Port and Resource to Market. These terms actually encompass a wider span than the literal meaning of M2M, as both begin with the mineral resource (the orebody) and end with the final product. For the purposes of this publication the three terms will be taken as equivalent and M2M will be the one used.

This publication is not designed to provide a comprehensive technical examination of the many aspects of M2M. The target readership comprises decision makers, such as board members, senior executives and management, who are seeking an understanding of M2M and the applications, associated benefits and keys to successful implementation.

M2M is no longer an abstract concept. There are now numerous case studies at mining operations across the globe. These case studies provide a convenient base from which to examine all aspects of the M2M approach. The core of this document is based on a selection of published case studies which describe a range of different M2M applications.

Published accounts are an extremely important source of information; however, published accounts do not always tell the full story. As is commonly the case with mining related literature describing innovative advances and applications, many of the publications end at the point of demonstration of concept. The literature is often silent when it comes to reporting the long term outcomes of technical innovation, and the M2M literature is no exception. Unpublished comments from those most closely involved in the implementations are often the only source of longer term information. Where available, such comments are included in this publication.

SOME DEFINITIONS

What is actually meant by the term M2M? Researching this publication revealed four explanations which provide depth and context to the M2M concept.

In the Foreword to the AusIMM Mine to Mill Conference, Scott and Morrell (1998) wrote:

There is a growing body of evidence to indicate that effective

- >> *Orebody characterisation*
- >> *Economic optimisation*
- >> *Tracking of ore through the production chain*
- >> *Modelling of the impact of mining practices on the nature of run of mine ore*
- >> *Modelling of the impact of ore characteristics on the processing operation, and*
- >> *Controlled implementation in the field can lead to substantial improvements in process performance of a wide range of operations.*

McCaffery (2012) suggested:

Mine to Mill (and geometallurgy) is really just code for making the effort and putting the processes in place to record, in an accessible format, an understanding of the orebody, how changes in the orebody and operating practice drive productivity and production, and understanding the operating parameters in the mine and mill which can be manipulated to improve productivity and operating cost.

It is what people in mining and processing at sites should be doing as a normal part of their day to day business.

The above descriptions are broad in scope, which is appropriate as M2M spans (at a minimum) the domains of geology, geotechnical/rock mechanics, mining and processing. Further, all of the precisely identified aspects listed by Scott and Morrell are implicit within McCaffery's explanation written 14 years later.

The 14 year span is interesting. The comments of Scott and Morrell were written not long after the first concerted investigation of M2M in the mid-1990s (see *Brief History* below). Within a short time, the necessary elements of M2M had been understood and benefits of successful implementation had been demonstrated. Yet, McCaffery's final comment ("… it is what should be done in normal operations…") implies there is still a way to go to ensure the concepts are part of normal operation.

A more specific and familiar definition is provided by Adel et al (2006):

Mine to Mill (optimisation) is a holistic approach to the optimisation of mining and processing operations. It attempts to minimise energy consumption of the particle size reduction processes.

The above M2M concept has an energy focus. Another familiar M2M application which has the objective of maximising grinding circuit throughput is summarised by Scott et al (2002):

Mine to Mill improvement involves optimising the chain of rock breakage processes from the in situ rock in the mine to the output of the concentrator.

It is this fourth definition, where the emphasis is on breakage and size distribution effects, which best captures the most common understanding of M2M. Although not stated, the definition carries the implication that optimisation in the mine (blasting) can result in increased comminution circuit throughput. Metal recovery was not a part of early M2M.

BRIEF HISTORY OF MINE TO MILL

Introductory Comments

The link between mining and various stages of mineral and metal extraction has existed as long as mining itself. Mining, mineral and metal extraction have always involved a series of well defined sequential stages. Whether these stages have ever been thought of in a genuinely integrated way is unclear. Certainly, the first and rightly famous mining textbook, De Re Metallica of Georgius Agricola (1560) presents the material in the standard logically ordered sequence of mining, beneficiation and smelting.

From the early 1900s mining and processing have been considered separate disciplines. In fact, the principal textbooks on mineral processing in the first half of the 20th century by Richards (1909), Taggart (1927) and Gaudin (1939) contain no mention of mining in their indices. With increasing specialisation of the mining and metallurgy disciplines, the barriers became more entrenched. The task of the mine was to produce ore at a required production rate and head grade target, and the task of metallurgists was to treat that ore, often regardless of the difficulty of the task.

Despite this separation, the realities of mining and processing have required some interaction between the disciplines. One driver of this is the impact different ore types with different processing characteristics have on the behaviour of the head grade. Ore type, generally associated with distinct geological domains and actual locations in a deposit, carries additional characteristics beyond head grade that can lead different ore types with similar head grades to behave quite differently in flotation.

Recognition of the importance of this information led to the practice of rigorous testing of ores well in advance of mining. Future ore testing had the added benefit of bringing together geologists, mining engineers and metallurgists and the frequently separate geology, mining and processing parts of an organisation.

It has been argued that this demonstrates that M2M is a very long established practice and the modern version of the concept is little more than a convenient name. In reality, the argument is unimportant. It can also be argued that it was the advent of widespread usage of computers in the mining industry from the 1960s which provided the impetus to provide a detailed quantitative link between mining and processing. Computers provided the ability to analytically assess aspects of mining and processing and perform modelling and simulations to predict the effects of changes in the mine on processing.

The Development of Modelling and Simulation

Presentations at the APCOM Conference (1969) were published in book form by the Society for Mining, Metallurgy and Exploration, with the instructive title *A Decade of Digital Computing in the Mineral Industry*. The APCOM Conference series was at the time the leading forum for papers dealing with mining industry computing applications. The 1969 event included papers on geological data storage, geostatistics, open pit design and mine planning, underground planning and mine scheduling. By this date quite detailed comminution and classification models had been developed and similar work was underway for flotation. Thus from the 1970s onwards, the models which would provide the tools for a sustained investigation of M2M opportunities were becoming available.

It is not clear when whole of operation modelling studies commenced. The 1969 and 1977 APCOM Conference proceedings do not contain any papers on whole of operation studies. However, modelling and simulation studies linking parts or all of mining operations were certainly being conducted in the mid-1970s. The author is aware of such work at Mount Isa Mines Ltd and no doubt other major companies were similarly engaged.

In 1977 the Julius Kruttschnitt Mineral Research Centre (JKMRC) commenced a project which was critical in advancing the practical understanding of blasting at mine sites. A series of Australian Mineral Industry Research Association (AMIRA) Projects, commonly known as the AMIRA Blasting Projects, began a systematic study of blasting using site based measurements. The JKMRC, which had earlier conducted pioneering research in grinding, classification and flotation modelling and simulation, rather simplistically considered blasting to be the first stage of rock breakage. Thus the AMIRA Blasting Projects had the objective of developing models which would predict fragmentation from blasting as well as muckpile shapes. The AMIRA research was concerned with metalliferous operations, while a similar research project at the JKMRC had a focus on overburden blasting for coal operations.

In 1984, Kai Nielsen conducted one of the earliest studies linking mining to processing. This work involved an analysis of the mining and processing operations at the Sydvaranger taconite mine in Norway. Nielsen, a mining engineer and staff member of the Norwegian University of Science and Technology at Trondheim, developed both technical and economic models of the mining and processing stages at Sydvaranger and demonstrated that both productivity and operating costs could be optimised by closer integration of the mining and processing steps.

Nielsen was also one of the first to consider the potential for blasting to precondition fragmented rock such that the energy required in subsequent crushing and grinding stages would be reduced.

In 1983, Claude Cunningham published a key paper describing an early fragmentation model based on his work in South Africa. Cunningham proposed the subsequently widely used Kuz–Ram fragmentation model. This model was one of the first to use input parameters including the blast design, explosive type and some rock mass parameters to predict fragmentation. The Kuz–Ram model became the basis of JKMRC fragmentation modelling work; however, the model was found to be less accurate in predicting the fine end of the size distribution. In 1994, Kanchibotla from the JKMRC developed a method to modify the Kuz–Ram model to rectify this. More recently the Swebrec function developed by Ouchterlony (2005) provided an excellent representation of a blast size distribution from coarse to fine (100 micron) size fractions.

The longstanding challenge in grinding had been to develop a robust model of autogenous and semi-autogenous grinding. One of the first true energy based and ore specific models of autogenous grinding was developed at the JKMRC by Leung (1988). The Leung model was subsequently developed by Morrell (1993) to include a robust prediction of power consumption in autogenous grinding.

Details of the modelling tools now available are presented in Part C. These include the incorporation of a range of geotechnical and other orebody parameters in the mine block model, a development which began in the late 1990s.

By the mid-1980s the JKMRC had vast experience in site based work in both blasting and milling (crushing and grinding) and associated early stage models. However, in a manner which mimicked industry, the JKMRC mining and processing groups existed in isolation.

The M2M breakthrough occurred when the self-evident was appreciated. It was well known that AG and SAG mills operated at higher tonnages with finer feeds. It had also been demonstrated that finer fragmentation from blasting could be achieved through manipulation of blast designs as well as explosive quantity and type. It should be possible to directly manipulate blasting to produce more appropriate mill feed size distributions for increased grinding circuit throughput. This led directly to a period when simulation, using blasting and comminution models, was used to explore the potential for increased mill throughput as described by Scott and McKee (1994) and McKee et al (1995).

The Role of Early Site Based Research

Site based studies have long provided a focus for research and development within the Australian mining industry and the JKMRC has been extensively involved in such work.

This work has been greatly facilitated by collaborative research undertaken through the Australian Mineral Industry Research Association (now AMIRA International) and the Australian Coal Association Research Program (ACARP).

Metalliferous blasting research was conducted by the JKMRC through the AMIRA Blasting Projects from the late 1970s till the mid-1990s. Over much the same period, the JKMRC investigated blasting in coal mining through a series of NERDDC projects (the predecessor of ACARP) and then a series of ACARP projects (JKMRC, 1982).

Both the metalliferous and coal projects were dominantly site based. One of the outcomes of this approach was the development of a detailed appreciation of the effect of the rock mass on blasting.

The simulation studies mentioned above, and the knowledge gained from the AMIRA and ACARP blasting studies, provided the impetus for a new AMIRA Project: AMIRA Project P483 – Optimisation of Fragmentation for Downstream Processing (JKMRC, 1998; JKMRC, 2002). This project undertook many site based M2M studies from 1996–2002 and played a critical role in exploring a range of M2M applications while generating widespread acceptance for the concept within the industry.

Technical Conferences

Technical conferences have provided an ongoing forum for the presentation and publication of papers relevant to M2M. For the last 15 years in particular, specialist technical conference series dealing with explosives, blasting and SAG milling have featured M2M papers.

The following conferences contain valuable papers on a variety of M2M themes:

- **ISEE Conferences**
  An annual conference held in the USA and hosted by the International Society of Explosives Engineers
- **FRAGBLAST Conferences**
  Beginning in Sweden in 1983 and subsequently held at international locations every three to four years
- **EXPLO Conferences**
  Hosted by the AusIMM every three to four years since 1988
- **SAG Conferences**
  Held in Vancouver, initially in 1989 and now every five years
- **Mine to Mill 1998**
  Hosted by the AusIMM in Brisbane

In Summary

From the early 1990s the realisation developed that there was significant potential to improve overall productivity by thinking of the mining and milling stages in a more formally linked manner. This approach was probably most clearly recognised in Australia where the term Mine to Mill was adopted in the 1990s. Two AMIRA Projects, conducted in Australia, were instrumental in providing a vehicle to bring the industry together and rigorously examine aspects of M2M strategy through research.

CHRONOLOGY OF MODERN MINE TO MILL DEVELOPMENTS AND APPLICATIONS

Experienced mining and processing people have been heard to say that the link between geology, mining and processing has long been understood and utilised in operations and this view is accepted. However, to best understand M2M application you must focus on the last two decades when M2M strategies have been actively developed.

Chronology of Mine to Mill <<

- Development of understanding, blasting and comminution models
- Anecdotal site studies

- Simulation studies
- Research projects
- First case studies at sites

- Site studies of wide range of Mine to Mill applications
- Early incorporations of orebody and processing parameters in mine block model

- On going population of block model with orebody and processing parameters
- Mine to Mill as a production planning tool
- Integrated simulation systems

The M2M story over the last 20 years (above) is shown as a timeline of significant developments. This time may be divided into three periods of development as follows.

Phase 1: 1990 to 2000

This first phase involved the investigation of M2M potential via simulation, the first research projects and early case studies as follows:

- 1993–1997: Simulation studies examining the link between blasting fragmentation and SAG mill throughput (Smith et al, 1993; McKee et al, 1995)
- 1995: Change in thinking in the Mt Isa Pb-Zn operations — the mine is a factory (Pease et al, 1998)
- 1993–1995: ACARP Project *Assessment and Control of Coal Damage and Loss*
- 1996–1998: First AMIRA Project *Optimisation of Fragmentation for Downstream Processing* involving numerous site-based case studies

Phase 2: 2000 to 2010

This ongoing second phase has involved the continuation of case studies with a wide range of mine site applications. This has seen the methodology extended to include the mine block model as an integral part of M2M, as well as the following developments:

- Completion of the AMIRA Project *Optimisation of Fragmentation for Downstream Processing* in 2002
- Investigation of more refined blasting techniques for fragmentation control, for example Paley (2010)
- Inclusion of ore hardness parameters (Amelunxen et al, 2001) and geotechnical parameters (Bye, 2006; McCaffery et al, 2006) in the mine block model and subsequent mill throughput optimisation

Phase 3: 2010 to Present

While the present work includes all of the earlier applications, there is now a far greater focus on the productive use of the wide range of geotechnical and metallurgical data now available for orebodies. This approach builds on the earlier work in Phase 2 to incorporate such data in the block model, and is opening the way for new M2M applications including production planning and selective upgrading of mined ore. Examples include:

- Inclusion of geometallurgy parameters in the mine block model (Wirfiyata and McCaffery, 2011) and for production planning (Bye, 2011)
- Development of an integrated simulation system which directly links blasting, comminution and flotation (Bye, 2011)

RANGE OF APPLICATIONS

The applications outlined below represent a wide range of M2M implementations. One of the criteria for selection is that the application must have been described in the literature. Another is that each application must have some features which are different from the others.

Quarrying: the effect of blast fragmentation on crushing and screening performance

One of the earliest reported studies is that by Kojovic, Michaux and McKenzie (1995). In this case study conducted in an operating quarry, the effect of different blast designs on blast fragmentation and muckpile shape were measured. This was followed by a systematic assessment of the resulting crushing and screening performance, including the size distributions and particle shape of final products.

Similar studies have been reported by Tunstall and Bearman (1997), Nielsen and Kristiansen (1995) and Adel et al (2006).

Selective underground mining for improved flotation performance

Pease et al (1998) describe a significantly revised mining strategy at the Mount Isa lead–zinc operations. Flotation performance had historically been adversely affected by the extreme variability of the ore. A systematic study of the flotation performance of ore from different parts of the active mining areas resulted in the decision to reject some ore from the mine plan. The result was a lower tonnage of ore being mined and processed, a step change improvement in the controllability and metallurgical performance of the flotation circuit, and substantially improved economics of the operation.

Increased AG/SAG mill throughput resulting from finer fragmentation from blasting

There have been numerous studies which have demonstrated that AG/SAG mill throughput can be increased by 15–20% as a result of changed blasting practices.

Morrell and Valery (2001) identified that mill throughput increases with finer feed size within reason. Finer blasting fragmentation persists through the primary crushing stage resulting in a fine feed size distribution to the mill.

Many of the earliest site studies were conducted by the AMIRA M2M projects which conducted trials at KCGM (Western Australia), Porgera (Papua New Guinea), Highland Valley (British Columbia) and Cadia Hill (New South Wales). These are reported in the SAG 2001 Conference, Karageorgos et al (2001), Lam et al (2001), Dance (2001) and Hart et al (2001).

The changes in blasting practice generally involved an increase in powder factor and in some cases changes in the blast hole diameter, drill pattern and delays and detonator system.

Measured increases in mill throughput were consistently in the 10–15% range as follows:

KCGM	14%
Porgera	15%
Highland Valley	10%
Cadia Valley	14%

Modified blasting to reduce coal fines

Fine coal (less than 1mm) is detrimental to the efficiency of coal recovery in preparation plants. Fine coal has lower yield, carries greater moisture, higher ash and is more expensive to wash than coarse coal. Fines are produced in blasting, excavation and transport. Any action that can be taken to reduce the generation of fines during these stages has a positive impact on preparation plant performance.

Scott and McKee (1994) report a study conducted at an open pit mine in the Hunter Valley where a reduction in powder factor resulted in a significant reduction in run of mine product (i.e. coal preparation plant feed).

Modified blasting in iron ore mining

Improving the proportion of lump to fine ore (the lump/fines ratio) is a common goal in high grade iron ore operations, principally because of the price premium attracted by lump ore (-31 +6.3mm) over fines (-6.3mm).

Kojovic et al (1998) reported that modifications to blast practice, including an expanded blast hole pattern, and low density and low VOD explosives resulted in improvements in the baseline lump/fines ratio of 50/50 to an average of 55/45. This was a significant improvement.

Eloranta (2001) discussed the blasting/grinding relationship in taconite mining and considered the distribution of costs between blasting and subsequent processing stages. The importance of geological structure in the orebody and its effect on blasting was also considered.

Blending for improved processing performance

Blending is standard practice in coal and iron ore operations where target product specifications are often achieved by combining different quality product lots to achieve a required overall specification. The other common application of blending is to achieve a more uniform feed prior to some beneficiation stage, particularly flotation. In these cases, blending can be considered as an alternative to a campaigning strategy where ore of varying processing behaviour is treated separately.

Blending to achieve more uniform ore for processing can be expensive in terms of both capital and operating costs. It can also be the means of achieving acceptable and sometimes greatly improved metallurgical performance.

Blending is a form of M2M management as it requires a mining and stockpiling strategy which deliberately either separates or combines ores of different characteristics.

An example of blending to achieve improved flotation performance is described by Scott and McKee (1994) for the Thalanga copper–lead–zinc operation. As a result of blending three ore types, recoveries of copper, lead and zinc all increased significantly at improved concentrate grades (see case study in Part B).

Blending of ore for improved flotation performance is also a feature of the approach at Mount Isa described by Pease et al (1998), and at the Red Dog Zn-Pb operation in Alaska, described in Paley and Kojovic's 2001 paper. Both of these case studies feature in Part B.

Blasting effects for heap leaching

A study conducted at the Cerro Colorado mine in Chile is reported by Scott et al (1998). At the time the production process involved crushing and screening of a number of different ore types followed by agglomeration with the addition of acid and leaching agents. The agglomerated material was stacked on leach pads, and copper was extracted by bioleaching. Experience indicated that copper recovery from leaching suffered if the amount of -150 microns material in the agglomeration feed exceeds 12%. Fines were equally generated in the blasting and crushing/screening stages.

Blasting tests in a blast chamber and a range of ore breakage tests were conducted to examine fines generation for the different ore types. The data was used to develop models of both the blast fragmentation and the crushing/screening stages. It was demonstrated that modifying the blast design could reduce the generation of fines. It was also shown that fines generation could be reduced by altering the crushing operation to non-choke feed conditions.

Blasting for reduced dilution

The control and reduction of dilution is an important aspect of M2M, and should be an objective of good blasting practice. Dilution is either low grade ore or waste which reports to recovered ore in excavation and is the result of inadequately defined ore/waste boundaries or blasting. Dilution is a problem in both open pit and underground blasting.

The most obvious side effect of dilution is a reduction in head grade of ore sent to beneficiation and an effective reduction in process plant capacity. The undesirable side effects of dilution exist for all minerals and are particularly serious in open pit gold mining.

Production planning

Production planning is the incorporation of ore processing characteristics in the mine block model with both short and long term planning. This is a major component of M2M application. Bennett et al (2001) describe the incorporation of ore hardness parameters in the mine block model using geostatistical methods described by Amelunxen et al (2001). The method requires extensive sampling within the mine blocks and associated hardness testing to provide sufficient data to be included in the block model.

The availability of an enhanced block model contributes to more effective M2M strategies in two ways. Firstly, it provides much greater predictability of downstream processing performance. Using the hardness information as an example, there is a much improved understanding of grinding circuit capacity as the ore source changes. Secondly, it becomes possible in some cases to adjust the mining schedule to provide ore of more uniform hardness and thus more uniform comminution circuit performance.

Bye (2006) advanced the rigour of the block model significantly by the addition of more parameters. In work which began at the Sandsloot open pit in 1997, geotechnical parameters, blastability indices and ore hardness measures were incorporated in the block model. A production strategy was developed which took into account mining productivity (principally shovel loading) and grinding circuit throughput, and blocks were blasted to optimise both. The outcome over a sustained two year period of operation was an increase in shovel loading rates of 12% and SAG mill throughput increases of 16%.

The Batu Hijau operation has developed an even more detailed production tool based on an enhanced block model (McCaffery et al, 2006; Wirfiyata and McCaffery, 2011). The Batu Hijau work began as a standard M2M application for the maximisation of SAG mill throughput. Geological, mining and processing variables have been incorporated into the block model, allowing blast designs to be tailored to ore types.

The developed methodology provides the basis for short and long term forecasting of mill production rates to an accuracy of 2% on a long term annual basis. Associated with this ability to predict expected performance is the ability to identify if grinding performance deteriorates, thus allowing corrective action to be taken in the mill.

Blasting to precondition rock

There have been numerous studies examining the use of explosive energy to precondition or weaken rock so that the energy required in subsequent crushing and grinding stages is reduced. The work of Nielsen and Kristiansen (1996), Nielsen (1999) and Michaux and Djordjevic (2005) provide additional reading.

Blasting for preferential liberation of mineral values

An interesting part of the AMIRA P483A (2003) project involved the use of blasting to take advantage of the propensity of some ores to break preferentially along grain boundaries where the mineralisation tends to be concentrated. Three ores were studied: a gold ore from Ravenswood, and copper–gold ores from Ernest Henry and Cadia. In all cases selective accumulation of gold and copper was observed in the fines and small particles, thus providing the possibility for selective recovery and treatment of the high grade fines.

Mining practice to increase the grade of mill feed

Focusing on the entire extraction sequence to reject gangue and increase head grades is not a new activity (Oltomo et al, 1988); however, the focus on scale and throughput in mining and processing has resulted in a loss of focus in the area. Consequently, in most cases mining methods focus on throughput: achieving the maximum tonnage through the mill. However, Grade Engineering™ recognises that production is not the same as productivity.

Grade Engineering™ reassesses the traditional view of mining and processing in order to identify opportunities to upgrade ore through the entire extraction process. Grade Engineering™ focuses on maximising the amount of metal processed by removing waste as early as possible. This method can significantly increase the financial return per tonne processed, while at the same time reducing cost per unit metal through reductions in energy and water use, and so transform the economics of large, low grade mining operations.

Case studies showing significant results are underway with mining operations at Telfer, Mogalakwena, Pebble, Frieda River and Escondida. These case studies are resolving key questions, such as:

>> What extraction system will leverage ore variability at low levels of workflow complexity?

>> What level of resource knowledge is required?

>> What is the unit scale of separation?

>> Where is the technical and economic balance between selective and mass processing?

The answers to these questions lay in methodologies being demonstrated through trials at the participating case study sites.

THE DOMINANCE OF OPEN PIT APPLICATIONS

The vast majority of M2M applications have been associated with open pit operations. This observation is considered in Part B.

IMPORTANT LITERATURE

our papers from the vast Mine to Mill literature are particularly useful for the way in which important aspects of Mine to Mill are presented. These papers, the first three of which are reproduced in the Appendix are:

>> Valery et al (2001) – a comprehensive description of the early application linking blasting to comminution circuit throughout

>> Scott and Morrell (2002) – useful consideration of the issues associated with assessing the outcomes and benefits of Mine to Mill applications

>> Bye (2011) – more up to date Mine to Mill applications demonstrating the way in which orebody characterisation data can be utilized

The fourth paper, Bearman (2013), is in press. It provides an up to date assessment of the opportunities to improve the productivity of comminution practice.

SUMMARY

The principal outcomes from a range of Mine to Mill studies have been:

>> Rapid take up of M2M concepts since the mid-1990s

Wide range of applications across quarrying, coal, iron ore, base metals and precious metals operations

>> Demonstrated productivity gains in the region of 10–20%

>> Main focus on open pit operations with only limited underground applications to date

>> Controlled blasting is a key in most M2M applications

>> The more effective the characterisation — from the scale of the orebody, to a mine block, to a blast bench — the greater the benefits which can be obtained

>> Inclusion of parameters relating to mining and processing characteristics within the mine block model has expanded the scope of M2M to include short and long term mine planning and scheduling

SELECTED CASE STUDIES

>> PART B

A wide range of Mine to Mill applications has been introduced in Part A. The purpose of Part B is to provide a summary of each application capturing its keys aspects, and a case study approach has been adopted to frame these summaries. The technical details of each application are available in the literature identified in each summary. Some applications are more numerous than others and in these situations more than one case study is presented.

The studies chosen broadly follow the three phases of M2M as described in Part A. Most of the early examples from the late 1990s are associated with blasting to achieve improved fragmentation and subsequently increased comminution circuit throughput. A range of applications beyond blasting and comminution are then summarised, demonstrating that M2M strategies can be widely developed for different mineral commodities. From the latter part of the period 2001–2010, a more advanced strategy emerges where orebody and metallurgical parameters are incorporated into the mine block model, providing the opportunity to improve operational predictability as well productivity.

CASE STUDY #1: Blasting for increased SAG Mill throughput — Example A

Site

Porgera, Papua New Guinea

Principal Reference

Lam et al (2001)

Brief summary of application

At the time of the study Porgera was an open pit gold mine with a conventional processing flowsheet consisting of: primary crushing followed by SAG and ball milling; flotation to produce a gold rich sulphide concentrate; and gold recovery by pressure oxidation and then a leach/CIP circuit.

The approach involved: characterising the blastability of the rock mass and determination of the breakage characteristics of mill feed; data collection in the mine and process plant to establish baseline fragmentation from a standard blast and baseline grinding circuit performance; tuning of the fragmentation model and the comminution circuit models to reproduce baseline blasting practice and grinding performance; simulation of altered blast designs to achieve finer fragmentation; selection of a promising blast design and testing of that blast design in practice; monitoring the resultant fragmentation and surveying the grinding circuit to assess performance resulting from the finer feed sizing.

In practice, the blasting powder factor was increased from the standard 0.24 Kg/tonne to 0.38 kg/tonne by tightening the drill pattern to achieve finer blast fragmentation and thus finer SAG mill feed. In addition to the baseline survey (Test 1), two grinding circuit surveys (Tests 2 and 3) were conducted with ore from higher powder factor blasts.

Outcome	Test 1	Test 2	Test 3
Powder factor (Kg/tonne)	0.24	0.35	0.38
SAG feed P50 (mm)	75	40	35
SAG Mill tph	673	NA	774
Mill tph increase		NA	15.0%

Comments

In Test 2, the recycle pebble crusher was unavailable so mill throughput could not be compared with that achieved in Tests 1 and 3.

CASE STUDY #1: Blasting for increased SAG Mill throughput — Example B

Site

KCGM (Fimiston, Australia)

Principal Reference

Karageorgos et al (2001)

Brief summary of application

The KCGM operation treats ore from the Super Pit at Kalgoorlie. This study was conducted as part of AMIRA Projects P483 and P483A. The first project involved the development of blast fragmentation and comminution circuit models, and simulation of changed blast designs. The second project involved updating the models to reflect the blasting performance in the current mining benches followed by implementation of a revised blast design, and monitoring of comminution circuit performance over an extended period approaching two years.

The KCGM comminution circuit comprised a primary crusher, Hydrocone crushers in parallel, a SAG mill with a pebble crusher and finally a ball mill — cyclone circuit.

The first stage of model development for both blasting and comminution models followed the standard approach as outlined for the Porgera study. To achieve finer blast fragmentation, the powder factor was increased by tightening the drill pattern and changing the explosive to a higher VOD emulsion. Blasting practice was changed to a higher powder factor and higher VOD explosive and the long term effects (2 year) were monitored.

Outcome	Design 1 Standard	Design 2 Simulated	Design 1 Simulated
Powder factor (Kg/tonne)	0.58	0.66	0.96
VOD (m/sec)	4550	6000	6000
SAG Mill tph	1250	1420	1480
Mill tph increase		13.6%	18.4%

Validation after implementation of Test 3 blast design

Long term SAG mill throughput with Design 1	1100 tbh
Long term SAG mill throughput with Design 3	1300 tbh
Throughput gain	18%

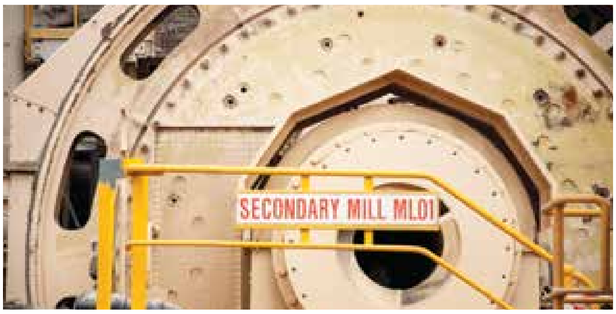
CASE STUDY #1: Blasting for increased SAG Mill throughput — Example C

Site

Red Dog (Alaska, USA)

Principal Reference

Paley and Kojovic (2001)



Brief summary of application

Over a period of 10 years at the Red Dog mine, blasting practice has been systematically modified and the effects on mill throughput have been studied. This summary covers the initial work. Subsequent developments, principally relating to the introduction of electronic detonators, are described by Paley (2010).

The Red Dog grinding circuit consists of a SAG mill in closed circuit with cyclones followed by a ball mill in closed circuit with cyclones.

Fragmentation and comminution models were developed in the standard manner. Blasting simulations were conducted to assess the effect of changed blast designs on fragmentation and subsequent performance. Results for the standard design (Design 1) and two subsequent blast designs to achieve finer fragmentation which were implemented in the mine are summarised below.

Outcome	Design 1	Design 2	Design 1
Explosive	ANFO	ANFO	70/30 emulsion
Powder factor (KG/tonne)	0.29	0.40	0.45
SAG Mill tph	125	132	140
Throughput gain		5.6%	12.0%

Economic impact

Red Dog also conducted an economic analysis of the impact of the changes in blasting and subsequent SAG mill throughput on revenue. The analysis included the effects of increased throughput offset by higher drilling and blasting costs, costs of increased waste removal and reduced concentrate recovery at higher plant throughputs. The annual net revenue gains (estimated at 2000 Zn and Pb prices) are:

Base case	$0.0m
Design2	**$0.0m**
Design 3	**$9.2m**

CASE STUDY #2: Optimising crushing performance in quarrying

Site

Mount Coot-tha (Brisbane, Australia)
Luck Stone Bealon Quarry (Virginia, USA)

Principal Reference

Kojovic et al (1995). Adel et al (2006)

Brief summary

Optimising the performance of a quarrying operation is a quite different task from that encountered in mining and mineral processing. In quarrying, the objective is to produce products in closely spaced size fractions. Particle shape is often important. Total throughput and energy consumption may be important.

The Mount Coot-tha study involved tracking the results of two blasts at different powder factors through the three stage crushing plant. Samples were taken at most points in the crushing and screening circuit, then sized and subjected to standard shape measurement.

The Luck Stone study involved an audit of the results of two blast designs on the performance of a three stage crushing and screening circuit with particular emphasis on energy consumed in crushing and screening.

Outcome

Mount Coot-tha	Shot A	Shot B
Powder Factor (kg/tonne)	061	0.52
+200mm Primary feed	48.5	54.1

No change in particle shape or size distributions of final products
Significant cost benefits with finer fragmentation (not quantified)

Luck Stone	Design 1 (standard)	Design 2	Saving
Powder factor (kg/tonne)	0.26	0.47	
Crushing energy (Kwh/t)	1.77	1.57	11.7%

Comments

Longer term assessment of the Design 2 blast revealed a much higher than expected proportion of very coarse blocks in the muckpile. This result is not consistent with the higher powder factor blasting, suggesting much of the modified blast was in different host rock. This clearly identified the importance of improved characterisation
of the rock mass.

CASE STUDY #3: Mining for improved flotation performance

Site

Mount Isa Pb/Zn (Australia)

Principal Reference

Pease et al (1998)

Brief summary

In the mid-2000s, the flotation performance of the Mount Isa Pb/Zn concentrator was unpredictable. The ore cut off value was determined by a formula based on Ag, Zn and Pb grades without consideration of the flotation performance of ore from various sources in the mine. This approach was challenged by a new General Manager who thought of the mine and mill as a manufacturing process. A new strategy was implemented which required an assessment of the head grades of each ore source, the associated concentrate grades and recoveries, and capital and operating costs for each source of mined ore.

As a result, about 30% of the ore was removed from the mine schedule and there was a similar reduction in operating costs. Equally importantly, with the removal of "bad" ore from the mill feed, the flotation operation became more controllable and predictable and performance improved significantly.

Outcome

The comparative performance of the year prior to the change and the eight months after the change is summarised below:

Reduction in tonnes mined and treated	35%
Change in silver recovery	5.0%
Change in silver production	6.5%
Change in Pb concentrate grade	2.0%
Change in Pb recovery	5.0%
Change in Pb bullion produced	10.0 %
Change in Zn concentrate grade	nil
Change in Zn recovery	2.0%
Change in Zn concentrate produced	-28%

Comments

The implementation of an integrated mining and processing approach transformed the performance of the concentrator and the economics of the overall operation. As stated by Pease et al (1998), "previously the orebody was scaled to suit the operation; now we scaled the operations to suit the orebody".

CASE STUDY #4: Ore blending for improved flotation performance

Site

Thalanga (Queensland, Australia)

Principal Reference

Scott and McKee (1994)

Brief summary

Thalanga is a Zn–Cu–Pb mine near Charters Towers. It was operated between 1989 and 1998 as both an open pit and underground mine, and reopened in 2010 as an open pit mine. The blending study described below refers to the first period of operation.

The ore grading 9.5% Zn, 1.5% Cu and 2.6% Pb was complex. Consequently, it was difficult to achieve concentrate grade specifications, particularly reducing the Pb content of the Cu concentrate and the Cu content in the Pb concentrate to acceptable levels. From the start of underground operations, flotation performance deteriorated with instabilities in the Cu circuit transmitted to both the Pb and Zn circuits.

Mill feed consisted of three distinct ore types and a blending practice was introduced. After developing close co-operation between the mine and mill, the three ore types were hauled separately to three separate stockpiles. Blending was then carried out by the mill to achieve a consistent mill feed. Along with the blended feed, reagent practice was altered.

Outcome

Three periods of flotation results are summarised below:

	Dec 91–July 92 Pre blending	July 92–June 93 Post blending	July 93–Feb 94 Post blending
%Pb in Cu conc	3.1	1.85	1.88
%Cu recovery	62.0	78.0	82.0
%Cu in Pb conc	5.13	2.48	2.32
%Pb recovery	68.0	71.0	74.0
%Zn in Zn conc	55.9	56.5	56.5
%Zn recovery	84.0	88.0	89.0

Comments

The Thalanga case study is an excellent example of a careful blending strategy. It is also an excellent example of a successful M2M strategy as it required the close co-operation of geology, mining and processing functions.

CASE STUDY #5: Optimising lump/fines ratio in iron ore mining

Site

Marandoo (Western Australia, Australia)

Principal Reference

Kojovic et al (1998)

Brief summary

One of the principal objectives in the Australian iron ore industry is to maximise the lump/fines ratio in the product from crushing and screening, as lump ore attracts a price premium. Testwork was conducted at the Marandoo iron ore mine where lump ore at the time was defined as -31+6.3 mm and fines as -6.3mm. The objective of the study was to demonstrate the potential for increasing the proportion of lump ore in product by modification of the blast design.

The Marandoo orebody contains a number of distinct ore types with different breakage behaviours. The approach involved surveys of the crushing and screening plant, determination of parameters for the fragmentation and crushing and screening models, and simulation of a range of blast designs for different ore types to demonstrate changes in lump/fines ratio. The simulations were conducted at the same crushing plant feed rate as for the audited surveys.

Outcome

The results for the original blast designs are measurements from actual surveys while the results from changed blast designs are simulated.

Ore Type	Blast Design	Lump/fines ratio
Ridge Upper	Original PF 0.30 kg/t	49/51 (measured)
	Reduced PF 0.19 kg/t	56/44 (simulated)
	Low density/Low VOD	58/42 (simulated)
Flats Upper	Original PF 0.24 kg/t	51/48 (measured)t
	Reduced PF 0.19 kg/t	55/45 (simulated)
	Low density / Low VOD	59/41 (simulated)

Comments

Ore characterisation to determine the breakage behaviour of different ore types was found to be critical, as was the delineation of the location of different ores. The results indicated a potential to improve the lump/fines ratio by changed blasting practice. The impact of the changed blasting on excavator productivity was not assessed in the study.

CASE STUDY #6: Reducing fines generation in coal mining

Site

Hunter Valley Mine (Australia)

Principal Reference

Scott and McKee (1994)

Brief summary

A study was conducted at a Hunter Valley coal mine in 1992 by the JKMRC to investigate the scope to reduce the fines content in run-of-mine (ROM) coal. Fine coal, defined as less than 1mm, has lower yield, a higher moisture content, higher ash and is more expensive to wash than coarse coal. Dewatering and disposal of fine tailings is estimated at three times the cost of coarse rejects.

The study determined that greater than 13% of ROM preparation plant feed coal was less than 1mm. There followed an extensive study of blast design and implementation practices which indicated that a reduction of the powder factor would achieve adequate coal breakage while reducing the proportion of resultant fines to less than 10% of preparation plant feed. Further reduction in fines production could be achieved by more tailored blast design in detonation practice and inter-hole timing.

Outcome

The variation of fines content of the preparation plant feed with reducing powder factor is shown below.

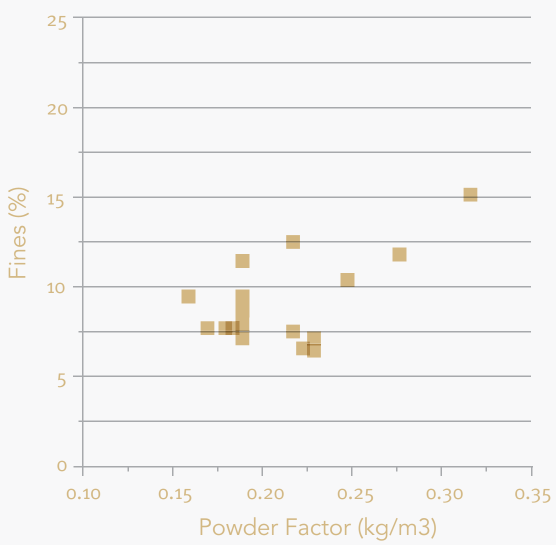
Economic Impact

A simple interpolation indicates a reduction in fines from 13% to 10% achieves potential revenue of $0.60 per tonne equalling over $4m annually at 1992 prices and costs.

Fines % in plant feed	5	10	15	20
Yield %	76.3	75.6	74.9	74.2
Ash %	12.0	13.0	13.0	14.0
Moisture %	9.0	10.0	10.0	10.0
Relative value/ROM tonne$	35.37	35.35	33.34	32.34

A simple interpolation indicates a reduction in fines from 13% to 10% achieves potential revenue of $0.60 per tonne equalling over $4m annually at 1992 prices and costs.

Effect of powder factor on percentage of fine coal <<



CASE STUDY #7: Blasting for improved mining and milling productivity

Site

Sandsloot (South Africa)

Principal Reference

Bye (2006)

Brief summary

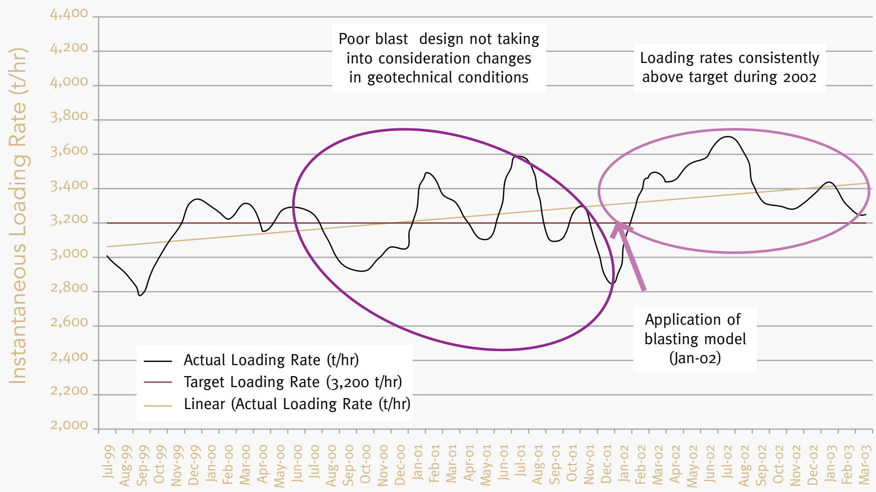
A study commenced in 1997 with the objective of improving operational performance in both the open pit mine and the mill by considering the performance of the total mine and mill system rather than the individual parts of the operation. The approach involved geotechnical characterisation of the orebody at a block scale and incorporation of the geotechnical date in the block model.

One of the applications of the enhanced block model was to study the impact of blasting of different blocks on shovel loading rates, fragmentation and subsequent mill throughput. The optimum mean fragmentation sizes for ore and waste were developed which provided a combination of best loading rates and mill throughput, i.e. the optimum sizes took into account the needs of both the mine and the mill. Simple blasting models were developed to allow tailoring of the blast design at block scale to achieve desired fragmentation.

Outcome

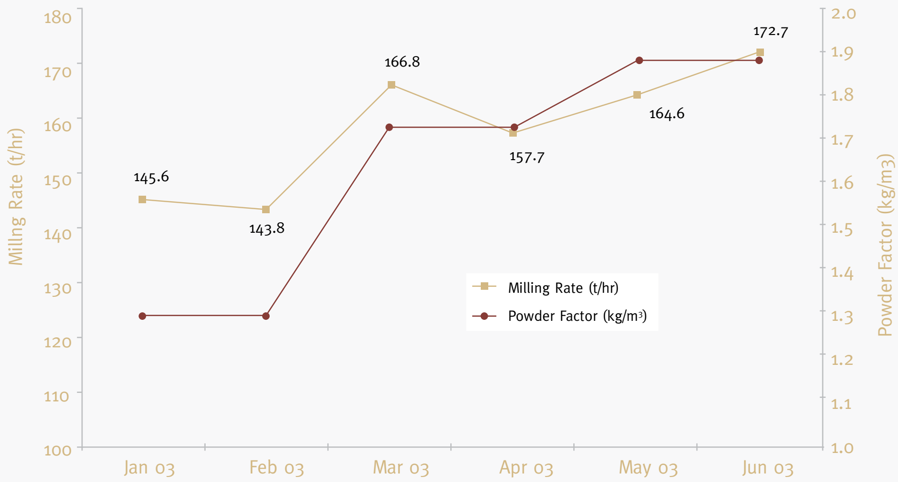
This work occurred over a number of years. The effects on loading rates and mill throughput are shown in the figures overleaf. The additional blasting cost per tonne of SAG mill throughput was estimated at $US0.01.

The Strategic & tactical value of a 3D geotechnical model for mining optimisation <<

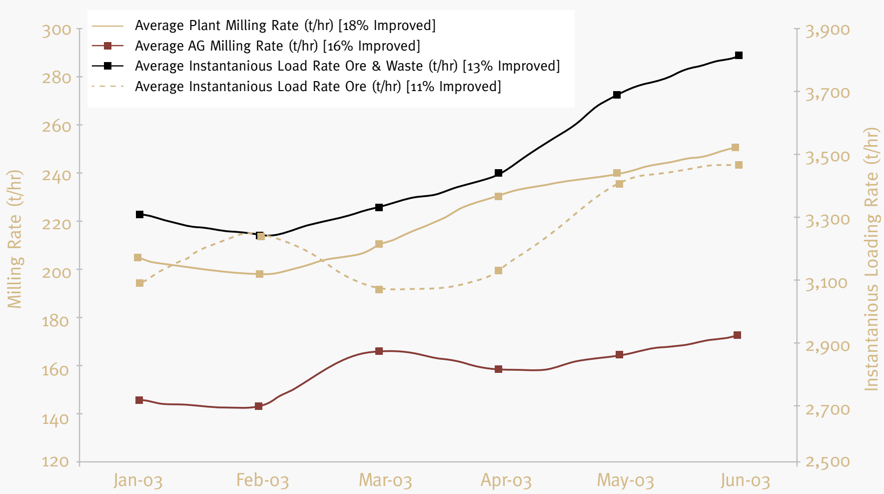


Loading rates showing the impact of the fragmentation model for the blast design

Impact of blast powder factor on autogenous grind milling rates. (2003)



Loading and milling performance from 2001 to 2003



Graph illustrating the performance of the drill and blast department's two customers during 2003. The loading rates include ore and waste and the milling rates include both the AG and ball mills

CASE STUDY #8: Production planning for the combined mine and mill operation (Part 1)

Site

Batu Hijau (Indonesia)

Principal Reference

McCaffery et al (2006)

Brief summary

The Batu Hijau copper–gold operation commenced a M2M program in 2001 with the standard initial objective of modifying blasting practice to increase SAG mill throughput. However, the way in which the study developed differed from the norm as characteristics of the orebody affecting grinding performance were considered from the outset. The Batu Hijau work is presented in two parts which together span 10 years of development.

Using rock mass characterisation data, ore hardness information and blast design data, simple regression models were developed which predicted SAG mill throughput. This was done for different zones in the orebody, ultimately resulting in separate throughput predictions for 16 orebody domains. JKSimMet models were used to enhance the initial regression models in order to more accurately predict the expected SAG mill throughput for different ore domains. Attention then turned to developing best blasting practice for the domains to reduce fragmentation top size in order to improve loading rates in the pit and increase grinding circuit throughput. Different blast designs were developed for each domain.

The modelling approach also provided a basis for ore scheduling and production forecasting; a development which has been greatly expanded in Part 2 of the Batu Hijau study.

Outcomes

Productivity gains of 10% for loading rates in the pit and 10–15% increases in SAG mill throughput for individual ore domains were reported. Some of the important requirements for effective implementation of the Batu Hijau M2M strategy included:

- The need for a dedicated team of involved staff from geology, mining, milling and IT support
- Strong and ongoing support of senior management
- Best possible orebody characterisation — an ongoing requirement with continuing updating of the domain models
- Accurate models of blasting and comminution to establish expected performance for each domain and the best balance in cost and effort between blasting and milling for each domain

CASE STUDY #8: Production planning for the combined mine and mill operation (Part 2)

Site

Batu Hijau (Indonesia)

Principal Reference

Wirfiyata and McCaffery (2011)

Brief summary

The second phase of the ongoing Batu Hijau study covers the 2006–2011 period. The focus of the second stage of work has been on improving prediction of mill throughput based on improved orebody characterisation, improving prediction of blasting performance and refining mill models. The other major advance has been the use of the modelling approach for both short and long term production planning.

In 2007, the equations linking mill throughput to measurable variables (see Part 1 summary) were coded into the mine block model so that throughput predictions became a direct output from the block model. As before, the throughput relations were based on regression models of tph as a function of characterisation variables. In effect, the models establish a benchmark performance which can be expected when mining and processing ore from different domains.

Outcome

The second phase of the Batu Hijau study provides the basis for a much wider range of M2M applications than just increasing SAG mill throughput. There is a demonstrated ability to predict mill throughput over the long term to +/- 2% accuracy. At the core of the latest developments is a greater ability to predict mill throughput with considerable accuracy for different ore sources. The applications of that capability include:

- The understanding of expected or benchmark performance against which actual performance can be compared. Deviations from the expected can be identified and remedial action to regain performance can be better targeted
- The availability of a sound basis on which improvements in the grinding circuit can be identified, implemented and measured
- A tool which is an integral part of both long and short term production planning to achieve required production rates

The importance of the first point above should never be underestimated. The best performing mills are those with a clear quantitative understanding of expected and acceptable metallurgical performance for different operating situations. This is because deviations from the expected can be quickly identified and remedied.

SUMMARY

In researching these case studies, in addition to the range of productivity gains from Mine to Mill applications detailed above, three associated observations became apparent. The first was the scope to adapt M2M thinking to establish the predictability of processing performance. The second was that M2M provides a means of making effective use of the orebody characterisation data which is routinely collected at mine sites. The third was the dearth of underground M2M applications. These topics are briefly considered below.

Productivity gains

M2M offers a wide range of applications which can achieve significant gains, particularly in open pit operations. Productivity gains in the 10–20% range are common and these are usually achieved at little additional capital cost and frequently lower operating costs when the costs of the combined mining and processing activities are considered.

Establishing predictability of performance

One nagging observation persisted in the comments of those experienced in M2M: the belief that processing plants to do not operate as efficiently as they used to. There are a number of reasons given for this situation including:

- Shortage of skilled operators
- Shortage of professional people with the time to spend on operational efficiency
- The disruptive effects of Fly In–Fly Out operations

However, another likely reason is that the understanding of what represents acceptable metallurgical standards is not as well defined as it was previously. In previous decades, most mills had well developed and understood relationships linking head grade, throughput tonnage and grind size with concentrate grade and recovery. These relationships, developed over the life of the operation, set performance benchmarks for metallurgy and also made it possible to detect when performance deteriorated from the expected.

M2M, as practised at Batu Hijau and described by Wirfiyata and McCaffery (2011), has the valuable outcome of providing predictability in metallurgical performance as a function of ore source and properties. Expected throughput, concentrate grade and recovery are all predicted on short term (hours) timeframes. Adding the understanding of performance predictability to other M2M objectives for an operation can be one of the most valuable outcomes of M2M.

Effective use of expensive data

Modern mining and processing operations routinely collect vast quantities of data which characterise the orebody and associated mining and processing. This data collection is maintained from the exploration through the life of the mine. The range of information frequently collected is summarised in Part C.

The cost of data acquisition is substantial. The challenge is to make effective use of this information. The very nature of M2M requires the availability and effective use of such data. Consequently, the discipline imposed in developing and implementing a M2M strategy ensures that value is obtained from routine and expensive data collection.

Underground applications

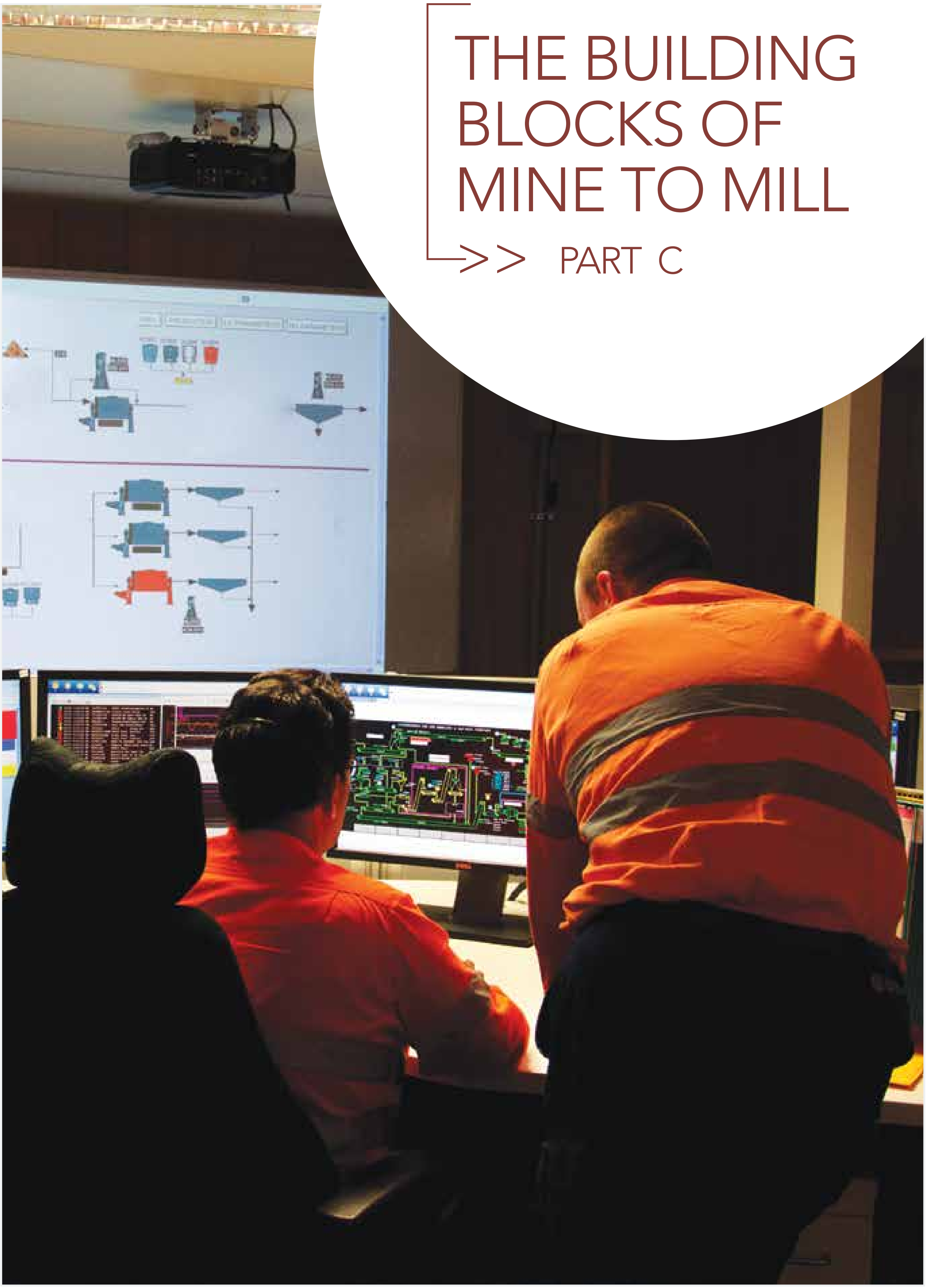
The underground applications of M2M outlined are concerned with selective mining for improved flotation response (Mount Isa) and surface blending of ore from different stopes for improved flotation performance (Thalanga). No blasting related examples of M2M in underground operations have been identified.

The key consideration for potential underground operations is associated with the mining method employed. Blasting is paramount in stoping operations. However, the general open pit approach of using greater blasting energy to achieve finer fragmentation is less applicable in stoping. Increasing explosive energy in stoping frequently equates to increased stope stability problems and increased dilution associated with the blasting and recovery of either low grade ore or waste. In addition, ore from underground operations is subject to significant and uncontrolled breakage in ore passes and grizzlies which all reduce the ability to achieve a more desirable fragmentation size as is possible in open pit mining.

The situation with caving methods is more complex still. In both sub-level caving and block caving the dominant breakage mechanisms are associated with the in-situ rock mass characteristics, the largely uncontrollable fragmentation associated with flow and degradation at draw points and subsequent transport.

The often combined effects on ore loss and dilution are another important aspect of underground mining. Poorly controlled blasting in stoping can result in significant dilution material reporting in mill feed with the undesirable consequences of processing higher tonnages of lower grade and possibly more difficult to float ore. The largely uncontrolled rock flow associated with both sub-level and block caving means dilution is a common problem with caving operations. In sub-level caving, ore loss can occur as a result of poor blasting practice in stoping and flow related effects which cause flow patterns to introduce low grade ore or waste into good ore and result in material which is less than cut off grade.

Thus, there are good reasons why most of the usual open pit M2M applications are restricted or unavailable in underground operation. An important common element between both underground and open pit mining is the need for the best possible orebody characterisation and block models which provide better definition of the orebody to guide subsequent mining.



THE BUILDING BLOCKS OF MINE TO MILL

>> PART C

INTRODUCTION

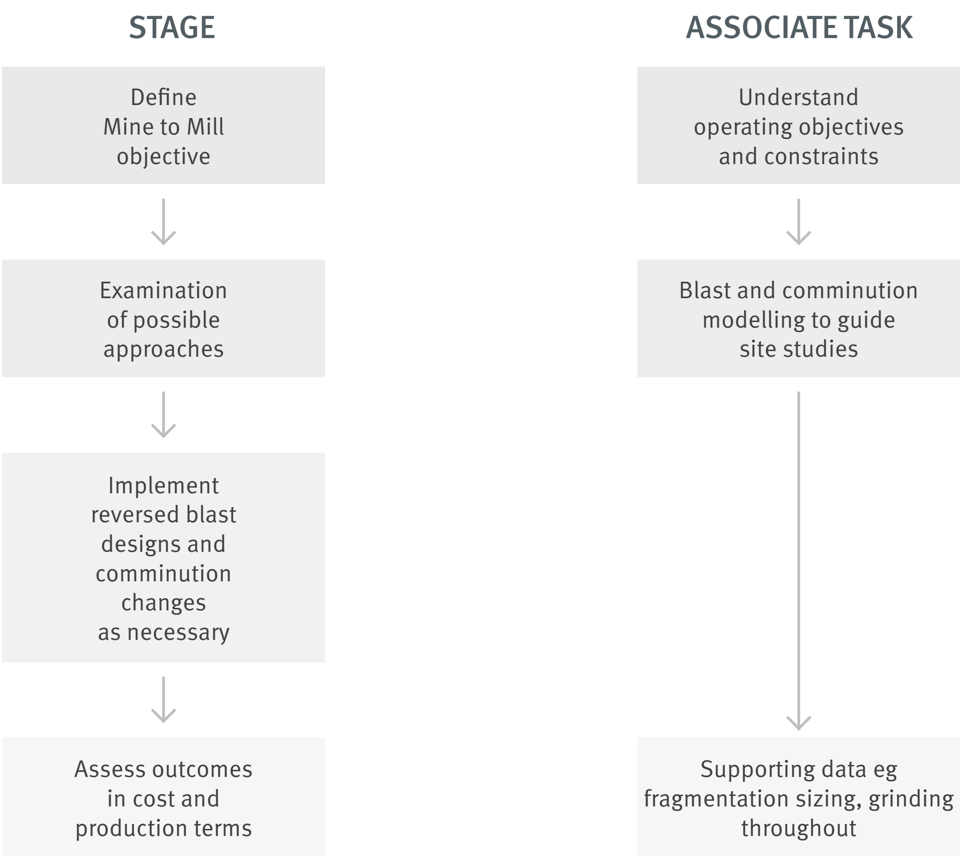
Using the experience gained from numerous Mine to Mill studies over the last 15 years, it is possible to list the essential building blocks of M2M applications. While not all will be required in every implementation, these blocks provide the foundations for the successful application of M2M.

The essential building blocks are:

- >> Site champion — ideally someone in a stable/long-term role
- >> A supported multi-disciplinary team
- >> A clear and attainable objective
- >> A clear understanding of the bounds of operating practice
- >> Characterisation — understanding the orebody and the metallurgy
- >> Predictive models
- >> Simulation systems
- >> Blasting techniques
- >> Measurements
- >> Means of assessing of outcomes

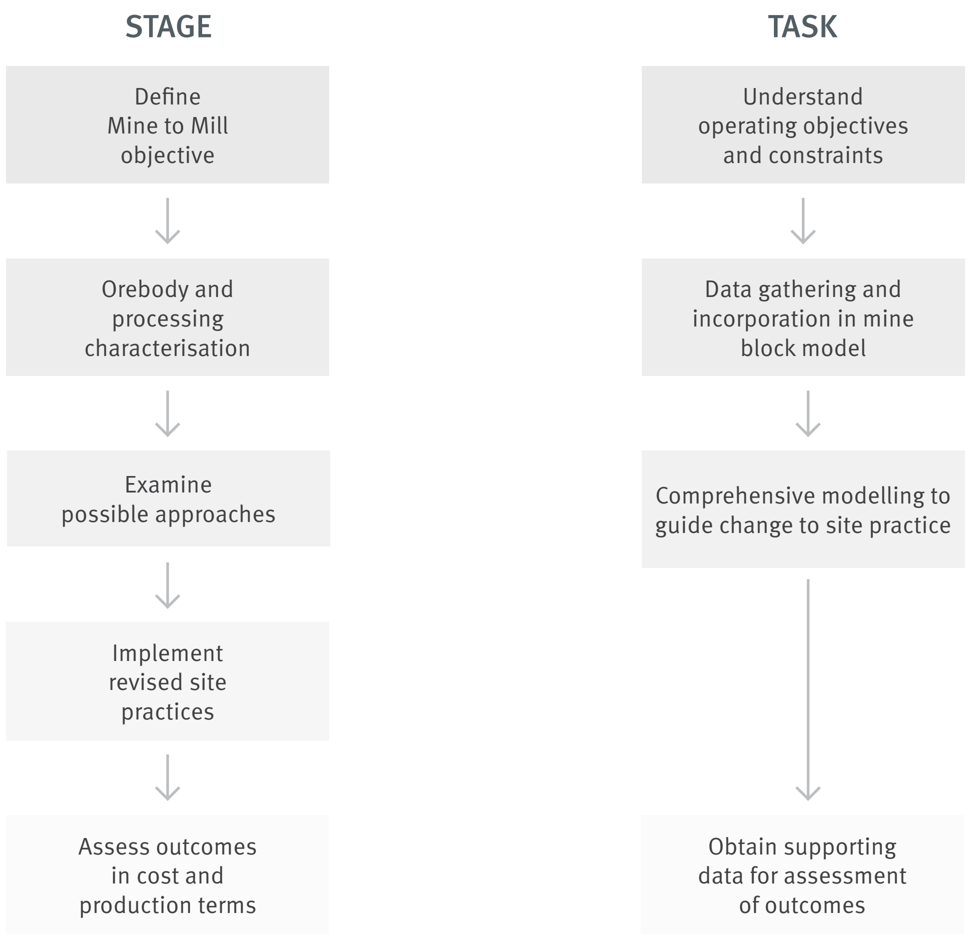
These building blocks form part of a sequence of activities, summarised in Figures 1 and 2. Figure 1 is applicable when only limited characterisation of the orebody is feasible or required. Figure 2 becomes relevant when extensive orebody characterisation is available and an enhanced block model is developed prior to individual blasting and comminution modelling stages.

STAGES IN THE DEVELOPMENT OF A SIMPLE MINE TO MILL STRATEGY



Limited orebody data available or required strategy largely dependent on changed blasting practice

STAGES IN THE DEVELOPMENT OF ADVANCED MINE TO MILL STRATEGIES



Significant orebody and processing data available

A SUPPORTED MULTI-DISCIPLINARY TEAM

The essence of M2M involves integration across often quite separate organisational units at a mine. This will always involve the mining and milling departments and should always involve geology. Ultimately, departments are only people, so M2M requires the active and committed participation of geologists, mining engineers and metallurgists. This often requires a serious cultural change in the way people work and communicate at the mine site.

Thus, the essential first step in planning, developing and implementing a M2M application is the establishment of a team of appropriate people from the different disciplines with a focus on production.

The committed support of senior management, and in particular that of the overall site manager, is absolutely critical for the success of a M2M initiative. M2M requires change and that change must be driven from the top.

CLEAR AND ATTAINABLE OBJECTIVES

A M2M study should begin with careful consideration of the desired outcome — in other words, having a clear objective. Embarking on a M2M application is no different from any other major operation type project in the mine or the mill: sound justifications are required. No M2M application is a simple exercise in terms of the people resources required and the potential impact on long-standing operating practices. Successful M2M studies will always result in changes in operating practice. Such changes are always challenging.

There are a number of similarities between the development and application of the M2M concept with the application of process control in processing plants. Long experience with process control development has demonstrated that having a clear objective for a process control system is one of the essential starting points (Thwaites, 2007). The same applies to M2M.

UNDERSTANDING THE BOUNDS OF OPERATING PRACTICE

This point is simple but critical. It also builds on the process control analogy. All mining and processing operations are subjected to constraints, particularly those determined by equipment capacities. For example, there is little point in embarking on a M2M study to increase grinding circuit throughput if the associated flotation circuit does not have the capacity to process higher tonnages while maintaining acceptable grade and recovery. Similar capacity constraints may exist with loading equipment in the mine.

However, capacity related constraints should not be confused with changes to operating practice, which are a necessary part of a M2M implementation. M2M requires changes to the way in which tasks are undertaken, with changes to blasting practice being an excellent example.

The key is to identify and understand operating constraints which cannot be readily eliminated and to design the M2M activity to be compatible with the constraints.

CHARACTERISATION — UNDERSTANDING THE OREBODY AND THE METALLURGY

An evolving topic

Almost without exception, every M2M study reported in the literature makes reference to the need for the best possible characterisation of the orebody, together with the statement that better characterisation will enhance the ability to extract better outcomes from a M2M application. The types of information relevant to characterisation are summarised below. In general, the greater the extent of data, the better the characterisation of the orebody properties. This characterisation is important in developing extraction and processing strategies which enhance the productivity gains possible from M2M applications (JKMRC, 1998).

At its simplest, characterisation is about developing the best possible understanding of the orebody, in particular its variability. Orebody characterisation is now becoming quite sophisticated in terms of the range of data collected, the means by which the data are incorporated in the mine block model and the ways the information is used in mining and processing.

One of the first comprehensive characterisation studies was reported by Simkus and Dance (1998) at the Highland Valley mine. Since the late 1970s, Highland Valley had developed a program mapping the hardness of different ore types, so this level of characterisation was well established in operational practice as more advanced technologies became available. By the late 1990s, drill monitors were being used to provide an estimate of ore hardness of subsequently blasted ore. Ore was then tracked to the stockpiles using the mine dispatch system and movement through stockpiles was modelled. An image analysis system was used to provide an estimation of the feed size distribution to the SAG mills. Finally, relationships were developed between ore hardness, feed size and mill throughout. This approach provided a strong ability to predict expected mill throughput - information which could then be utilised in process control.

Rock mass properties

Standard rock mass property data are usually obtained as geotechnical information from drill cores (Valery et al, 2001; McCaffery et al, 2006) and include:

- RMR (Rock Mass Rating)
- RQD (Rock Quality Designation)
- Point Load Index
- Young's Modulus
- Poisson's Ratio
- UCS (Unconfined Compressive Stress)
- In-situ block size
- Joint spacing

Most of these geotechnical parameters are used in blasting models for fragmentation prediction.

Metallurgical (processing) parameters

JK Rotary Breakage Tester (JK RBT)

These data typically include:

- Grades, including the grades of gangue minerals and minor elements
- Grindability data, principally related to ore hardness, as measured by Bond Work Indices, and JKMRC grinding model parameters (Napier-Munn et al, 1996)
- Flotation grade and recovery data as determined by laboratory flotation tests

The above data are usually determined from testing of drill cores (Wirfiyata and McCaffery, 2011).

Geometallurgical parameters

The meaning of the term geometallurgy is changing with time and now appears to include most of the metallurgical parameters above together with the following information (Bye, 2011):

- Mineral liberation
- Lithology
- Geological alteration
- Acid forming potential of ore

PREDICTIVE MODELS

Models frequently used in M2M studies include:

- Mine block models incorporating geotechnical and geometallurgical parameters
- Blast fragmentation models
- Muckpile models
- Comminution models

In addition to the above, models which predict the final muckpile shape resulting from open pit blasts are increasingly useful when it is desirable to understand where material of different properties, notably grade, reside in the muckpile after blasting.

Mine block models incorporating geotechnical and geometallurgical parameters

One of the limitations of the simulation systems described above is that they execute as separate simulations. Clearly, there would be significant benefit if simulations associated with the block model, blasting and comminution, and at times flotation, were linked within one seamless system. Bye (2011) describes a prototype simulation system developed within The University of Queensland which does link the separate simulation stages. It is likely that commercial software of this type will be available in the near future.

Blast fragmentation models

The most commonly used blasting models used in the M2M applications reported are those based on the Kuz–Ram model (Cunningham, 1983). It has been shown that the Kuz–Ram model provides a reasonable prediction of the coarse end of the size distribution resulting from blasting (Valery et al, 2001). However, the model consistently underestimates the fines content resulting from blasting. Kanchibotla (1994) developed the concept of a crushed zone immediately adjacent to the blast hole as being responsible for the production of a significant quantity of the fines observed from blasting. The total volume of finer crushed zone material is estimated from the number of holes in a blast design. The fragmentation model resulting from a combination of coarse fragmentation described by Kuz–Ram and fines from the crushed zone concept has been shown to provide a satisfactory estimate of the total size distribution resulting from a blast (Valery et al, 2001).

Parameters required by the blasting model include:

- Young's modulus
- UCS
- In-situ block size
- Joint spacing
- Powder factor

- >> Burden
- >> Spacing
- >> Blast hole diameter and length
- >> Column charge length
- >> Explosive type
- >> Explosive VOD
- >> Explosive density

Comminution models

The most commonly used comminution models are those developed over many years by the JKMRC. The models include descriptors of crushers (primary and secondary), AG and SAG mills, ball mills, and screen and cyclone classifiers. All these models are described by Napier-Munn et al (1996). Since then a model of the high pressure grinding rolls (HPGR) has been added (Daniel, 2007).

Central to the JKMRC comminution models are two ore specific breakage parameters: A and B. These parameters are usually determined from drop weight tests on multiple ore particles. Parameter A provides a measure of the maximum level of breakage for an ore type. Parameter B is related to the ore hardness with lower values of B indicating harder ore.

Muckpile models

Blast induced rock mass displacement can have a significant impact on ore recovery and downstream productivity in open pit mining operations. Examples include its influence on grade control (ore loss and dilution) and load and haul efficiency (muckpile shape and looseness). Several attempts have been made to develop empirical and numerical models capable of predicting both the magnitude of displacement as well as muckpile digability for given blast design inputs. These include 3DMuck (Yang and Kavetsky, 1990), Sabrex (Jorgenson and Chung, 1987), DDA_Blast (Mortazavi and Katsabanis, 1999) and DMC_Blast (Preece et al., 1993).

Generally however, these models have been limited by their oversimplification of boundary conditions, disregard of key processes such as inter particle collisions and/or their two dimensional nature. Recent developments and availability of both software and hardware dedicated to rigid body dynamics programs (i.e. physics engines) has facilitated new avenues in which to simulate particle motion and collision detection in three dimensions (Tordoir et al, 2009). Muckpile models are aimed at the production stages of operating mines where knowledge of the magnitude of displacement is required for post blast decision making.

SIMULATION SYSTEMS

The model types mentioned above have been incorporated into commercially available simulation packages which are designed for routine use by mining engineers and metallurgists. The more widely used simulation systems are briefly described below.

Mine planning

Resource estimation and mine planning and design software packages have been around for some time. Application of these packages has greatly improved the quality of designs as well as the overall economics throughout the mining process (Kaiser, et al, 2002).

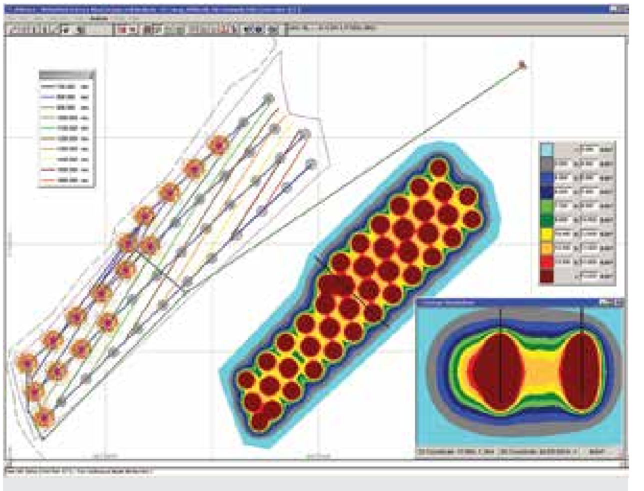
Over the past couple of decades, a number of software packages have evolved to carry out most of the functionality required on an operation or project (Kapageridis, 2005). The standard functionality carried out by these packages include:

- >> Visualisation
- >> Modelling
- >> Estimation
- >> Database Management
- >> Reserve Calculation
- >> Mine Design
- >> Mine Planning

Mine planning decisions are generally based on the data contained in the 3D resource model. Increasing amounts of cross discipline data are being included in these resource models. It follows that block models containing more sophisticated information such as rock mass properties and target powder factors will enable more informed mine planning decisions and most mines are pursuing this objective to some degree. It is important to note that the integrity of these sophisticated block models should always be investigated prior to adoption.

Blasting simulation

JKSimBlast



JKSimBlast simulation. Image courtesy of Soft-Blast Pty Ltd

JKSimBlast is a software package for blast design and analysis. The 2DBench open pit module has both the Kuz-Ram model and the JKMRC Crush Zone Model for fragmentation analysis, and the 2DRing underground module has the unique FragmentO analysis developed at the JKMRC.

JKSimBlast is supplied by Soft-Blast Pty Ltd, Brisbane, Australia www.soft-blast.com

Comminution Simulation

JKSimMet

The most widely used simulation system for comminution is JKSimMet. This system is based on the comminution and classification models of JKMRC and has been in continuous development by JKTech since 1985.

JKSimMet is supplied by JKTech Pty Ltd, Brisbane, Australia www.jktech.com.au

CEET

CEET (Comminution Economic Evaluation Tool) provides the capability for design and prediction of comminution circuit throughput and uses modelling concepts, including a SAG mill power index. It was originally developed by the Minnovex group (now a part of SGS). CEET interfaces with the mine block model.

CEET is supplied by SGS worldwide www.sgs.com

LIMN

LIMN is a general purpose spreadsheet package which allows the inclusion of spreadsheet models for simulation.

LIMN is supplied by David Wiseman Pty Ltd, Adelaide, Australia www.davidwiseman.com.au

Integrated simulation

One of the limitations of the simulation systems described above is that they run separately. An integrated system that combined block model, blasting, comminution, and flotation simulations would be significantly beneficial. The University of Queensland has developed a prototype simulation system which links these separate simulation stages (Bye, 2011).

BLASTING TECHNIQUES

Blast design

Blast design and execution is arguably the most important step in the comminution process. A poorly conceived blast design based on limited rock mass data will have serious downstream production and cost implications. Given an established bench height blast design involves finding the right mix of hole diameter, burden and spacing, sub-drill, stemming and explosive formulation. Ideally this blast design is informed by rock mass information collected from exploration drilling, face mapping and blasting field trials. Depending on the complexity of the rock mass and sensitivity of the downstream processes to the particle size distribution the blast design can be a single standard pattern all the way through to sophisticated 3D geotechnical model which predicts the optimum blast pattern for every mine blast (Bye, 2011). It is important to note that there is significant flexibility available in blast design to tailor a specific particle size distribution (PSD). This flexibility to manipulate a PSD in one process becomes increasingly limited as size reduction proceeds via conventional comminution.

Explosives and Detonation

In simple terms, explosives are chemical compounds or mixtures which upon ignition detonate to release heat and large quantities of high pressure gases which expand rapidly and with sufficient force to overcome the confining pressure of the surrounding rock mass. Over the last 100 years explosive formulations have evolved tremendously to provide a large range of flexible products that can be tailored to specific rock mass conditions. These formulations and the explosive trucks (MMUs - mobile manufacturing units) continue to evolve and can provide a customised product for each blast pattern, blast hole and even sub-sections of blast holes. Blast timing is a critical aspect of rock fragmentation and the introduction of electronic delay detonators has enabled millisecond control of each blast hole detonation so that the energy to fragmentation relationship is optimal. There is certainly no shortage of drilling, explosive or timing technology to tailor blast fragmentation to the specific requirements of shovels, mills or leach pads. The constraints are in the areas of rock mass knowledge, operator skill and quality control.

MEASUREMENTS

Blast movement markers and fragmentation measurement

There are a number of applications, such as upgrading ore, where there is potential to use highly controlled blasting. Such an approach requires knowledge of the spatial location of the ore, the different properties prior to a blast, and where parts of the original blasted volume are located after the blast. In recent years, extremely robust electronic markers have been developed for this purpose. The markers consist of a rugged external case containing a directional transmitter which is activated and installed in the blast hole. The marker is located after the blast with a hand held detector, providing an accurate three dimensional location of the marker.

One such marker system is listed below.

BMM

Supplied by Blast Movement Technologies, Brisbane, Australia www.bmt.com.au

An explanation of BMM and its application is provided by La Rosa and Thornton (2011).

Blast movement marker.
Image courtesy of Blast Movement Technologies

Ore tracking devices

The ability to track ore from the mine through ore haulage, crushing and conveying to the process plant is desirable as it creates the potential to adjust process plant operation in advance to suit the need of different ores. Radio frequency tags contained in robust enclosures provide a means of ore tracking from the blast hole to the mill feed.

One such tag is listed below.

SmartTag

Supplied by Metso, worldwide www.metso.com

An explanation of SmartTag and its operation is provided by Wortley et al (2011).

Fragmentation assessment

The ability to measure coarse size distributions resulting from blasting is one of the keys to assessing the results of changing blast designs. Likewise, measurement of the feed size distribution to AG and SAG mills is highly desirable, given the sensitivity of mill performance to changes in feed size distribution.

Systems which are based on cameras and image analysis techniques have been available for at least 15 years and these are frequently mentioned in the M2M literature. Three widely used systems are listed below.

Split

Supplied by Split Engineering, Tucson, USA www.spliteng.com

An explanation of Split and its applications is provided by La Rosa et al (2001).

Visio Rock

Supplied by Metso, worldwide www.metso.com

An explanation of Visio Rock and its applications is provided by Guyot et al (2004).

WipFrag

Supplied by WipWare, Ontario, Canada www.wipware.com

An explanation of WipFrag is provided by Simkus and Dance (1998).

MEANS OF ASSESSMENT OF OUTCOMES

Assessing the value of a M2M initiative is both inherent in the M2M system and essential to the continuing implementation of operating changes required of M2M. The assessment of value is well described by Scott et al (2002) and is presented in full in Appendix 1. While the topic is also considered in PART D, selected conclusions of Scott et al (2002) are presented below to provide a glimpse of the assessment issues.

- Demonstrating whether any change in the process adds value depends on being able to measure performance in both physical and economic terms
- Current mine monitoring and reporting systems may not be set up to measure performance to the accuracy required to quantify the value of M2M improvement
- Because M2M initiatives affect the revenue side of the value equation, higher level business parameters relating to finance and marketing are also critical to the assessment of its value

THE ROLE OF SPECIALIST GROUPS

Over the last 15 years a number of specialist consulting groups have made major contributions to the development and application of M2M. In addition to the JKMRC which provided much of the initial impetus via the AMIRA P483 Projects and, more recently, the contributions of the W H Bryan Mining and Geology Research Centre (Sustainable Minerals Institute, The University of Queensland) outlined by Bye (2011), three organisations have been active:

- Metso Process Technology and Innovation www.metso.com/pti
- Minnovex — now part of SGS www.sgs.com
- JKTech Pty Ltd www.jktech.com

SUMMARY

This analysis suggests that the tools required for implementation of the Mine to Mill approach are available in acceptable forms. Many of these hardware and software tools are provided by established suppliers and have been successfully implemented at mine sites. In addition, most of the tools continue to be the subject of research and further development.

The area of greatest need is the availability of tools to monitor M2M outcomes. To date, these have largely been developed at individual sites, as described by McCaffery et al (2006) and Wirfiyata and McCaffery (2011). The development of more generic software tools which can be tailored to the assessment needs of individual M2M applications would undoubtedly be useful.

THE LESSONS OF EXPERIENCE

>> PART D

OVERVIEW

The positive outcomes of Mine to Mill, as summarised in PART B, include:

>> The intangible benefits of integration across an operation

>> Productivity gains, usually as a reduction in total operating costs

>> The ability to achieve greater predictability, and thus consistency, of an operation

Two significant challenges associated with M2M include:

>> A requirement to change operating practice so that the operation runs holistically rather than conducting mining and processing as separate activities

>> Sustaining the implementation of M2M practice, rather than lapsing back into old operating practice

In summary, M2M is simple technically, but challenging in the operational sense because it requires sustained changes in operating procedures.

VIEWS OF THE EXPERIENCED

As part of our research into M2M applications, the views of people with long-term experience with M2M were sought. A number of key comments were identified and these are considered below.

1. Productivity and cost

>> Productivity gains of 10–20% are sufficient to be taken seriously, but in practice, such gains have not resulted in the widespread and sustained application of M2M methods

>> It is critical to adopt a cost model that reflects costs across the operation. For M2M methods to be accepted, it must be understood and accepted that increased costs in one area may be offset by reductions in another. For example, an increase in drill and blast costs may be offset by an even greater reduction in total costs

2. Operating objectives

>> Careful consideration is required to identify the objectives for a M2M application at an individual site

>> The objectives and particular application will be different for each site

>> The objectives for a site may change over time and it is critical to ensure that the objectives are updated as and if required

3. Orebody characterisation

>> Understanding the mining and processing characteristics of the orebody, and the variability of these characteristics, is critical to the selection of appropriate M2M objectives and thus the success of the application

4. Technical simplicity

>> M2M is technically simple and the emphasis should be on the simplest possible implementation

>> The notion that complex models are a required part of M2M is not correct

5. Not delivered in a sustained way

>> Many M2M applications have not been delivered in a sustained manner

>> Most of the reasons for this are summarised in points 6–11 below

6. Site leadership

>> M2M is a site activity

>> Leadership must come from the site General Manager

>> Long-term success will not be achieved if the M2M application is driven at only senior mine and process levels

7. Skilled team

>> A multi-disciplinary team consisting of geologists, mining engineers and metallurgists must be developed and maintained. Other areas relevant to the application will also be required

>> Successful application of M2M requires a high level of operational skill from supervisors and operators

>> Maintaining capability in the face of the general skills shortage and high turn-over of personnel presents a constant challenge

8. Organisational change

- The site organisation may require change to recognise, promote and support the establishment and operation of the multi-disciplinary team to achieve true integrated operation
- Even the smallest change which enhances the integrated operation concept is likely to produce intangible benefits

9. The corporate role

- Role of corporate is not to seek to impose M2M, but to support the initiative and disseminate successes to other operations in the group
- Engagement of the site activity with senior planners at corporate level is desirable so that the planners can appreciate the benefits possible from M2M

10. Assessment and consolidation of gains

- Gains must ultimately be expressed in whole of operation $ terms
- Tools are required to assist in quantifying gains (for example, effective means of monitoring field performance)
- The application must ensure that productivity gains are locked in and consolidated, so that M2M becomes entrenched practice

11. Appropriate KPIs

- KPIs for individual positions must reflect the productivity and costs across the total integrated operation rather than be narrowly specific to individual operating areas

SUMMARY

Four critical conclusions can be drawn from the views of experienced Mine to Mill practitioners. The first is that significant productivity gains can be realised by application of appropriate M2M strategies. The second is that M2M is technically simple. None of the experienced people raised a deficiency of a technical type as an impediment to success. The third is that many M2M applications have not resulted in sustained delivery. The fourth is that the majority of challenges are related to the requirement for skilled people and supportive management systems.

The keys to successful M2M application identified by experienced practitioners are all readily understandable and quite simple. However, simplicity should not be mistaken for necessity. The successful M2M applications are those where each of the keys has been recognised and adapted in a way which is suitable for the application and the site.

DELIVERING THE POTENTIAL

>> PART E

The summary of the views of experienced Mine to Mill practitioners contains the keys to unlocking the considerable potential of M2M strategies. The challenge is to adapt what is essentially simple technology and achieve consistent productivity gains of 10–20% and other associated benefits. Benefits of that magnitude, which are achievable at little increased cost, and in many cases reduced cost, should not be sacrificed because aspects of implementation require people with necessary skills and changes to operating practice and management structures. M2M is one of those operating strategies which should not be allowed to fail.

The remainder of Part E restates the gains which can be achieved through effective M2M strategies. The document concludes with a summary of the keys to successful and sustained implementation.

BENEFITS OF INTEGRATION

Regardless of the activity, it is universally recognised that benefits flow when all parts of the activity work effectively and harmoniously together. These benefits are sometimes measurable but are often intangible. They can include a more satisfied, cohesive and productive workforce; a greater capacity to find solutions to problems which arise; and a better final outcome in terms of quality and cost.

All of this is true for the mining industry, which historically has partitioned many of its production functions into isolated departments. The M2M concept, more than any other, offers an opportunity to achieve a high degree of integration between people and production activities at a site level where the actual on the spot decisions are made and mining and processing occurs.

PRODUCTIVITY AND COSTS

The mining industry has recently enjoyed a period of high demand and associated high prices for its commodities. However, at the time of writing (2012/13) there has been some reduction in both demand and prices received.

There is a widespread recognition that during the high demand years the principal operating goal has been to maximise production and during that period costs have increased in an unsustainable manner. Industry leaders are now stating that the focus will increasingly be on reducing costs. There is nothing new in this industry reaction. Effectively implemented M2M strategies, with their demonstrated capacity to reduce costs, have a major part to play as the cost focus of the industry intensifies.

Clearly, one of the goals of best practice is a combined focus on both productivity and cost control. A simultaneous focus on both productivity and cost is much more beneficial than focusing one or the other. A technology or approach which combines both productivity and cost control outcomes should be highly desirable. M2M can contribute to this combined goal.

PREDICTABILITY AND CONSISTENCY OF OPERATION

The ability to achieve consistency of operation, in terms of achieving production and cost targets, is increasingly accepted as a very strong driver at the corporate level.

Markets do not react well to undesirable surprises or failures to achieve target production. A key to consistency in mining production is the ability to understand and predict production performance in the short term (i.e. a few months, or one to two years). Orebody characterisation of the type required for a M2M application has been shown to provide the ability to predict forward production rates and processing performance with high accuracy.

Performance predictability arising from orebody characterisation also provides the basis for establishing processing performance benchmarks. This provides a powerful tool for metallurgists as it becomes possible to promptly identify a reduction in metallurgical performance and thus seek reasons and quickly implement corrective action.

VALUE FROM DATA

Because M2M operations require the types of expensive data which are routinely collected at mine sites, M2M provides a practical means of extracting value from this data.

KEYS TO SUCCESS

The extensive M2M literature, supported strongly by comments from those associated with M2M initiatives at mine sites, suggests that there are a number of keys which together can deliver success. These keys are:

- Thinking and operating as one integrated mining and processing operation
- The identification of the appropriate M2M objective for an operation and the understanding that the objective may change with time and require updating
- The availability of appropriate technical knowledge and tools and the means of monitoring outcomes
- The availability of a team of people with appropriate skills
- The existence of strong and on-going management commitment and support
- Appropriate organisational structures and staff KPIs, and
- The ability to measure and lock in improvements in normal operating practice

The integrated operation

A truly integrated operation where boundaries do not exist between distinct activities such as mining and processing seems a totally self evident goal. However, long experience indicates such integration is difficult in practice. Reasons for this include people trained within inflexible disciplinary bases, people with little interest in activities outside discipline boundaries, and the presence of generally separate mining and processing departments.

To motivate individuals and departments to break through these boundaries, appropriate KPIs need to be in place. This theme of appropriate organisational structures and KPIs dominates the list of challenges suggested by those experienced in M2M. For example, if a mining manager has KPIs which stress tonnage and production cost/tonne targets, there is no incentive to change a well established blasting practice even if it improves milling productivity, because such a change may increase the blasting cost/tonne. However, if the KPIs stress overall production costs and output, a change in blasting practice that produces significant gains in milling productivity will be encouraged if it outweighs the increased blasting costs.

Technical knowledge

All of the technical tools required to implement M2M applications exist. It is clear that greater detail of orebody characterisation allows better planning and implementation of successful M2M strategies. Simulation systems are readily available which make it possible to test quite complex operating strategies. The resulting models of individual production stages are sufficiently robust to allow testing of promising changes in operating strategy, prior to the selection of a changed approach for actual testing at a mine site.

Issues associated with characterisation, models and simulation systems are all the subject of on-going research. Thus, the technical tools will continue to develop and improve.

If there is a technical shortcoming, it is in the area of production reporting systems. So far there are no systems which operate across the entire integrated operation. Such a system would make it possible to readily quantify the effects of a M2M strategy in both production and cost terms.

Team of skilled people

M2M requires multi-disciplinary skills. At a minimum, it requires geologists, mining engineers and metallurgists to form a team which provides the foundation of an integrated approach. The various steps required in the planning and implementation of a M2M study also require skills in orebody characterisation, modelling and simulation. Additionally, expertise in the design and implementation of altered blast designs is required. All of these aforementioned skills are usually found at the professional level.

It is equally important that quality operational skills are required of drill and blast crews, loader operators and mill operations personnel. Above all, the success of a M2M application requires the willingness of operations staff to understand why standard practice is being altered and to routinely implement these altered practices. The same acceptance of change is required of supervisory staff.

Thus, M2M is demanding on the entire workforce at an operation. It is critical that these professionals, supervisors and operators, who traditionally have had little in common or experience working together, are willing to work as an integrated team.

Management support

It is well known that the committed support of senior management to any change process is essential for success. However, the level at which management support is critical varies according to the company culture. In all cases, there must be support at the most senior site level. Opinions vary regarding the extent to which higher level corporate support is essential. For organisations with a tradition of strong site independence, attempts to dictate a change in operating procedures, as required by M2M, may not be effective. In other situations, the active involvement of senior off-site people may be required and beneficial.

The role of management is more than that of support. Anything which encourages integrated thinking and the adoption of changes in operating practices is beneficial. Thus, management has an important role in ensuring the availability of the appropriate skills mix and in recognising that performance KPIs for critical people may have to be changed to encourage integrated thinking.

Organisational structure

A traditional organisational structure with separate operating groups, particularly for mining and processing, does not encourage integrated thinking. True integration involves the recognition that the functions of planning, geology, mining, metallurgy and cost control must work as an integrated team with shared goals and KPIs. Each operation will have the capacity to develop an organisational structure which best achieves integrated thinking and outcomes for that operation.

Sustaining improvements

Arguably, the hardest task of all is developing the means at an operation to lock in the gains which result from improvements. Sustaining gains from M2M has proven difficult but M2M is not alone in this regard; maintaining the gains possible from good process control is another excellent example.

One of the keys to sustaining gains is based on the ability to make quantitative field measurements which are appropriate for the particular operation and M2M application, and the ability to analyse and present this information and associated cost data in an integrated system which presents a whole of operation picture.

Success will have been achieved when, in the words of one experienced person, ‘M2M is the way we do business.’

ROLE OF THE OPERATIONS CENTRE

A recent development has been the establishment of operations centres, both on site and remote, where substantial parts of a total operation are monitored and controlled. Such centres are designed to oversee multiple parts of an operation and thus directly assist in establishing the desirable integrated thinking. While operations centres are not essential to develop integrated thinking and operation, there appears to be little doubt that they will help facilitate this goal.

Some operations centres have associated higher level analysis and planning capabilities where production data are analysed in an off line manner. This is one way in which higher level planners can be directly connected with a M2M activity as advocated in Part C.

SUMMARY

Mine to Mill is ultimately about excellence in operations. It is not the only approach in the quest of such excellence but it is one of the few which encompasses such a breadth of the production activities at a mine site. Effort is required to achieve the benefits from an appropriate M2M strategy but that is always the case when in pursuit of greater productivity. The gains possible from M2M have been clearly demonstrated and are possible for all operations willing to embrace the approach and sustain the emphasis on best operating practice.

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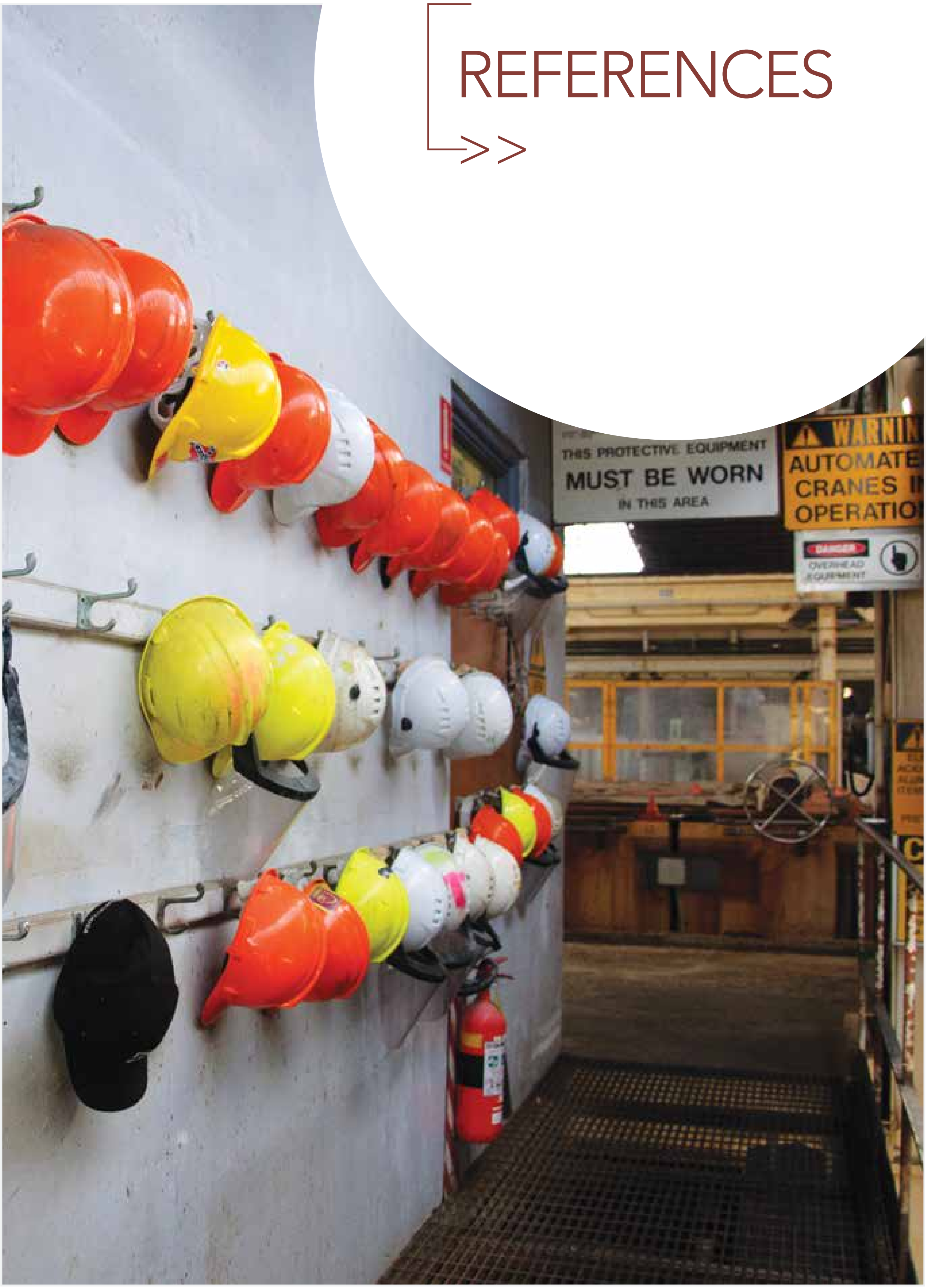
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APPENDICES

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APPENDICES 1

CASE STUDIES DEMONSTRATING VALUE FROM GEOMETALLURGY INITIATIVES

A R Bye

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Case Studies Demonstrating Value from Geometallurgy Initiatives

A R Bye[1]

ABSTRACT

The mining industry is facing some key challenges that provide a compelling case for geometallurgy initiatives. Over the last 30 years, the average grade of Australian orebodies being mined has halved while the waste removed to access the minerals has more than doubled. In the last eight years, the industry's energy consumption has increased 70 per cent while multi-factored productivity has fallen 24 per cent. The paper documents a broad range of industry case studies which demonstrate strategies for gaining value from geometallurgy.

The mining industry constantly faces the key questions of how significant ore variability is on mine valuation and how would knowledge of the variability change the mining schedule, mine to mill design and operation. Using case studies the paper describes the methods used for incorporating mineral extraction attributes into orebody models and their technical integration into daily operation as well as mine planning optimisation.

While pit optimisation from a fully attributed geometallurgical model highlights areas of opportunity and risk it is shown that during the scheduling phase of mine planning that significant value can be added. The benefits from these projects included reducing geotechnical and environmental risk, improving mine to mill performance, option analysis and quantified cash-flow risk.

There is growing acceptance within the minerals industry that 'realistically assumed modifying factors' defined by a competent person/s are not sufficient to mitigate the risk of funding mining ventures. Geometallurgy is moving away from factored ore reserves to data-rich block models providing reliable information for mining, metallurgical and environmental considerations.

INTRODUCTION

The aim of the paper is to document the research and case studies that have enhanced the understanding of spatially modelling and applying geometallurgical/geotechnical attributes. Some of these case studies progressed all the way through to mine planning and economic optimisation (drill core to cash flow) and the benefits of this fully integrated geometallurgical approach are also documented.

Information from seven case studies is documented to illustrate the various approaches to different data sources and how the data are not only spatially modelled but are also used to change day-to-day mining and processing decisions. There are two case studies from Australia, two from Africa, one from South America, one from South-East Asia and one from North America. Three of the projects had a strong geometallurgical focus while the other four predominantly focussed on geotechnical data. Two of the studies involved fully comprehensive core to cash flow analysis.

Traditional open pit mine design and optimisation has been limited by the amount of detailed geotechnical and geometallurgical information available. The spatial modelling case studies are discussed to highlight the approaches and benefits of building 3D Geometallurgical models. The case studies show significant potential for the geometallurgical mine planning models to add value to mining and processing operations. These included:

- significantly better understanding of the orebody variability and impact on the production schedule and what constitutes economic ore,
- leads to risk based strategic planning that can reduce the incidence of failed or underperforming projects, and
- was based on a holistic approach to mine planning that incorporates the full spectrum of disciplines.

The paper documents a broad range of industry case studies which demonstrate strategies for gaining value from geometallurgical initiatives. An additional important aspect of geometallurgical is to provide more robust geometallurgical information that can be incorporated into corporate governance procedures.

INDUSTRY CONTEXT

Given the increased energy and water required to process Australia's growing lower quality deposits, mine sites are not well equipped to meet the environmental legislation, water shortages and carbon trading systems that are changing the mining economic environment. Mine wide process optimisation that considers the generation of CO_2 and consumption of energy and water in mining operations is a critical issue for mining companies. New tools and models are required to effectively incorporate these new metrics into mine economic assessments. In addition site engineers need to be

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able to consider changes to the design, layout and operation of mines so as to minimise their environmental footprints and increase metal production.

Economics

The mining sector's contribution to Australian GDP has grown from a long-term average of four to five per cent to currently represent eight to nine per cent of Australian GDP (ABS, 2010b). This is also reflected in the value of Australian mining exports which have grown from approximately 30 per cent of the total value of Australian exports to currently represent over 50 per cent of all goods and services exported from Australia (ABARES, 2010a).

Sandu and Syed (2008) have attributed the significant, recent growth in the Australian mining sector to a considerable increase in the value of mining exports rather than an increase in the capacity and productivity of the mining industry. This can be observed from the substantial deviation in measurements of the value added by the Australian mining sector when stated in terms of value compared to volume (Figure 1).

The declining multi-factored productivity (MFP) of the Australian mining industry has become an area of considerable interest. MFP is a measure of the efficiency in which capital, labour and raw materials are utilised in the production of goods and services. It reflects improvements in technology, efficiency and management in utilising the inputs of production to generate output. In the case of the mining industry, MFP also reflects the quality and accessibility of resources and the effort that is required to extract those resources (Topp *et al*, 2008).

A recent report from Topp *et al* (2008) highlighted a 24.3 per cent decline in MFP in the Australian mining industry between 2000-01 and 2006-07. The latest experimental estimates of the Australian Bureau of Statistics (2010c) has indicated further decline in productivity within the Australian mining industry, revealing a 31.4 per cent decrease in MFP between 2000-01 and 2009-10 (refer to Figure 3).

Topp *et al* (2008) has attributed the declining productivity of the Australian mining industry to two dominant effects. The first being the depletion effect which is due to declining resource quality as an input to mining production. This effect is permanent and will continue to affect the long-term productivity of the mining industry. The second is the capital lag effect which refers to the lag time that exists between when capital expenditure is incurred and when that expenditure actually results in increased/improved production capacity.

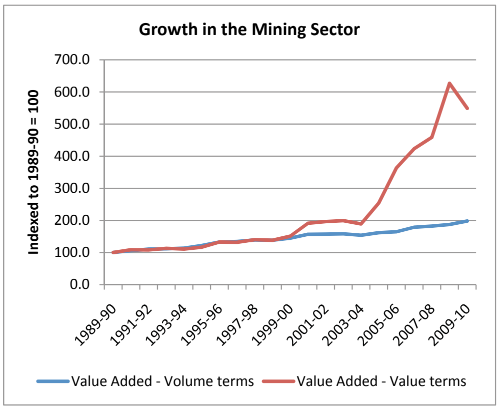


FIG 1 - Growth in the mining industry predominantly through metal price rather than production. Adapted from Sandu and Syed (2008) using data from the Australian Bureau of Statistics (2010a) and (2010b).

Energy and emissions from mining

Energy consumption in the Australian mining industry has been rapidly increasing over the last 30 years and predominantly relies on natural gas, automotive diesel oil, and fossil fuels (Figure 3). Increasing energy consumption will therefore result in increasing emissions generated by the Australian mining industry.

Recent reports have shown that the real energy intensity of the Australian mining industry has grown at an average rate of 3.7 per cent pa over the period 1989-90 to 2005-06 (Sandu and Syed, 2008). This implies that 3.7 per cent more energy each year was required to generate a unit of mining product. This equated to an additional 112 PJ of energy consumption by the Australian mining industry without any increase in production between 1989-90 and 2005-06 (Sandu and Syed, 2008). Sandu and Syed (2008) attributed this increase to the declining quality of mining deposits and the increasingly depths and remote locations that are being developed.

Furthermore, the mining industry's energy consumption is projected to significantly increase at an average rate of 6.1 per cent pa to the year 2029-30 (Syed *et al*, 2010). If current production and energy consumption patterns remain

FIG 2 - MFP in the australian mining industry (Top *et al*, 2008; and ABS, 2010).

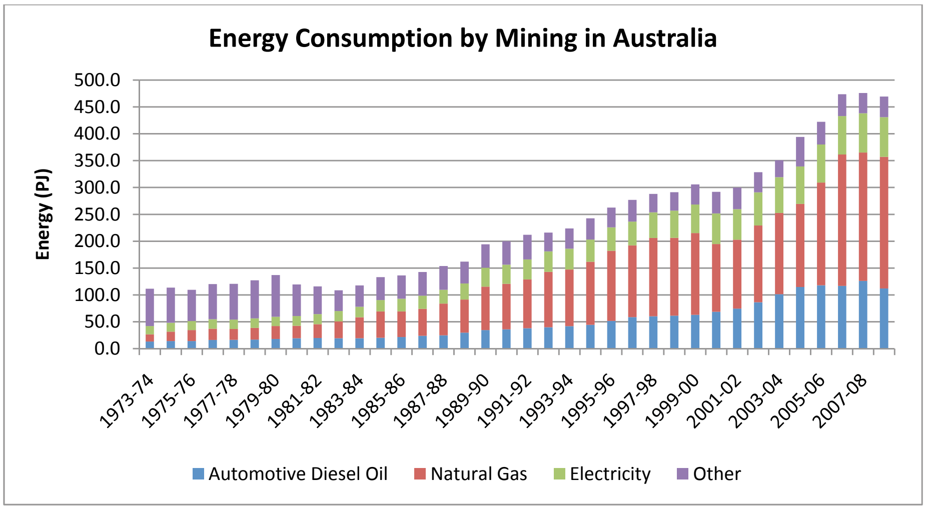


FIG 3 - Energy consumption by mining in Australia from the Australian Bureau of Agricultural and Resource Economics and Sciences (2010b).

unchanged, then the Australian mining industry will require an increasing amount of energy, and generate an increasing volume of emissions, to produce a unit of product. Therefore, energy efficiency will play a vital role in managing the growing risks of energy availability and potential emission prices for the Australian mining industry.

GEOMETALLURGICAL DATA

Geometallurgy requires integration across a wide range of existing activities and includes aspects of geotechnical engineering, process mineralogy, mine geology, metallurgy, process control, resource modelling, geostatistics and mine planning. What geologists observe at core scale is commonly not easily reconciled with how the rock is likely to behave, from an engineering point of view, in terms of processing performance. Much of the cross-discipline confusion that underlies geometallurgical integration relates to the different language and concepts behind these different viewpoints. A machine-based language needs to know about physical breakage properties, not necessarily what a rock was or why it is mineralised.

The dominant trend in geometallurgy is towards larger numbers of smaller volume (lower-cost) tests that can support definition of inherent variability. Constrained sampling that reflects and defines inherent variability is a key geometallurgical requirement and early compositing of samples can disguise this. Sampling approaches that fail to address variability, or use predetermined boundaries that were not correlated with processing performance, can produce seriously flawed geometallurgical results.

Mineral extraction performance attributes

For the primary geometallurgical data as listed in Table 1 to be useful to mine planning and process optimisation they need to be converted into performance attributes such as the ones listed below. This conversion needs to be undertaken in an auditable and statistically robust manner addressing:

- throughput (t/hr),
- recovery (per cent),
- specific power(kWh/t),

TABLE 1
Indicative list of non-grade type data used in the case studies.

Geometallurgical	Geotechnical
Drop weight test (DWT – Axb)	Uni-axial compressive strength (UCS)
Bond mill work index (BMWI – kWh/t)	Point load index (PLI)
Crushing indices (JKCi)	Rock elastic moduli / properties
Recovery (%)	Rock mass rating systems (RMR, Q, etc)
Mineralogy	Rock quality designation (RQD)
Multi-element assays	Fracture frequency per metre (FF/m)
Lithology	EQUOtip (measure of relative hardness)
Alteration	Blastability indices

- stable slope angles (°), and
- required blast powder factor (kg/m³ or kg/t).

New tools and models are required to effectively incorporate these new metrics into mine economic assessments. An example of these integrated process optimisation tools is discussed later in the paper.

GEOMETALLURGICAL DOMAINING

The application of spatial domains to constrain the estimation of grade is a well established and an essential process used in most ore reserve models. Defining the geometallurgical domains for an ore deposit is an equally important process in developing a fully attributed geometallurgy block model. It should be noted that ore domains and geometallurgical domains are normally not directly related.

Traditional approaches have focussed on defining the orebody into 'ore types' as illustrated in Figure 4. This is an important step and depending on the complexity of the deposit it does not always capture the ultimate process performance of the ore types in terms of recovery and throughput.

Figure 5 is an example of a 3D mineral class model. The mineral classes have been derived from a principal components

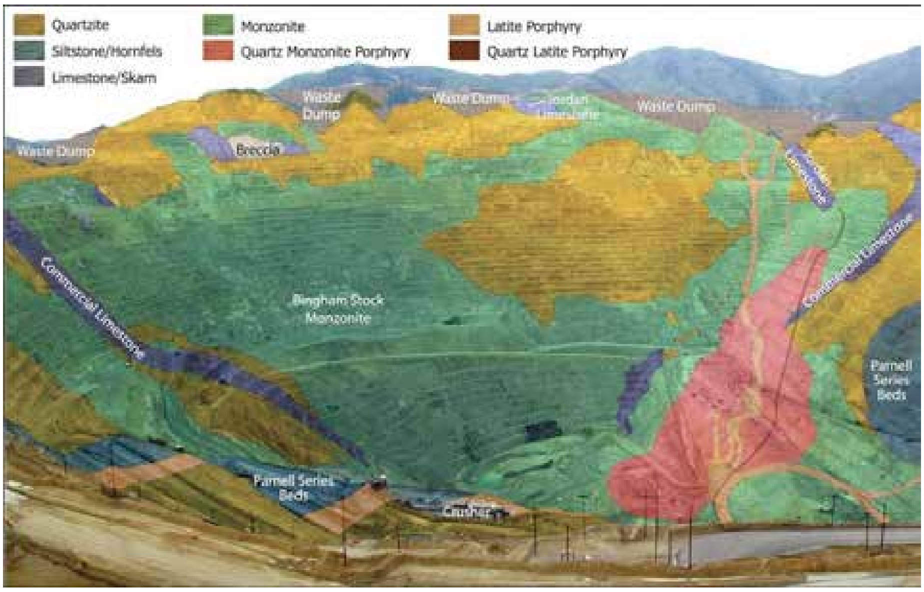


FIG 4 - Example of spatially defined ore type domains.

analysis (PCA) and the spatial modelling has been done using indicator kriging. The mineral classes are spatially contiguous but do not relate directly to the primary geology domains.

Figure 6 illustrates the spatial complexity of a mineral class model (MMG) in a large porphyry copper deposit. The mineral classes are not as spatially contiguous as in Figure 5 and again the mineral classes do not relate directly to the geological units.

Sectional interpretation and wireframing

Sectional interpretation is an intensive manual process of connecting drillhole attributes from section to section to form a closed wireframe volume of the domain. Manual interpretation methods are not appropriate for all data sets but they are often used to define lithology and structural domains that are contiguous. Figure 7 illustrates a complex set of structural and lithology domains. These domains can be used effectively to constrain the modelling of geotechnical attributes into a 3D geotechnical block model.

Indicator kriging for domain definition

Indicator kriging (IK) is a geostatistical approach that can be used to model categorical variables such as rock type. It can therefore also be used for modelling mineral class domains (MMG). The 0/1 indicator values for each mineral class are estimated into model cells. In Figure 8 each cell has four indicator variables with values between zero and 100 per cent, one for each mineral class (MMGB). These can be interpreted either as the proportion of each mineral class in each cell or as the probability that the cell is a particular mineral class.

Figure 9 is a section through a geometallurgical block model illustrating the nine mineral classes that have been defined for the deposit. The proportions of each mineral class are

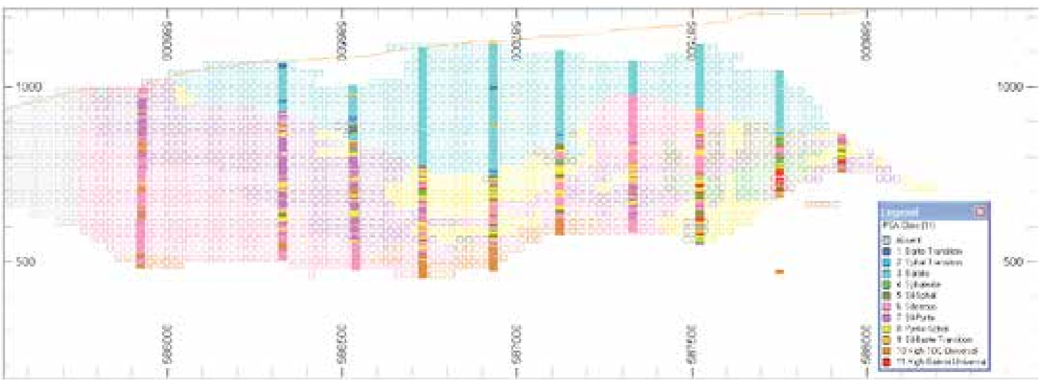


FIG 5 - Example of a zinc deposit showing less complex and layered mineral class domains.

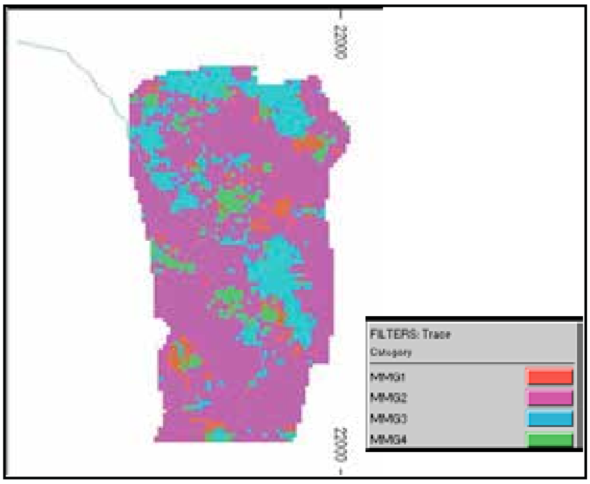


FIG 6 - Mineral class domains for a porphyry copper deposit are more spatially complex than those shown in Figure 5.

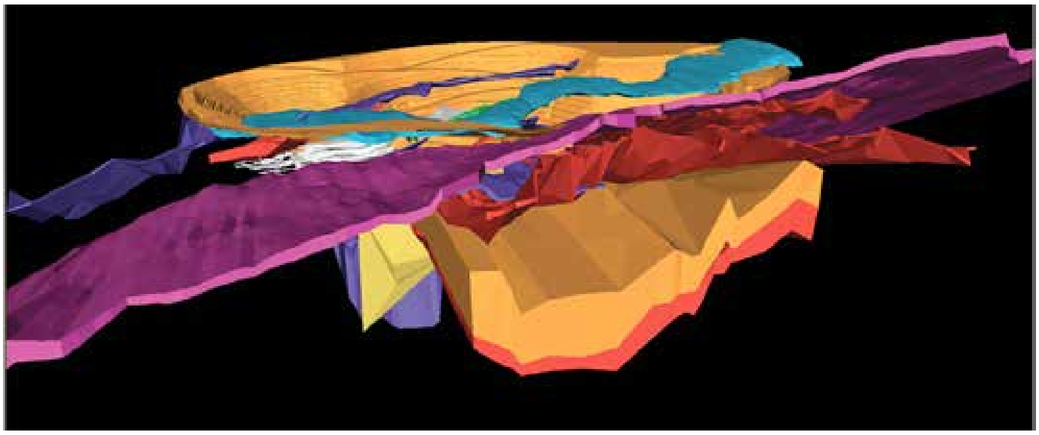


FIG 7 - Complex structural domain model used to constrain the modelling of geotechnical attributes.

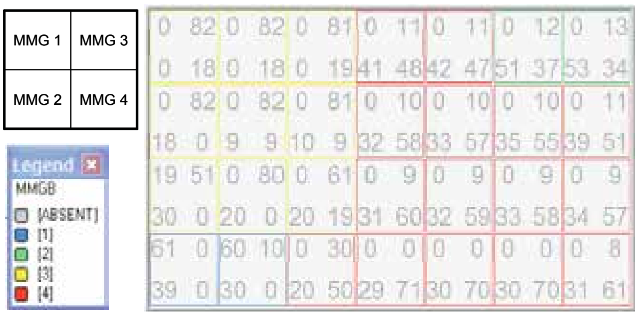


FIG 8 - Section through a block model illustrating the proportions of each mineral class in each model cell.

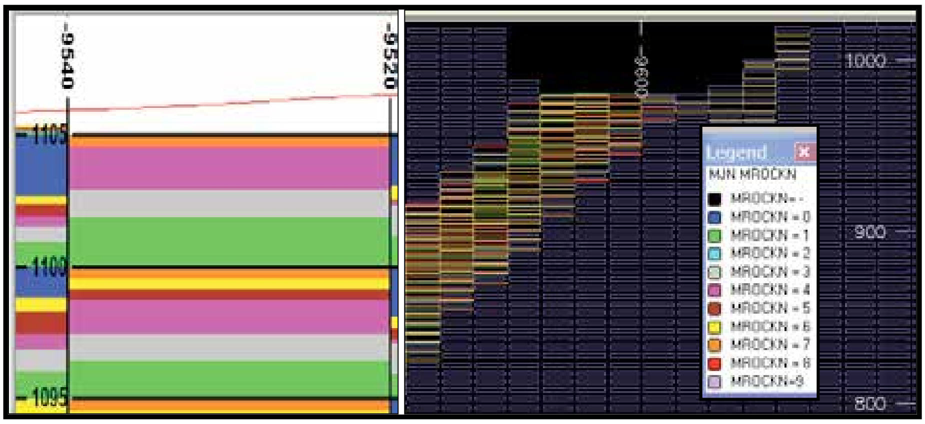


FIG 9 - Mineral class block model with the proportion of each mineral class represented in each model cell.

represented in each model cell. This is very useful for mine planning as the tonnages of each mineral class are estimated for each cell.

GEOSTATISTICAL MODELLING

The development of block models containing non-grade or geometallurgical data must follow the same due diligence practices as the development of ore reserve models. Most geostatistical estimation methods such as ordinary kriging assume that the variable being estimated is additive or linear. This assumption is valid for variables such as grade (per cent, g/t, etc) but this is not necessarily the case for the comminution parameters or other mineral processing performance indices. Therefore, the estimation procedure must use variables that are additive or the effect of potential non-additivity must be tested and accounted for. In this case alternative geostatistical techniques should be used that do not assume the additivity of the sample data.

Modelling of non-grade data is a challenging problem and the issues to consider are described by Dunham and Vann (2007). An understanding of the spatial modelling assumptions is key and is often more important than the specific geostatistical technique applied.

Point estimation and simulation

Point estimation and simulation offers a possible solution to the additivity challenge. If a grid of points is estimated in space then there is no blending/averaging of data into a model cell. It is simply an estimate of the value of a variable at a set of points. However, if the value of a model cell is estimated then most estimation methods such as inverse distance and ordinary kriging will represent the cell by a 3D matrix of discretisation points and the estimate will be a blend of point values. If the variable is not machine additive then the cell estimate will be biased. A possible solution is to have a 'blend response model' to accommodate the non-linear relationship between the cell and point values and so remove the bias of the linear estimators. The blend response model is discussed later in the paper.

Conditional simulation is a geostatistical technique that creates multiple sets of point data with the same statistical and geostatistical properties as the actual sample data. As the technique creates point data it can be used to simulate a non additive variable. It is therefore possible to simulate a set of points within a defined volume (eg model cell) and to calculate the distribution (histogram) of the points. The quantiles of the distribution can then be used to give a ballpark estimate of the block value. For example if the variable measures hardness, with high values having a disproportionate effect on the block value, then the 30th or 40th percentile could be used as an estimate of the blended block value.

Additionally, conditionally simulated data provides a data distribution in the model cells. The average of this distribution is not a blended average it is simply the most likely value. Doing multiple simulations and applying a blend response model will give a distribution of possible block values. Software packages such as NPV scheduler accept multiple simulated models to give a distribution of net present value (NPV). The link of simulated geometallurgical models to mine planning optimisation is discussed later in the paper.

BLEND RESPONSE MODELS

The blend behaviour of performance indices such as DWT, recovery and BMWi are specific to the processing plant or machine through which the material is processed. It follows that machine additivity must be handled through an appropriate laboratory test that defines a blend response model.

A porphyry copper example of how geometallurgical data models can be developed and combined with a blend response model is detailed below:

- Mineral class values were estimated into 5 × 5 × 5 m cells using indicator kriging.
- Ten sets of Axb values were simulated on a 2.5 m point grid for each mineral class.
- The points were then blocked into cells of 25 × 25 × 15 m.
- Each block model cell has 10 × 10 × 6 = 600 points per cell.
- Each 5 × 5 × 5 m cell has a unique mineral class.
- The larger 25 × 25 × 15 m cells include simulated points with proportions of each mineral class.
- Figure 10 shows the process described.
- Table 2 shows the corresponding individual model cell statistics.
- Figure 11 illustrates graphically the individual model cell data.

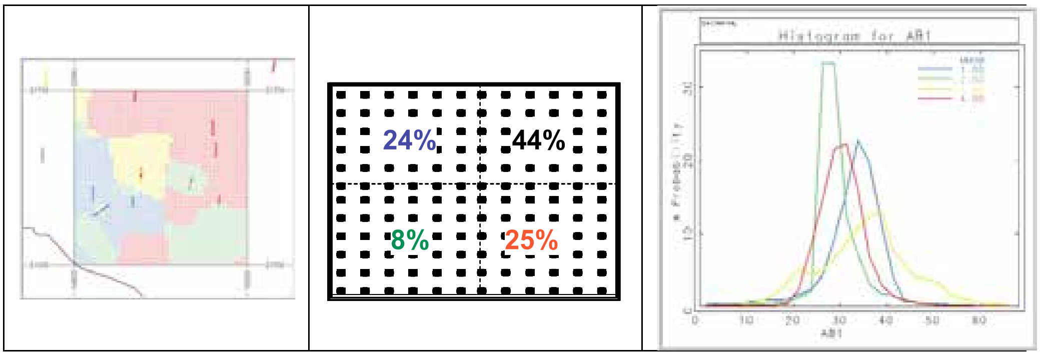


FIG 10 - Illustration of point data in a block model with Axb distributions for each model cell.

TABLE 2
Axb statistics for an individual block model cell.

Mineral class (MMGB)	Volume		Mean	Std dev	Percentile		
	m^3	%			30%	40%	50%
1	2250	24	42.3	11.4	37.7	38.4	39.2
2	750	8	32.8	3.7	30.3	30.9	31.9
3	4125	44	36.6	5.4	34.8	36.6	37.5
4	2250	25	34.9	5.0	33.2	34.3	35.4
All	9375	100	37.3	7.8	34.3	35.7	37.0

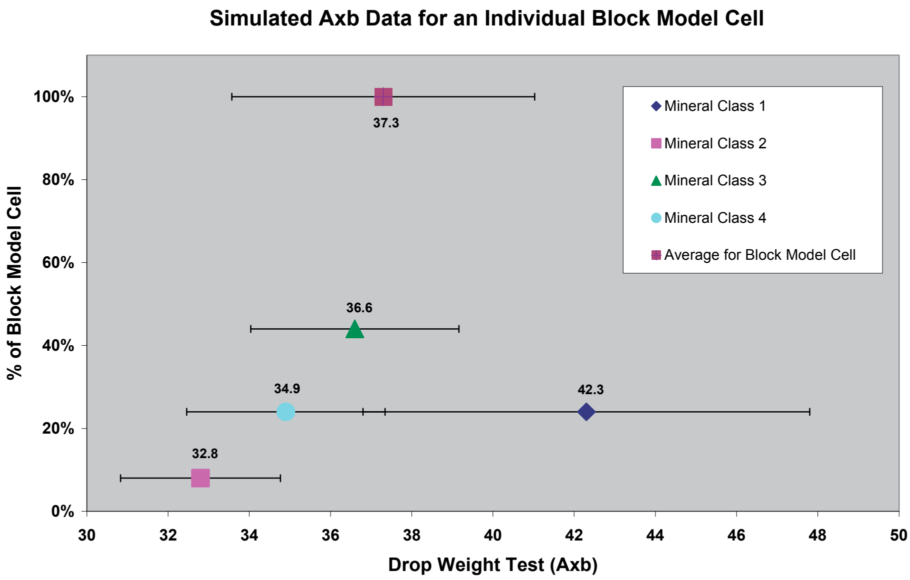


FIG 11 - Conditionally simulated DWT (Axb) data from an individual block model cell. The horizontal lines are error bars around the estimate. The volume/proportion of each mineral class in the cell is also known. This data forms a key input to a blend response model.

This process will deliver the type of data that can be input to the blend response model to estimate the most appropriate Axb value.

Figure 12 illustrates the non-linear response of a processing plant to different material hardness (Axb). This response curve combined with the mineral class proportions in each block model cell provides valuable information for assessing the blend response of that model cell. The proportions of mineral classes combined with their performance data can be used for ore feed scheduling. For mine planning the proportions of each mineral class are known and this can be optimised in the extraction schedule.

EXAMPLES OF GEOTECHNICAL MODELS

Geotechnical information collected at mine sites often represents large databases of spatial rock quality information. There are significant risks in building 3D geotechnical models and some of these are discussed by Dunham and Vann (2007). However if due diligence is followed in the development of these models and they are both well constrained and use appropriate geostatistical methods to handle the non-additive data then they can be very useful tools (Egaña *et al*, 2008). At a minimum they can be used to identify areas of limited geotechnical knowledge and poor rock quality or high risk areas.

Figure 13 illustrates an oblique view of a rock mass quality model represented on the open pit and underground layouts. The model was used to identify areas with sparse data and areas of weak rock mass. The model was configured to provide indications of underground support requirements as well as slope design categories.

Geotechnical block models can be effectively used to assess high variability in rock mass properties. The variability transfers to uncertain slope design conditions and this can be represented spatially as illustrated in Figure 14 below.

A very large geotechnical data set comprising exploration core, face mapping, orientated drilling, laboratory testing and measurement while drilling data (Aquila system) was used to build a 3D geotechnical model for a large copper deposit (Figure 15). The model was used to aid dynamic blast design for the mine to mill program and identify slope risk areas

GEOTECHNICAL MODEL FOR COPPER/GOLD OPERATION

Geology and the detailed understanding of its engineering properties are fundamental to the optimal design and successful operation of any mine. Extensive fieldwork and lab testing is undertaken at most mine sites, this information however, is often not used to its full value throughout the mine life. The integration of all geotechnical data into a single 3D geotechnical model provides the platform for operational improvement at mine sites.

A 3D geotechnical model has application to any major civil or mining venture that requires a detailed understanding of the variability in rock mass conditions. A geotechnical model does not propose to generate solutions by creating information from a limited data set. It does, however, give the engineer a tool whereby he can assess the spatial variability of the rock mass information and thereby identify data-deficient or high risk areas.

The 3D geotechnical model provides information well ahead of the mining face and the model can be used for the following:

- identifying zones of high geotechnical risk (due to high variability or lack of data),
- identifying key areas requiring additional data collection,
- blast design strategies, and
- slope design strategies.

The model is used as an input into the blast design process. This enables the appropriate powder factor of an individual blast to be selected to deliver a target fragmentation. Improved fragmentation can potentially improve loading rates, transportation and mill throughput.

The model was used for the visualisation and analysis of a range of data in a single environment that had hitherto not been combined, and therefore will improve the understanding of the orebody and ground conditions at the mine.

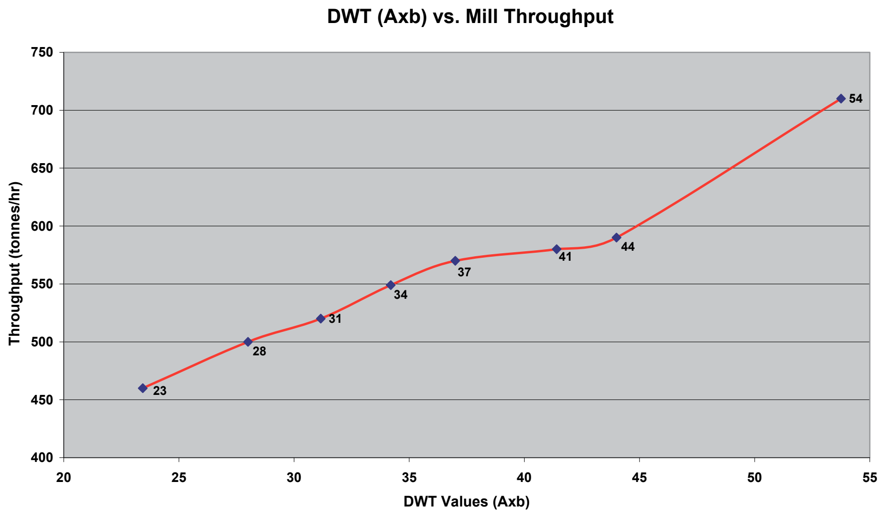


FIG 12 - Example of the non-linear response of plant throughput to drop weight test (Axb) data. This data can be used in conjunction with Figure11 to assess blend response.

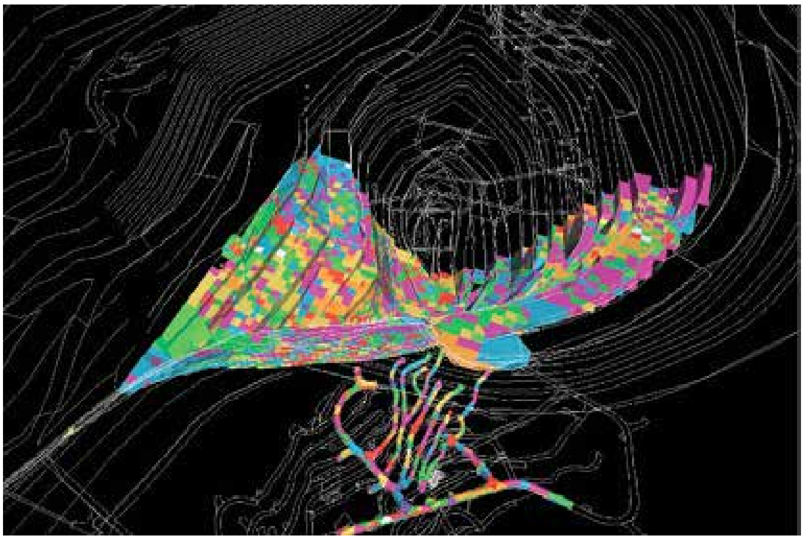


FIG 13 - Rock mass quality from a geotechnical block model represented on both the open pit and underground layouts. (Green = good quality; purple=poor quality)

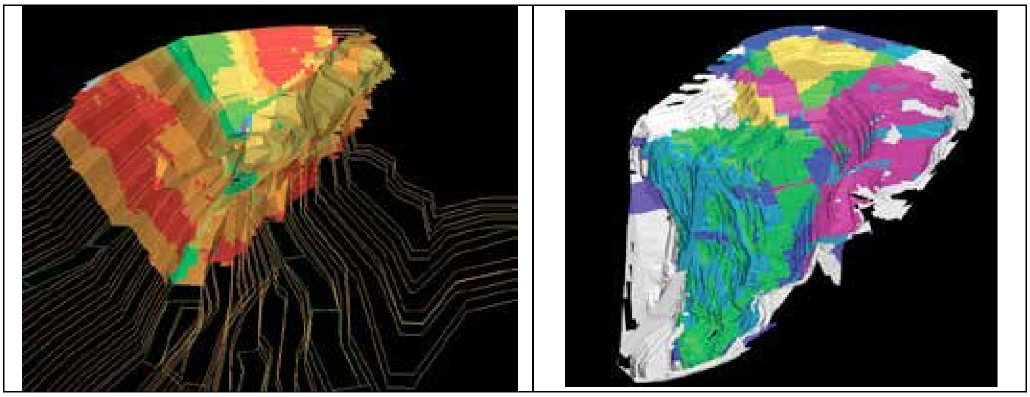


FIG 14 - Geotechnical models coloured to illustrate zones of high slope risk where design slope angles exceed rock mass conditions. Hotter colours represent higher risk.

Geostatistics also has its limitations when applied to geotechnical data. On this basis, users should be prudent and use 3D models as an aid to design rather than an explicit design tool. As more data is collected and the model is validated the confidence with which the model data can be used will improve. Geotechnical models will provide gross trends indicating where the rock mass properties are changing thereby providing early warning to engineers so that they can apply proactive design engineering.

Detailed below are a number of model images (Figure 16-20) illustrating the information available in the 3D geotechnical block model.

Model validation

It is essential that all models are validated. In this example the geotechnical blasting model was queried to see if it was producing realistic information. In Figure 20 the geotechnical model indicated that 50 per cent more explosive energy was required for a historical blast. On inspection of the blast muckpile it was evident that the standard blast powder factor used was significantly lower than required. The result was coarse blast fragmentation, limited blast movement and difficult digging. Proactive blast design using a 3D model will minimise the occurrence of inappropriate blast design for the ground conditions.

LINKING EXTRACTION PERFORMANCE TO GEOMETALLURGICAL DATA

Process optimisation, the generation of CO_2 and consumption of energy and water on mining operations are critical issues for mining companies. Most companies have targeted significant

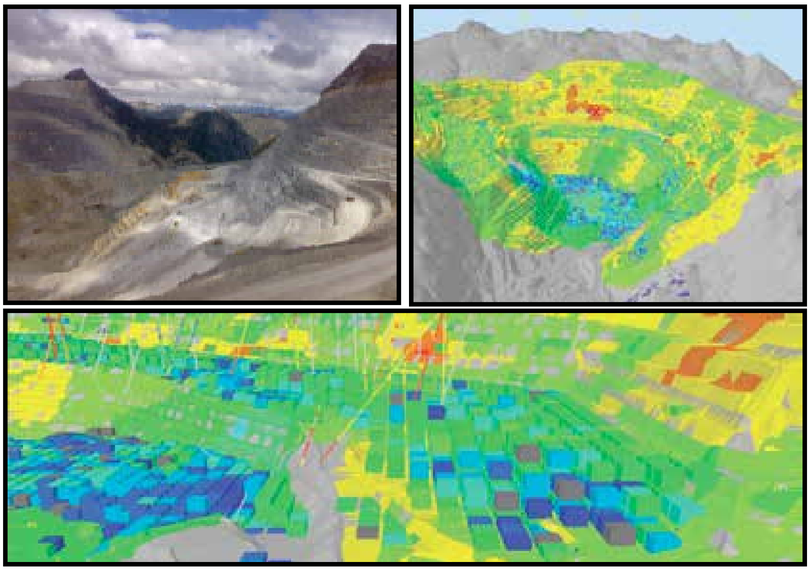


FIG 15 - Geotechnical block model developed for a large porphyry copper deposit.

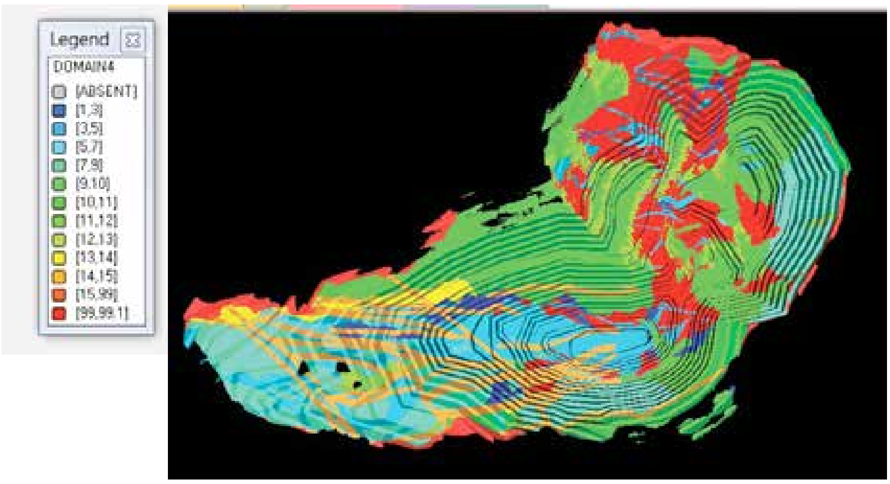


FIG 16 - 3D view of the geology and structural domains used to constrain the modelling.

improvements in energy, water and CO_2 emission levels over the next ten years. In order to achieve these targets the design and management of a mining operation should be analysed as an integrated extraction process ('geology-mine-plant'). New tools are required to model the extraction process.

In partnership with Anglo Platinum the Sustainable Minerals Institute (SMI) has developed an integrated process optimisation tool that considers key eco-efficiency attributes. The software tool involves the integration of functionality from JKTech's JKSimBlast, JKSimMet and JKSimFloat software packages. The geology-mine-plant management tool provides an integrated software and technology system for the optimisation of energy, water and greenhouse gas emissions. Additionally, the software provides the optimisation link between a 3D geometallurgical model and mine evaluation techniques.

This process optimisation project is extending the traditional mine to mill model into a holistic analysis of energy consumption and the sustainability footprint on a mining operation. Initial site application has demonstrated significant value associated with geology-mine-plant integration and management.

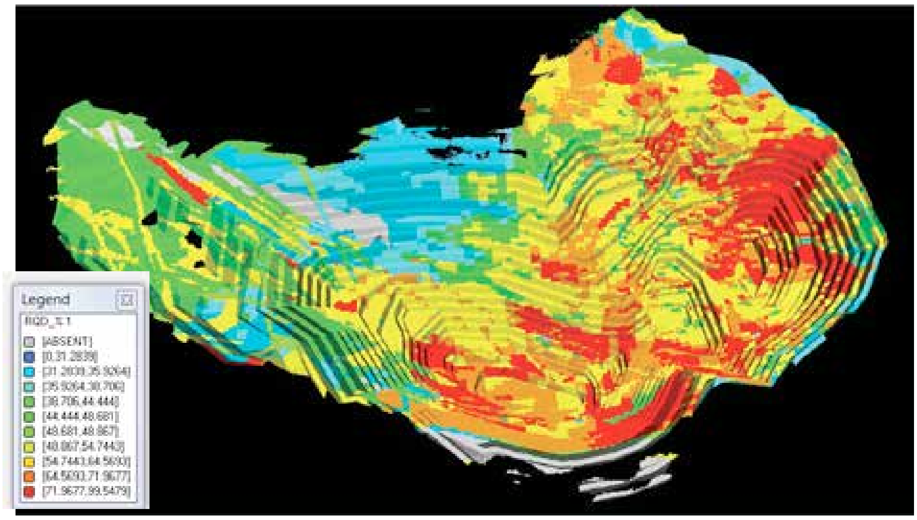


FIG 17 - 3D Rock Quality Designation (RQD) model. The primary data came from 1456 boreholes containing 137 527 RQD measurements.

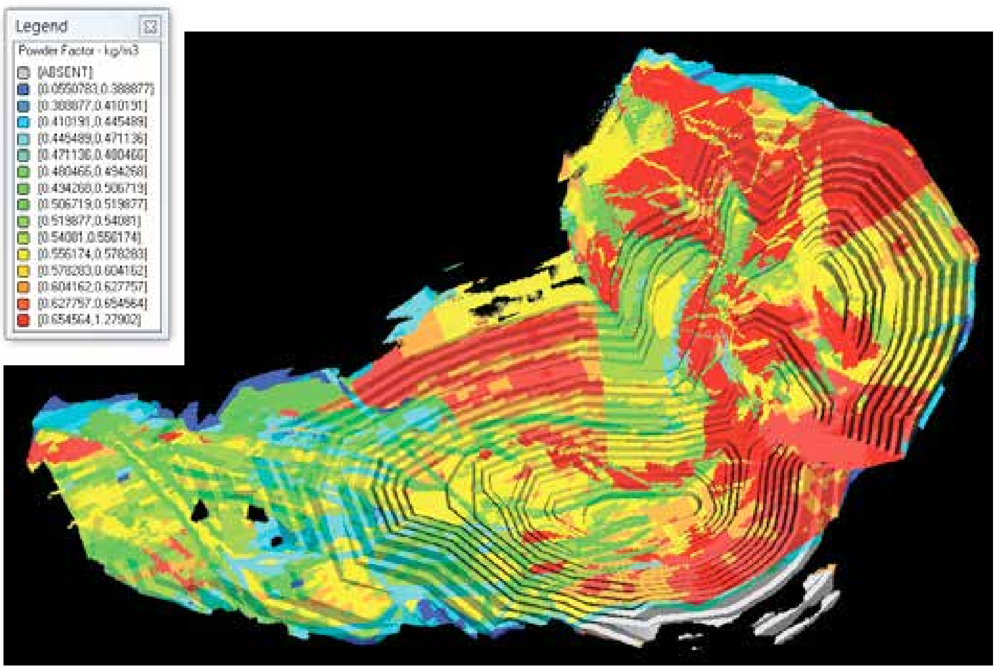


FIG 18 - Indicative blast powder factor (kg/m^3) for the prescribed ore and waste fragmentation targets.

The developed software (Figure 21) and guidelines have enabled the integration of energy efficiency into daily business as well as improve measurement and accounting. The project will enable corporate tracking and comparison of business unit energy efficiency per unit metal produced. In addition it allows site engineers to consider changes to the design, layout and operation of mines so as to minimise the sustainability footprints and increase metal production.

Software overview

The University of Queensland's Sustainable Minerals Institute (SMI) has broad expertise in the minerals industry and is

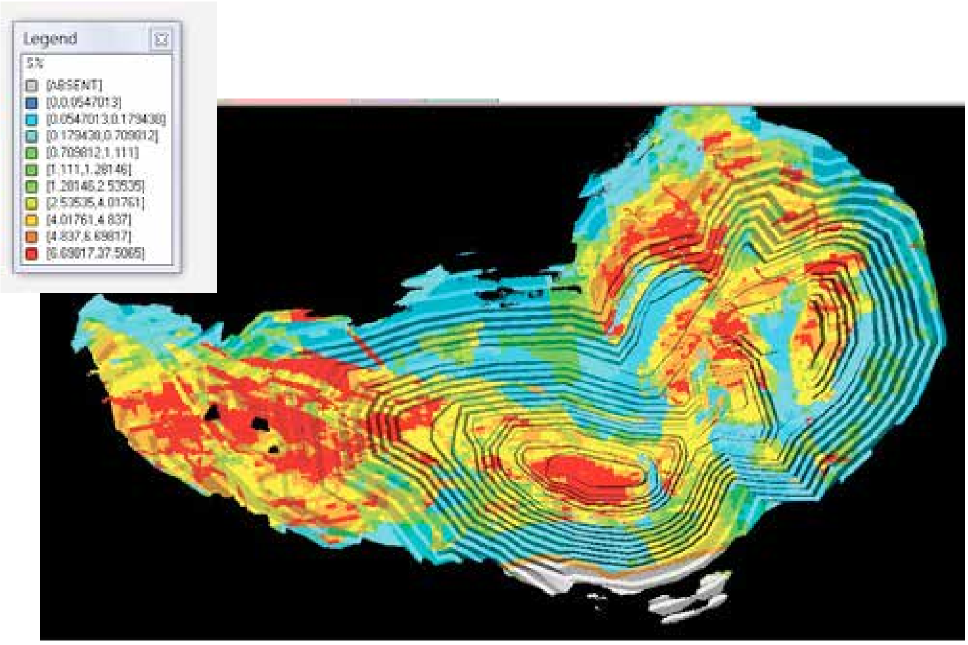
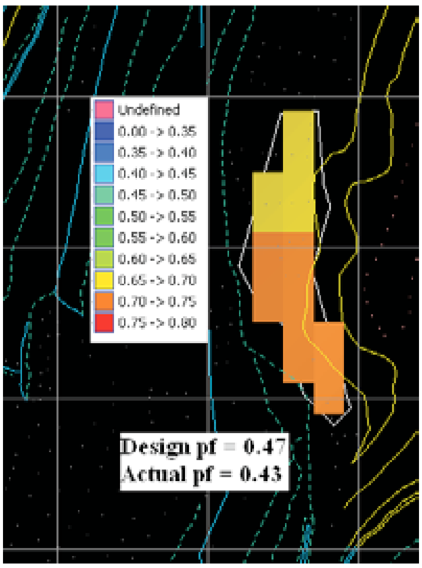


FIG 19 - Modelled sulfur per cent which may possibly be used as crude proxy for acid rock drainage potential.



Actual Blast Design	
Plan Powder Factor	0.47
Actual Powder Factor	0.43
Model Powder Factor	0.65

FIG 20 - Model validation against actual pit blast . The photograph in the bottom right indicates the tight muckpile with course fragmentation resulting from insufficient blast energy.

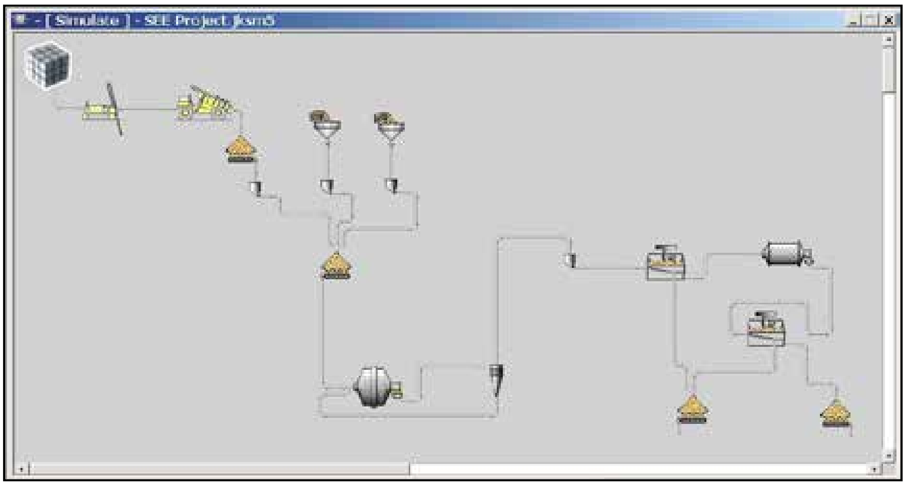


FIG 21 - Prototype view of the software interface.

particularly noted for its mineral processing research (Napier-Munn *et al,* 1996). Through its commercialisation arm JKTech provides specialist software products such as JKSimBlast, JKSimMet and JKSimFloat to the industry (JKTech, 2009). This project combined elements of the standalone software products into a single integrated platform. The product is a mine-plant simulation tool which is driven by geological information. The basic architecture of the software is illustrated in Figure 22.

Scenario Analysis

Figure 23 illustrates the type of analysis that can be generated from using the software. The left graph shows the tracking of production metrics through the mine-process sequence. This allows the user to identify optimisation opportunities. The right graph illustrates a number of scenarios which trade off metrics such as water and energy. A much more rigorous net cost considering eco-efficiency parameters can be generated

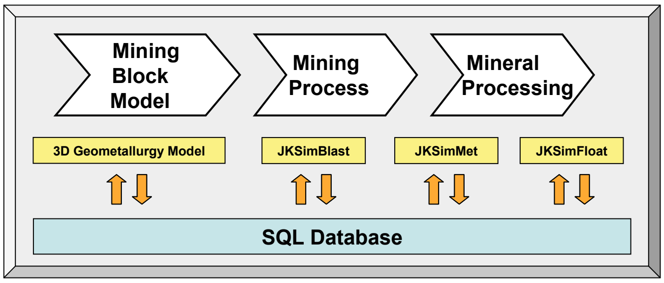


FIG 22 - Overview of the software architecture.

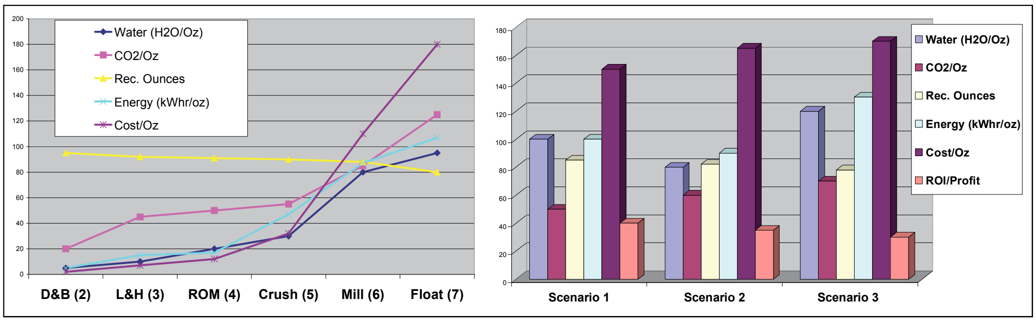


FIG 23 - Diagrams to illustrate the information and scenarios that can be considered through this initiative.

for business decisions. The simulations allow the user to optimise mineral extraction for metrics such as:

- metal tonnes,
- cost ($/tonne),
- total energy (kWh/tonne),
- water (ML/tonne), and
- carbon emissions (CO_2-e/tonne).

As can be seen in Figure 24 variations in ore properties have a significant effect on the simulated circuit performance.

Reporting

One of the main driving forces for the study was the derivation of key reports at each stage of the mine-process sequence. Figure 25 illustrates the stages of reporting for each process step as well as a cumulative report.

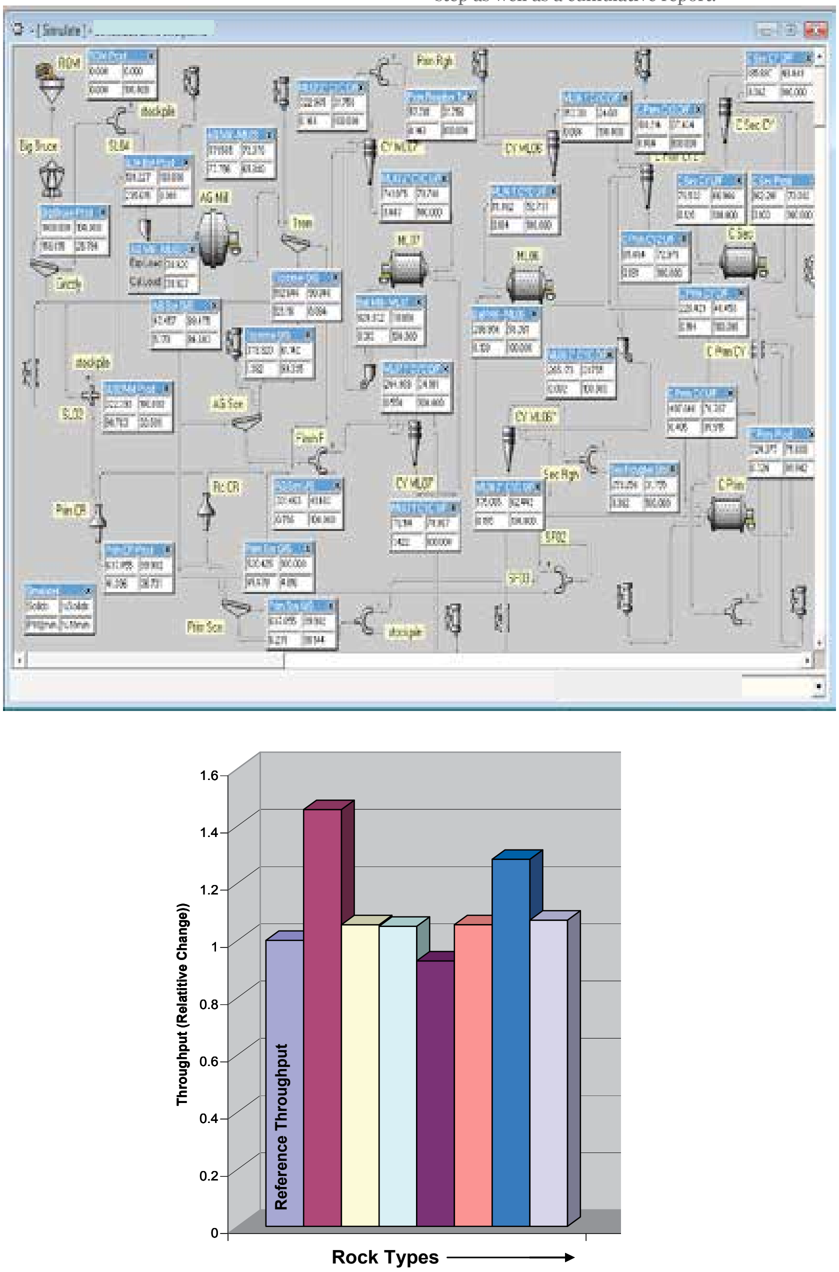


FIG 24 - Plant circuit layout and performance of the various rock types. The right hand graphic represents the variance against plan throughput.

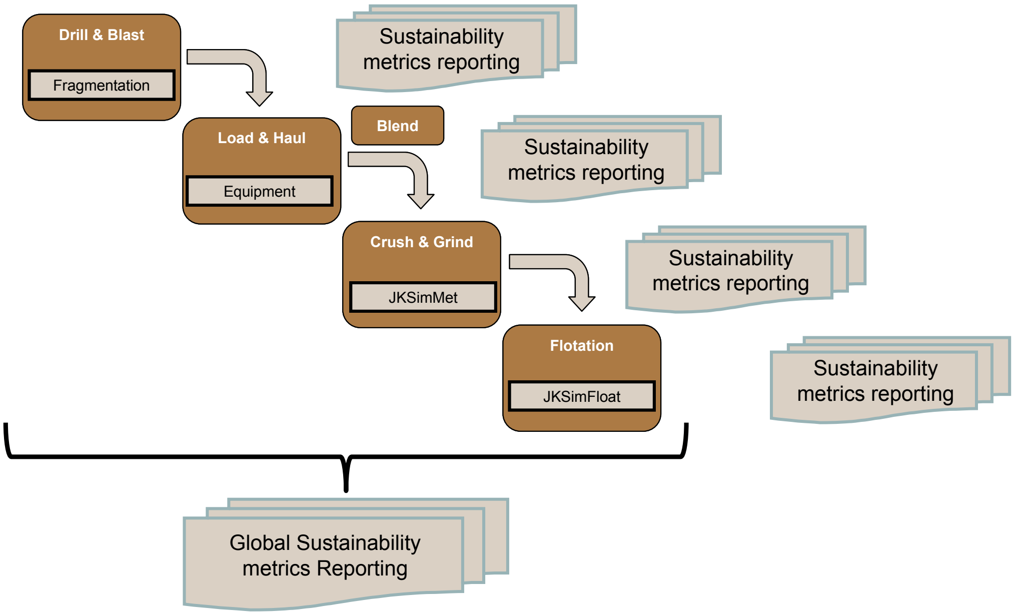


FIG 25 - Reporting phases of the mine-process software.

Energy/CO_2-e optimisation results

Part of the validation study was also to look at the energy consumption and CO_2-e (equivalent) production across the operation. The dominance in energy usage and equivalent CO_2 production by the comminution circuit is clearly evident in Figure 26.

Environmental legislation, water shortages and carbon trading systems are changing the mining economic environment. Mine wide process optimisation that considers the generation of CO_2 and consumption of energy and water on mining operations is a critical issue for mining companies. New tools and models are required to effectively incorporate these new metrics into mine economic assessments. The SMI has developed a mine-plant evaluation tool for this purpose.

The study has incorporated elements of *JKSim Blast, Met and Float* onto a single evaluation platform. When the software was supplied geometallurgical information from a 3D planning model significant benefits were identified. For example, what material was uneconomic due to poor process performance as well as what material schedule and blend would maximise NPV. This geology-mine-plant research project and software development will extend the traditional mine to mill model into a holistic analysis of energy consumption and the sustainability footprint on a mining operation.

EXAMPLES OF SPATIAL GEOMETALLURGICAL MODELS

The aim of this case study was to create a block model containing performance indices such as zinc recovery, throughput and specific power that could be used to help optimise mine planning and scheduling activities. Illustrated below is an example of geometallurgical spatial models that were developed for the project. The uses of these models in mine planning and evaluation resulted in a change in NPV of ten per cent for the operation.

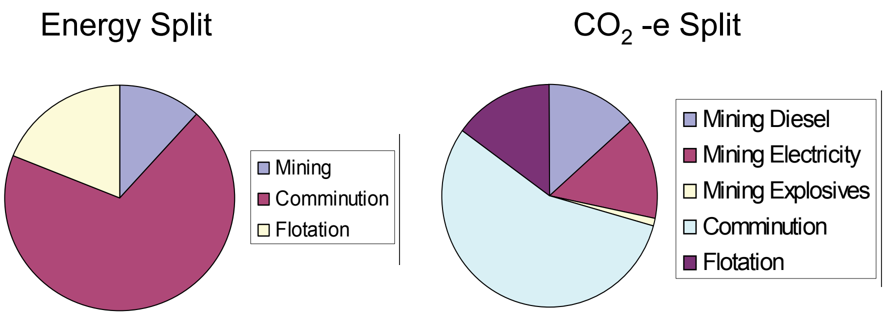


FIG 26 - Pie charts representing the energy usage and CO_2-e production splits on the operation.

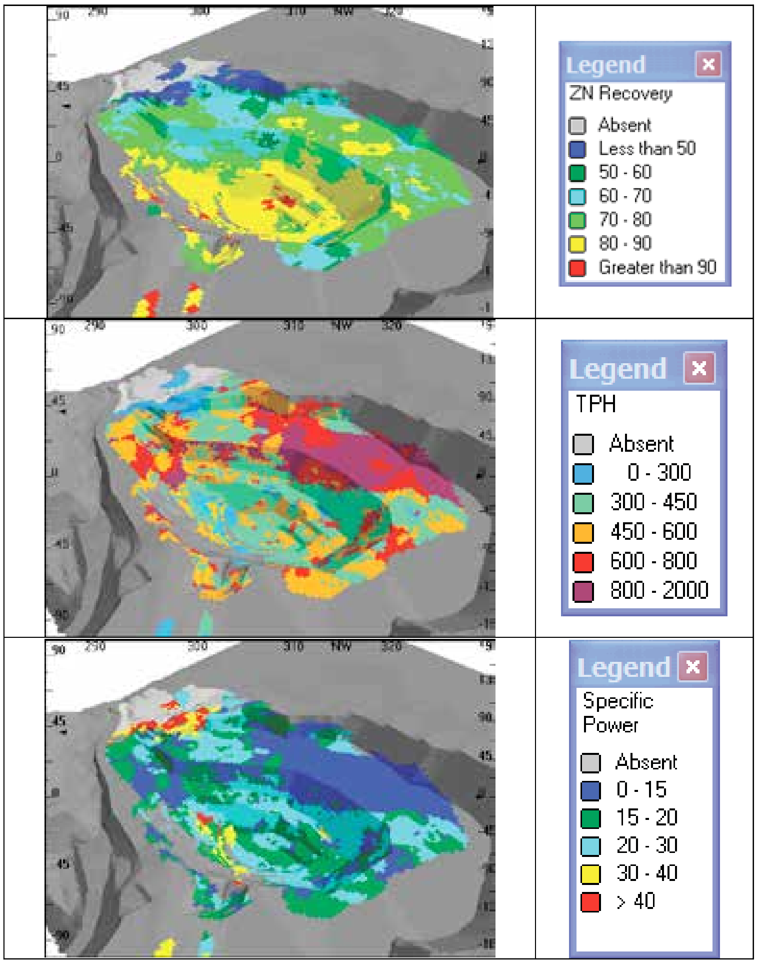


FIG 27 - Recovery (top), throughput (t/h; middle) and specific power (kWh/t; bottom) spatial models.

GEOMETALLURGICAL DATA CONFIDENCE

The availability of limited data has not previously stopped the development of 3D geometallurgical models on mine sites, however it is essential that the confidence of these models is well understood. Key questions such as: 'how much geometallurgical data are enough?' and 'what should be the sampling interval or drilling grid?' are common on mine sites and feasibility projects. 3D risk control diagrams can be developed to assess data density and data variability.

The kriged variance can be calculated when the performance indices are estimated into the model cells. This is not intended to be used for calculating absolute confidence limits for individual blocks, but can be used to indicate the relative confidence of estimates for a block and indicate where additional drilling would be beneficial (Figure 28). For a quantitative measure of confidence/uncertainty conditional simulation is the preferred approach where a distribution for each geometallurgical variable is available in each model cell and the probability/standard deviation for each attribute can be assessed.

Figure 29 illustrates the model confidence for a 3D geotechnical model developed from a closely drilled deposit with a very large geotechnical data set. The high risk areas in red represent structural zones where the geotechnical data is highly variable. The white zones indicate insufficient data to undertake modelling and are also therefore high risk. The high risk red zones can be seen to extend into the underground workings in places.

GEOMETALLURGY AND MINE PLANNING

Traditional open pit mine design and optimisation have been limited by the amount of detailed geotechnical and geometallurgical information available (Bye, 2006). The aim of this study was to build a fully attributed geometallurgical mine planning model where each model cell has a unique mining and processing cost as well as plant recovery. Given a fully attributed geometallurgical model the study then assessed the impact on the ultimate pit and cash flow schedule against the base case mine model.

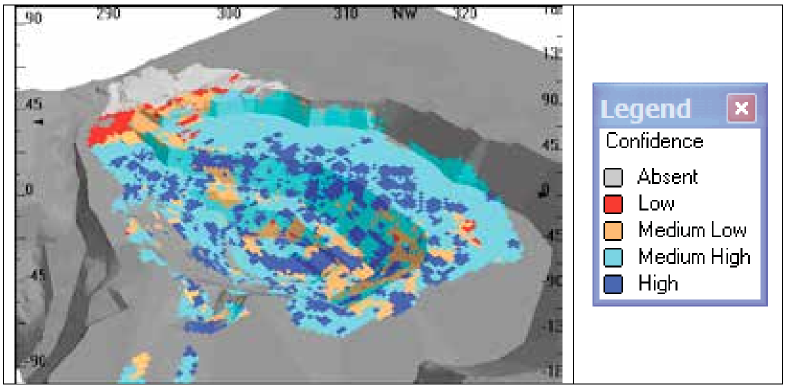


FIG 28 - Geometallurgical confidence model.

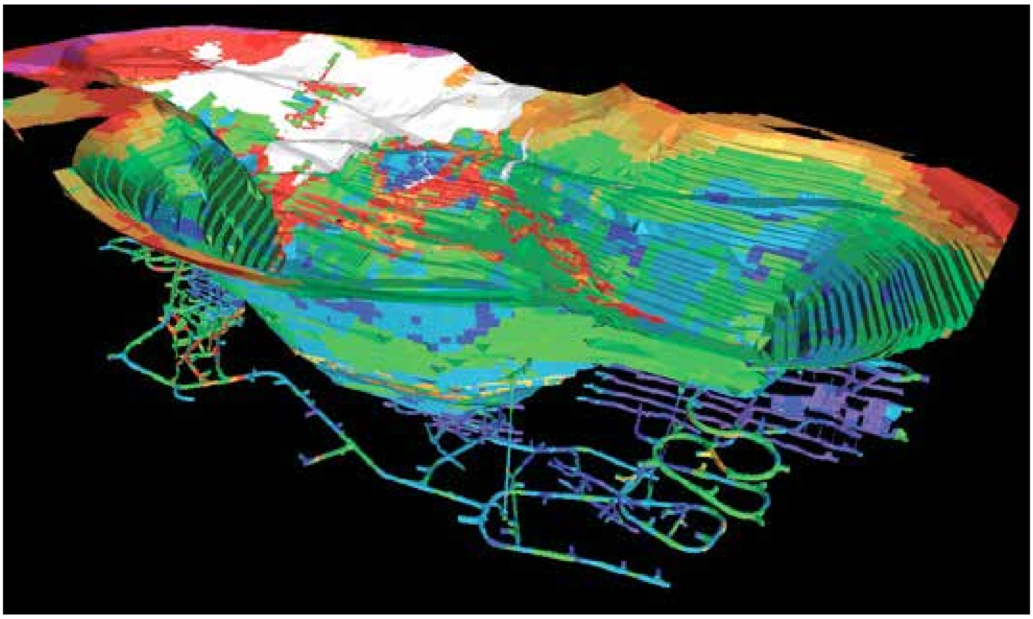


FIG 29 - 3D model illustrating areas of data confidence. High uncertainty (Red); Low (Green).

The work included:

- Base case analysis to develop pit shells and cash flows using methods currently employed at the mine.
- Development of pit shells and cash flows using the additional metallurgical data and comparison against the base case.
- Analysis of the simulated models to assess the likely variance of cash flow and derive confidence limits. Identify high risk years.
- Investigate different processing plant options.

Figure 30 illustrates the old pit shell defined by the mine's traditional mine planning approach. Overlain onto this shell is the new ultimate pit shell generated from the geometallurgical model containing performance attributes for each rock type. The circled areas represent uneconomic material that would have been included in the traditional pit optimisation. Through the inclusion of detailed geometallurgical information on hardness and recovery certain parts of the ore reserve were identified as uneconomic.

The mine in question used a fixed processing cost adjustment factor (PCAF) as an input into the pit optimisation economic model. As more detailed geometallurgical information was available in the geometallurgical model a unique PCAF was calculated for each model cell. The processing cost was adjusted based on material hardness for issues such as steel ball usage and energy consumption. Figure 31 illustrates the

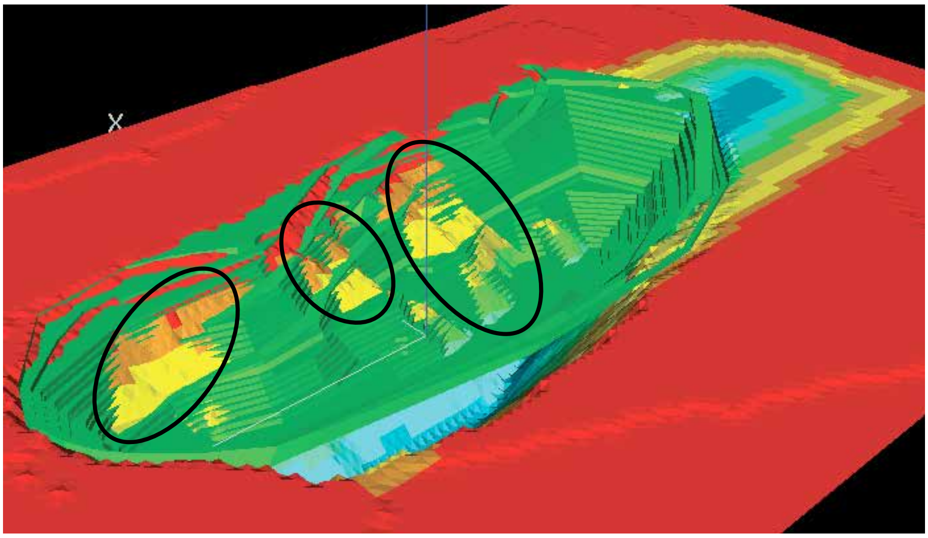


FIG 30 - The circled areas represent uneconomic ore due to hardness and poor recovery. Prior to this study the material was considered economic.

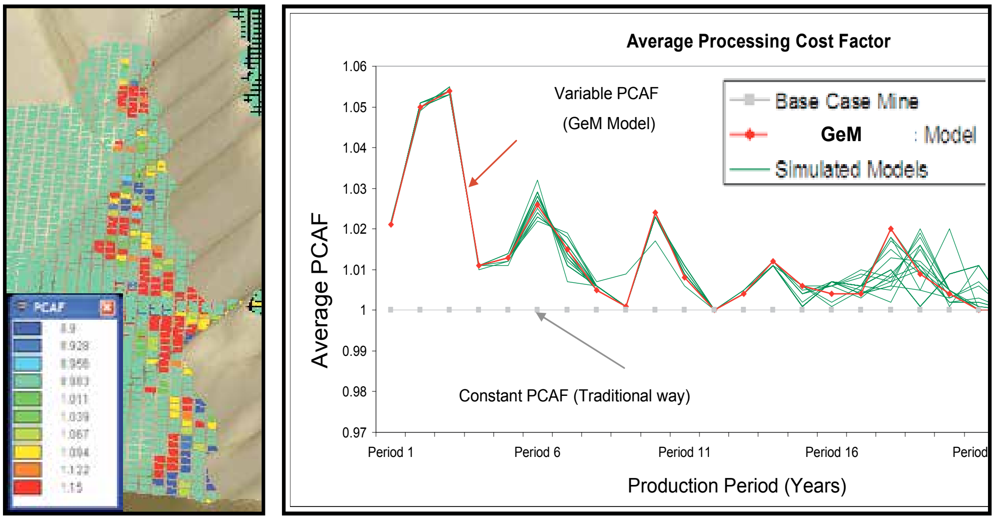


FIG 31 - Comparison of fixed processing cost versus processing costs calculated from the geometallurgical model. The plan section through the block model on the left shows the spatial variation of the processing costs.

significant difference in cost information, up to 15 per cent, that is now included in the mine planning model. This was also done for the mining costs where harder material was allocated higher drill and blast costs.

The net impact of the geometallurgical mine planning model when compared to the base case model can be seen in Figure 32, represented as an annual cash flow comparison. The difference in cash flow between the plans is as high as $50 million per annum. The real value of this approach is to highlight the impact of ore variability on the mine plan and identify high risk periods. The operation can then put strategies in place to minimise risk and optimise the schedule.

Simulation models and quantified cash flow uncertainty

Twenty simulated geometallurgical models were created using the sequential gaussian simulation method. Each model was then analysed using NPV scheduler. The resulting cash flow distributions are represented in Figure 33. From the cash flow analysis the most likely return for that year can be defined or the probability of achieving a certain value can be seen. Two clear periods of highly likely low cash flow are evident (Years 11 and 20-21). This is valuable information for identifying high risk years that can often be addressed through re-scheduling the mining sequence.

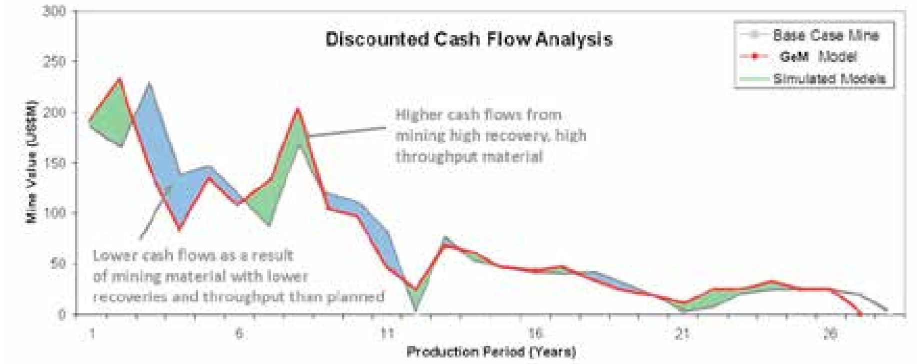


FIG 32 - Difference in cash flow predicted from a fully attributed Geometallurgical mine planning model versus the mines traditional ore reserve model. The variation is up to $50 M per annum.

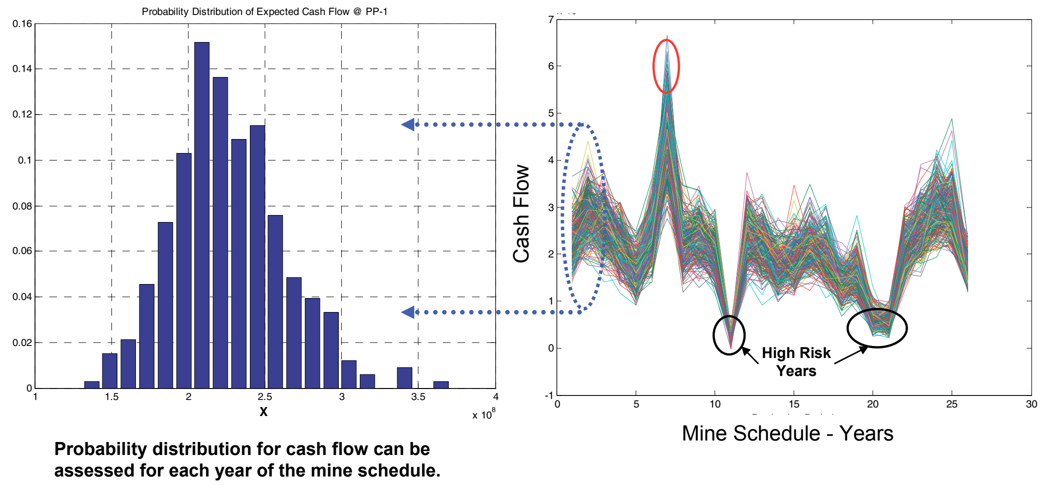


FIG 33 - Distribution of possible cash flows for each year of the mine plan.

Three out of the 20 ultimate pits that were generated from the simulated geometallurgical models are presented in Figure 34. Changes in pit length in excess of 500 m are evident in the southern portion of the pit. The significant changes in possible pit volume are clearly evident and highlight those areas that are economically marginal.

As a result of this work it was possible to determine the impact that recovery and throughput estimates have on the project economics and how the variability of the geological and geotechnical parameters might influence the schedule. The study leads to an understanding of the potential risk of achieving the predicted annual cash flow and project value, which are expressed in terms of the cumulative discounted cash flow.

GEOMETALLURGICAL SCHEDULING

While pit optimisation from a fully attributed geometallurgical model highlights areas of opportunity and risk it is during the scheduling phase of mine planning that significant value can be added. Most large mining operations have a selection of mining areas, crushing plants and concentrators or leach pads to which they can supply ore. Figure 35 is an example of the complex ore extraction options for a large copper mine.

Figure 36 illustrates an optimised mining schedule for supplying ore to two different processing plants. The schedule was based on a fully attributed geometallurgical model where the softer material was scheduled to the SAG mill plant and harder material scheduled to the HPGR plant. The scheduling of specific ore types to different plants yielded a potential NPV increase of +5 per cent.

CORPORATE GOVERNANCE

Mineral resource codes set out a required minimum standard for the public reporting of exploration results, and mineral resources/reserves, and are generally prepared as information for investors or potential investors and their advisers. The SAMREC (2007) code states that:

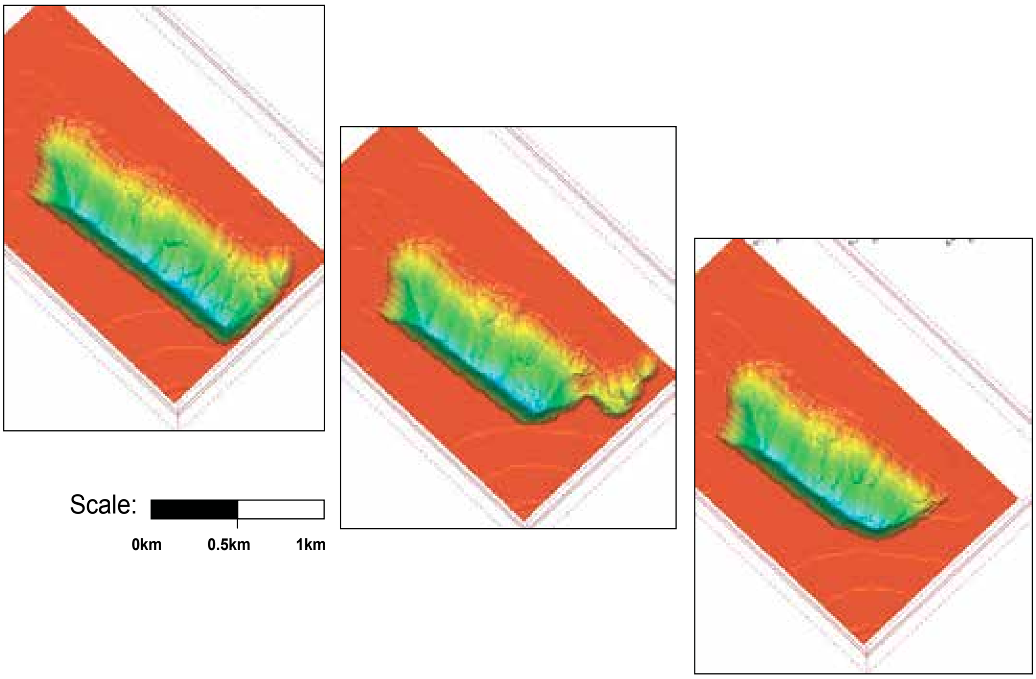


FIG 34 - Three of the 20 ultimate pit shells derived from the simulated geometallurgical models using NPV Scheduler. The range in possible pit size and shape is clearly visible.

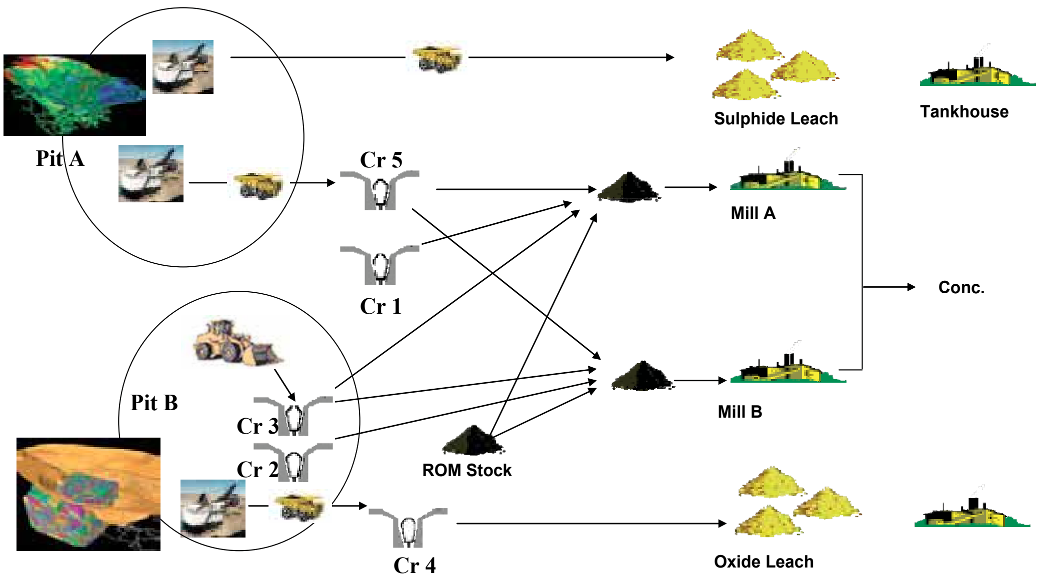


FIG 35 - Complex scheduling is common in most large mining operations.

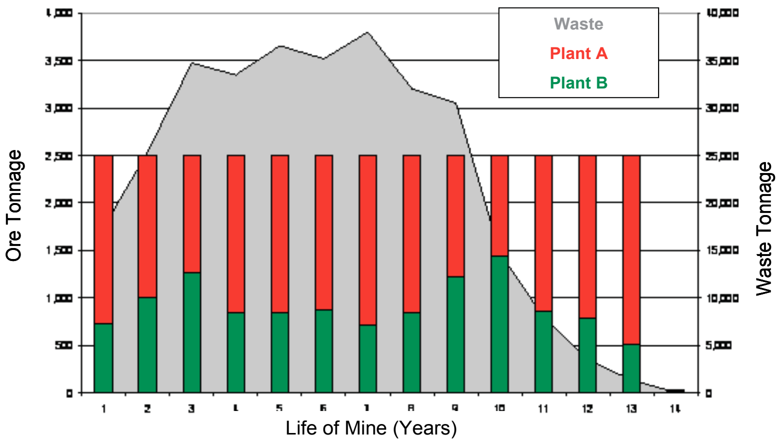


FIG 36 - Selective scheduling of hard and soft material, based on a 3D geometallurgical model, can be used to optimise plant performance.

'...a comprehensive design and costing study of the selected option for the development of a mineral project in which appropriate assessments have been made of realistically assumed geological, mining, metallurgical, economic, marketing, legal, environmental, social, governmental, engineering, operational and all other modifying factors, which are considered in sufficient detail to demonstrate at the time of reporting that extraction is reasonably justified (economically mineable) and the factors reasonably serve as the basis for a final decision by a proponent or financial institution to proceed with, or finance, the development of the project. The overall confidence of the study should be stated.'

Geometallurgical information is often insufficient to enable 'realistically assumed modifying factors' to be confidently applied.

There is growing acceptance within the minerals industry that 'realistically assumed modifying factors' defined by a competent person/s are not sufficient to mitigate the risk of funding mining ventures. The geometallurgical approach is to move away from factored ore reserves to data-rich block models providing reliable information for mining, metallurgical and environmental considerations.

Figure 37 is an example of a mineral resource reporting code highlighting the required shift from factors to geometallurgical attributes. The geometallurgical initiative is aimed at

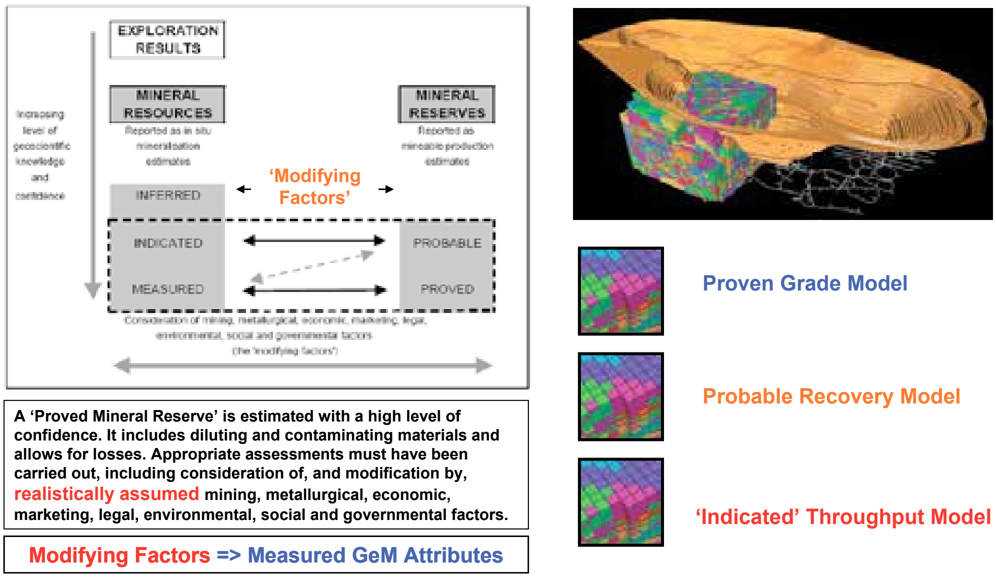


FIG 37 - Example of a mineral resource reporting code with greater emphasis on geometallurgy. Moving away from modifying factors to measured geometallurgical attributes.

providing comprehensive measured geometallurgy attributes to replace 'modifying' factors. Well defined uncertainty models can be derived from this data to support the classification of geometallurgical performance indicators such as throughput and recovery into indicated, probable and proven categories.

CONCLUSIONS

The paper has documented a broad range of industry case studies which demonstrate strategies for gaining value from geometallurgical initiatives. These include both day to day operational benefits (ie proactive fragmentation control) as well as adding value to the strategic planning process. The building of geometallurgical domain models are a very important phase in the geometallurgical journey. Both indicator kriging and conditional simulation provide useful tools for handling non grade data. Blend response models are seen as a key research development that will aid the incorporation of non-additive performance information into block models for schedule optimisation.

Environmental legislation, water shortages and carbon trading systems are changing the mining economic environment. Mine wide process optimisation that considers the generation of CO_2 and consumption of energy and water on mining operations is a critical issue for mining companies. New tools and models are required to effectively incorporate these new metrics into mine economic assessments. An example of these integrated process optimisation tools has been discussed.

Building a fully attributed geometallurgical mine planning model where each model cell had unique geometallurgical attributes enabled the impact of variable recovery, processing and mining costs on the mine cash flow to be assessed. The net impact of the geometallurgical mine planning model when compared to the base case model was as significant as $50 million per annum. The real value of this approach is to highlight the impact of ore variability on the mine plan and identify high risk periods. The operation can then put strategies in place to minimise risk and optimise the schedule. An example was given where the geometallurgical model provided the ability to value which material should be scheduled to which plant so as to maximise value.

There is growing acceptance within the minerals industry that 'realistically assumed modifying factors' defined by a competent person/s are not sufficient to mitigate the risk of funding mining ventures. The geometallurgical approach is to move away from factored ore reserves to data-rich block models providing reliable information for mining, metallurgical and environmental considerations.

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APPENDICES 2

TRACKING AND QUANTIFYING VALUE FROM 'MINE TO MILL' IMPROVEMENT

A Scott, S Morrell and D Clark

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Tracking and Quantifying Value from 'Mine to Mill' Improvement

A Scott[1], S Morrell[2] and D Clark[3]

ABSTRACT

'Mine to Mill' improvement involves optimising the chain of rock breakage processes from the *in situ* rock in the mine to the output of the concentrator. A growing number of paper studies and case histories from metalliferous mines (AusIMM, 1998; JKMRC, 1998; Clark and Scott, 2002) demonstrate that generating more breakage in the pit and the primary crusher can lead to benefits to milling that result in significant improvements to the economic performance of a mining project. However, unless the 'value' of doing this (benefit over cost?) can be appropriately quantified, the approach cannot be effectively managed and the increases in blasting and monitoring costs cannot be justified.

Mining operations have traditionally been organised into the separate departments of geology, mining and processing based on the specialist skills required and the different professional disciplines involved. Process optimisation across these boundaries has commonly been frustrated by management requirements to minimise the costs incurred by each department without adequate reference to the 'value' being created. Companies have tended to discard positions that provide a technical over-view of the value chain, reducing the number of people with the opportunity to influence practices across these process boundaries.

This paper discusses these issues and identifies measures required to quantify and manage the 'value' provided by 'Mine to Mill' improvement generated by the intense blasting of ore.

INTRODUCTION

Cost versus value from blasting

In everyday language, 'value' is a very personal assessment of the worth of something. In business it is a description of monetary or material worth. The value of ore in the ground can be estimated based on the expected revenue derived from its mineral products less the costs required to mine the ore, process it and transport the resulting saleable products to their future owners.

Throughout the world, most mine blasts are assessed to be satisfactory based on the absence of problems rather than on the basis of the value that they add to the mining operation. Modern accounting systems have little difficulty tracking and reporting the cost of these operations. It is much more difficult to measure the benefit that is derived or the value that is added.

The value contributed by a blast will be maximised if:

- blasting operations are safe;
- batters and mine slopes are formed that meet the short- and long-term operational requirements of the mine;
- excavation rates are maximised and bench floors and benches can be excavated to design;
- rock fragments are pre-conditioned or weakened by blasting;
- the proportion of fines (eg particles smaller than the grate size of the mill) is maximised; and
- targeted crushing rates can be achieved at a closed side setting that produces mill feed with the desired coarse size distribution.

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3. WMC Resources Pty Ltd.

Exactly what represents 'maximum', 'desired' or 'meeting operational requirements' is specific to any particular mine and must be determined from an understanding of the overall economics of the operation.

Risks

There are a number of potential risks associated with the design of the high intensity blasts required to achieve downstream comminution benefits. These include:

- wasting money;
- cratering or early release of stemming allowing the early escape of explosion gases and reducing the effective work done by the explosive;
- fly-rock;
- excessive movement of the muck and dilution of ore;
- noise; and
- damage to slopes and benches.

The design of these intense blasts must focus on eliminating or managing these risks.

Impediments to 'Mine to Mill' improvement

Common impediments to the successful optimisation of rock breakage throughout the mining and processing chain include:

- **A paradigm shift** – It is necessary to break established rules of thumb regarding blasting practices and target performance.
- **Mismatch between 'pain' and 'gain'** – Increased blasting costs are readily observed and reported by the mine, whereas the benefits from an increase in throughput are more difficult to measure and are enjoyed by the mill. Corporate performance targets and reward structures may not encourage a mining manager to risk additional expenditure without being able to claim the subsequent benefits. If a contractor is responsible for excavation, then benefits from improved excavation performance may also fail to materialise on the mining report card.
- **Sensitivity to damage and dilution** – Intense blasting may tend to increase blast damage or dilution if field practices are not of a high standard.
- **Lack of proof** – The most effective way to kill off a new idea is for the production reporting system to be blind to the benefits generated by a change in practice.

Measurement

To be effective, measurements need to be of the right thing, of sufficient accuracy and to be reported to the right people in the right form at the right time. Not all mining measures meet these criteria.

There has been rapid development of the industry's measurement capability based on global positioning system (GPS), radio telemetry and computer database technologies. However there have been many examples of operations that suffer from an overload of data and a shortage of useful information. Many production databases become 'black holes' into which data are absorbed and never seen again. Most companies end up having to write custom software to interrogate these databases to extract the information they need.

In practice, most mines only achieve a fraction of the potential promised by their production monitoring and reporting systems. This shortfall in performance is often due to a failure to support these systems in terms of their maintenance and calibration. While some systems (eg drill performance and truck payload monitoring) have not always been found to provide the accuracy or reliability required to drive process optimisation, the information that is available is seldom fully utilised to manage the mining process. Most data is simply accumulated and reviewed later in an historical context rather than being relied upon to guide operating practices. This is in contrast with most process plants where on-line measurements are increasingly being used as part of the process control system.

Available mine monitoring technology still falls short of being adequate for process control. GPS and communications technologies probably meet the standards required provided there is adequate satellite coverage. Data describing overall production performance is available from mine monitoring systems but measurements of quality (eg size, hardness and moisture) and quantity (eg truck payloads, stockpile capacity and conveyor tonnages) still lack the accuracy required for detailed production optimisation.

Some operator input is invariably required by mine monitoring systems. The concept of 'garbage in – garbage out' applies to the quality of the resulting information. A very effective approach used in some mines is to ensure that the data that is being collected is made available to the operators concerned in a form that helps them to do their job. This means that they have a vested interest in the inputs that are required.

Uncertainty

Measurements made in the field are inevitably subject to uncertainty and have to be interpreted with an appreciation of their reliability. As an example, the following relative uncertainties could be expected for measurements in a surface metalliferous mine given reasonable conditions and regular calibration checks:

Volume to be mined	±1 per cent
Survey	±1 per cent
Density	±3 per cent
Plan to actual	±1 per cent
Truck factor	±5 per cent
Truck count	±1 per cent
Weightometer values	±3 per cent
Moisture content	±30 per cent

Where a parameter is derived from a combination of measurements, the individual uncertainties propagate through the calculation and can be estimated for the outcome. For practical purposes, if two parameters are added or subtracted, then the *absolute* uncertainties are added and if the two parameters are multiplied or divided then the *relative* uncertainties are added.

These values lead to the measurement uncertainties shown on Figure 1 for measurement systems commonly used in the production chain. Mine planning and survey systems allow quite accurate estimates to be made of the volume of ground to be mined and actually mined. Uncertainty in the values used for density and variation between the actual volume mined and the volume planned to be mined contribute most to the uncertainty of these estimates.

The dry tonnage of the production trucked is vulnerable to uncertainty in the truck factor used or the accuracy of the truck weighing system. The moisture content is also likely to be only roughly known. The same variables affect estimates of the

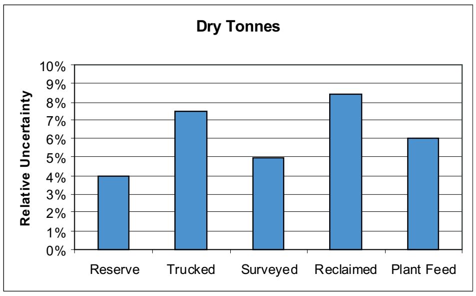

FIG 1 - Example of uncertainty for measures within production chain.

tonnage reclaimed from stockpiles and plant feed data are vulnerable to calibration errors or drift of weightometers and uncertainty with respect to moisture content.

It is a fundamental problem that changes of say five per cent in mill throughput may be worth millions of dollars to an operation but may not be discernable within the background variability and uncertainty inherent to the measurements made by the production monitoring system.

The uncertainty of these measures can be improved by engineering the measurement system to suit the reliability required. However, interpreting the value added by optimising 'Mine to Mill' breakage generally requires reference to longer-term trends rather than short-term changes in measured performance.

QUANTIFYING MINE TO MILL PERFORMANCE

Important measures for the management and assessment of rock breakage and comminution include:

- the breakage characteristics of the ore,
- blast performance,
- excavation performance,
- tracking through stockpiles,
- fragmentation,
- crushing performance,
- grinding performance, and
- cost.

These are discussed in the following sections.

Ore breakage characteristics

The breakage characteristics of the ore need to be understood if the blasting and comminution processes are to be optimised. Blast fragmentation is largely controlled by the material strength of the rock and the structure of the rock mass. Rock mass structure is important because it has a strong influence over the coarse end of the fragmentation curve and hence the excavation and crushing performance expected for the run-of-mine (ROM) ore. A detailed description of rock mass structure is complicated by its statistical nature and the limited access generally available for it to be observed prior to mining. Access to mining faces allows structure to be mapped and tools are becoming available to observe and analyse relevant features remotely (Poropat, 2001). Significant progress has been made with the modelling of structure driven by research into mass mining technologies at the Julius Kruttschnitt Mineral Research Centre (Brown, 2002; Harries, 2001).

The author has had considerable success utilising an estimate of the 'larger' natural blocks in the rock mass in the design of blasting operations and the prediction of blast fragmentation. For the purposes of blast design the 80 per cent passing size of the *in situ* structure is found to be useful and can be adequately estimated from observation of a representative face or from un-biased fracture frequency data.

The substance strength of the rock affects blasting, crushing and milling performance. However, the strength of rock varies with the size of the rock being considered (Hoek and Brown, 1980). On a scale relevant to blasting, it is the strength of the *in situ* blocks that is relevant while crushing is controlled by the remaining strength of the blast fragments. Grinding tends to deal with the strength of the intact rock material substantially free of structural defects.

The strength of a rock mass is conventionally described in qualitative terms in mining geomechanics. Terms such as rock block strength and bulk strength are used to describe strength estimates that include the effect of defects that may or may not be regarded as significant by those primarily focused on slope design and stability issues.

Rock material strength is traditionally measured in the laboratory using prepared specimens of uniform dimension. The resulting test values of unconfined compressive strength, tensile strength or shear strength may not appropriately represent the actual breakage criteria for the rock in the mine. However, other properties from these tests such as Young's modulus and Poisson's ratio are important parameters for some breakage models.

A number of field ratings have been defined based on the response to a blow from a hammer, scratch of a knife, etc (Berkman, 2001). These ratings can be very useful in the characterisation of rock mass strength and its variability, but can lack consistency when determined by different people.

Comminution parameters are required that relate the degree of breakage to the energy consumed. Appropriate parameters are generated by the JKMRC Drop Weight Test (JKMRC, 1996) and traditional abrasion tests.

The Point Load Strength (PLS) index (Brook, 1985) has been found by the authors to provide a very useful guide to blasting requirements. Despite its 'crudeness', the ease with which the test can be performed on either core or hand samples from the field means that enough tests can be performed to provide a reliable measure of effective strength. The index has also been found to correlate quite well with the more sophisticated energy based breakage tests used to characterise crushing and grinding performance (Figure 2).

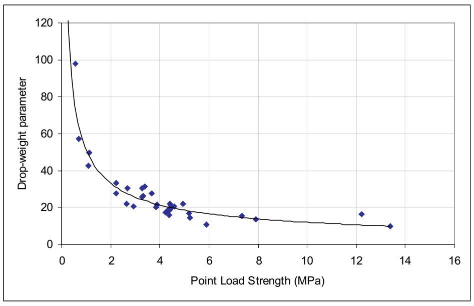

FIG 2 - Relationship between PLS and comminution properties.

Because of its simplicity, Point Load Strength can be used to map the strength of the ore within a given mining volume if systematic sampling and testing is carried out. This attribute of strength can then be tracked through the production chain in the same way as grade or any other significant descriptor.

Indirect measures may also be used to map the strength of the rock substance. Considerable work continues to be applied to derive measures of rock competence from blast hole drills (Segui and Higgins, 2001; Hendricks and Peck, 1990) but few mines that have invested in these systems have managed to make routine use of the data for this purpose. Geophysical properties also have significant potential but tend to be collected only during exploration or during specific investigative programs.

Greater value can undoubtedly be gleaned from geological data than is routinely utilised. The mechanical properties of some orebodies can be effectively correlated with lithology or extent of alteration (Clark and Scott, 2002). Insights into the formation and structural history of a deposit may guide the interpretation of the available data to improve the estimation of rock properties in areas yet to be mined. It is very much a question of putting the engineering or scientific effort in to the analysis in order to get the benefits from it.

Blast implementation and performance

It is important to quantify a number of parameters associated with the implementation and performance of each blast as part of the management of 'Mine to Mill' operations. Intense blasts must be designed and implemented to a high standard if problems with fly-rock, bench damage and excessive dilution are to be avoided. Experience has shown that these outcomes can be effectively managed, but the operations are vulnerable if field controls are poor.

All mines have some sort of checklist or rating system by which blast performance is assessed. For intense blasts, particular emphasis should be given to the performance of stemming and any tendency towards cratering or fly-rock, damage and the distribution of swell in the muckpile. Observation of videos taken from a suitable vantage point and conventional survey techniques are adequate for these measurements providing they are undertaken consistently and routinely.

Observations of problems such as cratering or damage can be used to drive the refinement of blast designs, especially with regard to the distribution of explosive energy and detailed blast initiation timing. Qualitative measures of back-break should be routine and designs should be tested by quantitative measures of blast vibration and the response of mine benches and slopes. The distribution of muckpile swell is relevant to the 'looseness' required for efficient excavation and in interpreting mechanisms for ore dilution.

Excavation performance

Conventionally, blast designs are refined (reduced in cost) until any obvious digging problems are avoided. The result can be a long way from the economic optimum and most operations report an increase in excavation efficiency when the intensity of blasting is increased.

Considerable investigation has been undertaken into the effect of fragmentation on the time and energy required to fill an excavator bucket (Williamson *et al*, 1983; Sari, 1998). While this is an obvious component of 'digability' it is not the only important factor associated with the impact of blasting on excavation performance. Table 1 shows the factors affecting shovel productivity and how they may vary for a 'good' blast and for a 'poor' blast.

TABLE 1

Factors affecting shovel productivity.

	Effect	
	Good blast	**Poor blast**
Swing out	Same	Same
Dump time	Same	Same+
Swing back	Same	Same
Prepare face and spot bucket	Low	High
Wait on auxiliary equipment	Low	High
Bucket fill time	Low	High
Bucket load	Even	Erratic
Truck load	Even	Erratic
Wait at crusher	Low	High

The time to swing out to the truck and back to the face will be essentially independent of the quality of the blast. The dump time into a truck may be a little longer if the bucket contains large fragments, which require careful placement in the truck tray. Otherwise the dump time should be independent of the quality of the blast.

A poor blast will result in a tight muckpile, which will require additional face preparation. It is likely that the shovel will have to rake the face from time to time to gather loose fragments at the toe of the face. The assistance of a bulldozer may also be required. This additional face preparation time is an important aspect of the effect of blast performance on shovel productivity and should not be ignored in any comparison.

The bucket fill time would be expected to be lower in a poor blast. However, owing to the efforts put into face preparation, the actual fill time may be no worse than for a good blast. What is likely to vary is the consistency of bucket fill. Bucket loads will tend to be lighter, and will certainly be more variable in poor muck. This variability then translates to variable truck loads or the need, from time to time, for an extra pass to achieve an adequate truck payload.

Coarser muck will be slower to crush leading to an increased waiting time at the crusher.

Raw productivity measures such as tonnes per hour are therefore not sufficient on their own to quantify the improvements in excavation productivity arising from more intense blasts. Measures are also required of:

- what the shovel is doing – ie idle, wait on dozer, face preparation, relocating, maintenance, operating, etc;
- total time to load each truck; and
- the number of bucket loads into each truck.

The force or energy required to load each bucket and the weight of each bucket would be more direct measures of the 'digability' of the muckpile. However, these parameters are difficult to measure and calibrate and do not have as strong an influence on the productivity of the overall system as the parameters listed above. Some operator input will probably be required to capture these data even with the more sophisticated monitoring systems becoming available.

To complement these shovel data, the following truck data are also required:

- load on each truck;
- truck waiting time at the shovel;
- travel time; and
- truck waiting time at crusher.

An effective GPS tracking system is required to tie these two data sources together and to gain an overall view of the efficiency of the operation.

Material tracking

Tracking the movement of material through the production process is a source of considerable confusion in many operations. The task is relatively straightforward if there is a single production stream and minimal stockpiling between the mining source and process stream. However, most operations mine from a number of sources and ensure continuity of feed by providing stockpiles prior to crushing and milling. Accounting for the tonnage in a stockpile is still a challenge despite modern equipment monitoring capability, and tracking the properties of the material placed on the stockpile and taken from it is an even greater challenge.

Some operations (eg KCGM's Fimiston operations and WMC's Mt Keith mine) go to considerable trouble to blend the ROM ore so that a consistent feed can be provided to the crusher and mills. The technical benefits of this strategy (Scott and McKee, 1994) are indisputable, but it creates a real challenge to track material through the process. Some success is being achieved using GPS data to match the source of a truck load of ore (and its associated characteristics) to its location in the stockpile so that the blended stockpile properties can be calculated and 'scheduled' as that part of the stockpile is reclaimed and fed into the comminution system.

Detailed stockpile accounting such as that described above is still an 'add-on' to the basic pit monitoring tools. The uncertainty of these predictions or the extent to which detail is blurred by the inherent measurement difficulties has yet to be assessed. Mount Keith (Clark and Scott, 2002) has gone to the trouble of sampling the stockpile itself to rebuild a model of hardness to guide the interpretation of subsequent mill performance.

Classic conical stockpiles of crushed mill feed behave relatively simply during periods of steady state cone geometry where ore tends to funnel fairly directly through to the feeders. However, when the stockpiles are being drawn down there is little relationship between the ore being placed on the stockpile and the ore being drawn. The dynamics of stockpile behaviour and the flow of fragmented rock can be tackled with the emerging distinct element and particle flow codes. Focused effort will be required by researchers and instrumentation companies to tackle this problem and create a robust tool to model and track the passage of material through these processes.

Fragment size

The assessment of blast fragmentation is usually based on the number of large fragments or boulders that are encountered in the muck pile. Because only the surface of the muckpile (which is a small and biased sample of the material that lies within the muckpile) can be seen and because it is difficult to physically measure objects with awkward shapes like broken rocks, the measurement of blast fragmentation is not easily achieved.

The distribution of particle sizes is conventionally presented on the basis of the weight of the material that is smaller than any particular size. The average size is regarded as the size for which 50 per cent of the particles are lighter and 50 per cent are heavier. A fragment size distribution is conventionally plotted with the cumulative weight per cent passing any given size against the logarithm of that size. The logarithm of size is chosen so that adequate detail can be observed in the fine end of the fragmentation curve.

It is very tempting to manually observe a muckpile and to form an impression of the average size or the 80 per cent passing size. However, these parameters are very difficult to 'guesstimate' because they are based on weight. It is possible to form an impression of the most common block size or to suggest that one muckpile is finer or coarser than another, but it is beyond the ability of the human brain to calibrate such estimates by weight. Measurement is therefore required if any quantitative decisions are to be made based on particle size.

Image analysis techniques for the estimation of the fragment size distribution of blasted muck have been under development for the last ten or fifteen years. For the last five years or so these techniques have been able to achieve a useful standard in terms of repeatability and accuracy. A digital image of the fragments is required and these are analysed by a computer to define the edges of the visible particles. Once defined, the system calculates the dimensions of the visible particle and assigns a representative size to each particle. The systems are imperfect in that in any pile of rock fragments, only some of the fragments are fully visible, the others being partially obscured by the fragments above. The edge detection algorithms are not perfect and good quality images (clear of dust and sharp shadows) are required if reliable results are to be achieved.

Because the measurement of size is initially made as an area, the third dimension must be estimated in order to derive a volume and hence a mass. The exact definition of size also varies between fragmentation assessment systems, but in general they attempt to replicate the measurements that would have resulted from physical sieving.

Any image analysis system will have a cut-off size below which particles cannot be individually identified or measured. The vendors of these systems utilise techniques based on the percentage of the image that cannot be resolved and assumed curves for the distribution of size in the fine fractions to extend the observable particle sizes below the observable threshold. These approaches have proved to be satisfactory provided these estimates are calibrated by comparison with physical analyses of adequate samples.

Despite all of the drawbacks identified above, the estimation of fragment size distribution using image analysis can be reliably achieved to a standard that is adequate when analysing open cut mining performance. The quality of the measurement will be strongly influenced by how well individual particles can be seen and whether the sample analysed is a fair representation of the material in question. The following are listed in order of increasing reliability:

- images of the excavation face,
- images of the muckpile,
- images of the truck load,
- images of the truck tipping, and
- images of the ore on a conveyor.

Being human, it is difficult to avoid making judgement about what is seen in the muckpile, in the face or on a truck. But in statistical terms these impressions are heavily flawed because of the biased view provided of the fragments. Only the last two approaches provide reasonable measures for long-term use in managing production or assessing performance in a quantitative sense.

Similarly, some useful data can be acquired using hand held cameras in an ad hoc program of measurement (Figures 3 and 4). However, the resulting data need to be regarded as indicative only. The quality of the result depends heavily on the consistency and effort made in acquiring the images. Reliable fragmentation data can be obtained from well-engineered permanent installations where images are collected under consistent presentation of the ore and lighting. Successful examples include KCGM, Mt Keith, Mt Newman and Hamersley Iron.

FIG 3 - View of muck on a tipping truck.

FIG 4 - View of muck on a conveyor.

Crushing performance

In a conventional primary crusher – milling system, the task of the crusher is to prepare a suitable mill feed size distribution from the ROM ore in a single process. As this crushing process will generate few fines, the fines content of the mill feed is largely determined by blasting while the crusher defines the coarse end of the feed size distribution.

Crushing costs are most strongly affected by the hourly running costs and maintenance costs. If the same tonnage of feed can be crushed to a smaller top size in a shorter period of time (higher throughput) and with reduced wear, then significant gains can be made. The top size of the crusher product is controlled by the closed side setting of the crusher, but reducing this usually results in a reduction in throughput. This can be countered by providing finer, weaker ROM ore from intense blasts. Figure 5 shows operating data reported by Clark and Scott (2002) for WMC's Mount Keith operation.

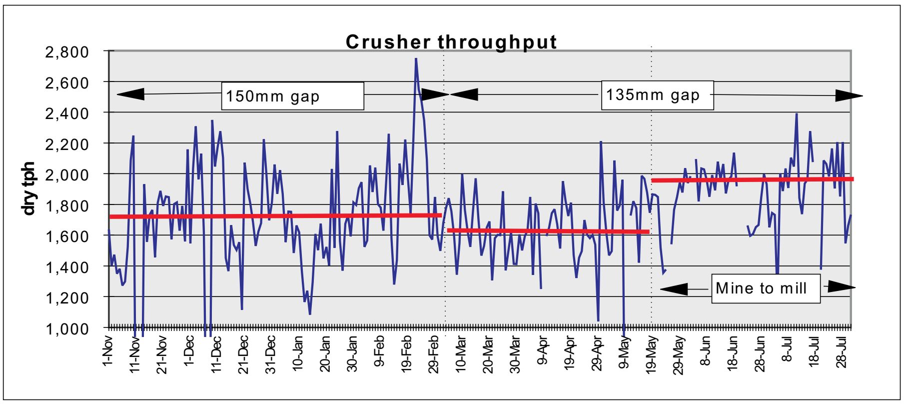

FIG 5 - Crusher throughput pre and post intense blasting.

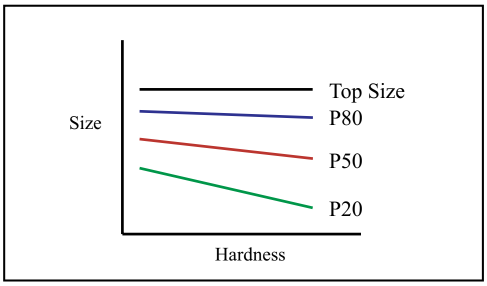

FIG 6 - Variation in crusher product size with rock hardness.

The higher throughput achieved at the reduced crusher gap is a result of the improved fragmentation achieved by intense blasting. The effectiveness of the effort expended in blasting can be assessed by monitoring the throughput achieved for ores of different hardness.

Online particle size measurement systems can report size for various percentages of the material in the crusher product and the mill feed. In order to normalise these size distributions against varying ore types, data from these systems can be plotted against the point load strength index. The size reported on the crusher product conveyor is expected to provide trends like that shown on Figure 6. The effectiveness of intense blasts can be gauged by a reduction in the sizes reported on such a plot.

Once base line performance has been established for these relationships it is possible to quantify the improvement that has been achieved in breakage performance.

Grinding performance

Grinding performance is controlled both by the hardness and the size distribution of the feed ore (Simkus and Dance, 1998). It is important to measure the 'grindability' of the ore so that milling performance can be correctly interpreted if the properties of the feed ore change either because of the inherent properties of the ore or because of changes to the mining process. Spot or routine feed samples can be tested to check against the ore properties tracked through the production process from the mine.

The most basic measure of performance is the energy consumed to grind each tonne of ore. Figure 7 shows the kWhr/t observed at Mt Keith as reported by Clark and Scott (2002) showing a step change when utilising intense blasts. Other influences such as different ore hardness from different stages of the pit development are also apparent. This change in energy consumption was accompanied by a seven per cent increase in mill throughput.

Milling is a complex transformation process and there are many other influences over throughput and energy consumed than are accounted for here. Changes in lifter design, ball load, transfer size and a host of more complex operating parameters can affect throughput and these also need to be taken into account when interpreting the influence of blasting on overall performance.

Cost

The overall cost of a mining operation tends to be measured and reported quite precisely. However it is much more difficult to subdivide these costs into components that relate to the unit operations that are managed and controlled by mine and mill personnel on a daily basis. For example, it is unhelpful to be able to report the amount of emulsion, ammonium nitrate and fuel oil consumed in a month by blasting operations if this cannot be broken down into the quantities of different types of explosive used in each blast.

Cost comparisons for the use of different blast designs are needed that cover the blasts themselves, the cost of clean up and wall control, secondary breakage, excavation, handling, crushing and milling. These costs need to be expressed in engineering terms and not just in terms driven by convenient accounting codes or warehouse inventory practices. Neither engineers nor accountants are in a position to establish such a reporting system on their own.

Quantifying value

Ultimately, the value generated by a change to operating practice can be measured from the net revenue earned by following that strategy compared with the net revenue earned by maintaining the status quo. Figure 8 shows a plot of the estimated increase in net revenue generated by a 15 per cent ($0.05/t) and a 30 per cent ($0.10/t) increase in blasting intensity for a theoretical operation. The components of the improvement from direct savings in

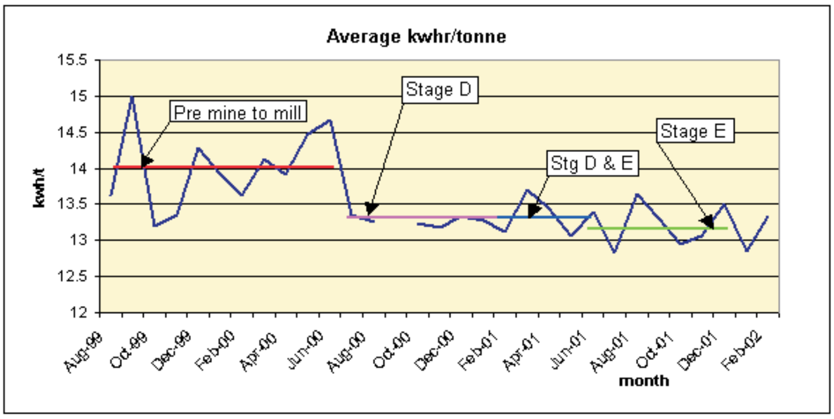

FIG 7 - Mill throughput pre and post intense blasting.

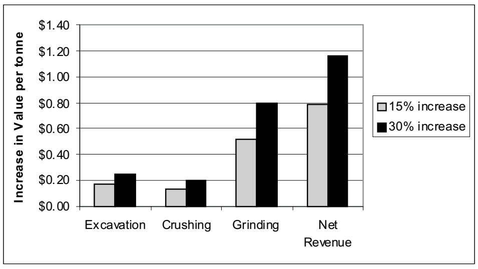

FIG 8 - Potential increase in value per ROM tonne.

excavation, crushing and grinding are also shown. The values shown should be viewed as being indicative only, but the general trends are a true reflection of observed field results.

An improvement in net revenue of over $1 for the expenditure of approximately $0.10 constitutes a good investment. However, the simple analysis shown makes no allowance for an increase in revenue arising from increased mill throughput. Marketing and financial expertise are also required to evaluate the value to the operation of additional throughput. These numbers are often guesstimated by field personnel or consultants but are rarely generated or validated by a team with the range of expertise required to produce reliable estimates.

There is no doubt that an optimum point will exist where an increase or decrease in blasting intensity will result in a reduction in overall 'value' from the investment in blasting. This optimum point is unlikely to be achieved by applying the practices established by independently minimising the cost of each component process. Experience to date demonstrates that, providing adequate rock mass, mine and plant performance data are available; modelling can be used to provide useful guidance as to where this optimum point will lie. Continual tuning and refinement will be required in the field to establish and maintain optimum performance and an appropriate balance between component operations. This on-going refinement depends on field measurement and tracking of 'value' throughout the rock breakage and comminution chain.

CONCLUSIONS

This discussion results in the following conclusions:

- Optimising the performance (minimising the cost) of each operation in the rock breakage and comminution chain is unlikely to result the maximum value being realised by an operation.
- Appropriate characterisation of the orebody and modelling the performance of each process can guide the optimisation of the rock breakage and comminution system.
- Demonstrating whether any change to the process adds value depends on being able to measure performance in both physical and economic terms.
- Current mine monitoring and reporting systems may not be set up to measure performance to the accuracy required to quantify the value of 'Mine to Mill' improvement.
- Focussed observations of rock mass characteristics, blasting, excavation, crushing and milling performance are required to manage 'Mine to Mill' improvement. The overall benefits are more likely to be observed as longer term trends in performance rather than immediate responses to short-term changes.
- Because 'Mine to Mill' initiatives affect the revenue side of the value equation, higher-level business parameters relating to finance and marketing are also critical to the assessment of its value.

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APPENDICES 3

MODELLING AND SIMULATION TECHNIQUES APPLIED FOR OPTIMISATION OF MINE TO MILL OPERATIONS AND CASE STUDIES

Walter Valery Jnr. , Steve Morrell, Toni Kojovic, Sarma Kanchibotla and Darren Thornton

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"Modelling and Simulation Techniques Applied for Optimisation of Mine to Mill Operations and Case Studies"

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ABSTRACT

Mine fragmentation can influence the operational performance of the comminution sections of the treatment plant. Recent work at the Julius Kruttschnitt Mineral Research Centre (JKMRC) has proven that changes in blast design can have dramatic effects on overall profitability whether the mine feeds a milling or crushing comminution plant. Field experimentation in this area is often found to be difficult because of high implementation costs and insufficient understanding about the effect of fragmentation at different stages in a comminution circuit. Modelling and simulation of blasting and comminution processes provides a more economic alternative to explore the impact of blast design changes on the down stream operations. The JKMRC has been conducting research in understanding and modelling of comminution for the past three decades and hence are ideally placed to determine the blast fragmentation/milling interactions as well as the effect on further downstream comminution steps. This paper briefly describes the techniques utilised and results obtained from case studies where optimisation of mine to mill processes were conducted.

INTRODUCTION

The JKMRC has developed and applied tools to explore ways of improving overall mine to mill process performance. One such way is to modify blasting so that a more favourable size distribution is presented to the comminution step thus leading to increased throughput or change in product specification eg lump:fines ratio in iron ore operations. From a comminution viewpoint, it is possible that to generate a more favourable run of mine (ROM), the mining cost will increase, hence offsetting, at least in part, the increases in revenue due to enhanced throughput and/or product quality. Whether such changes can be obtained by modifying blasting and what their associated costs are can be determined by trial and error in the field. However, this is likely to be a very costly approach with no guarantee that a successful outcome will result. Simulation of the blasting and comminution steps provides a cheap way to explore the potential for making beneficial changes to blasting and provides data with which to conduct financial analyses of the consequences.

Historically, blast modelling has confined itself to sizes of more direct importance to mining operations - typically > 50-100mm, and hence has ignored the material smaller than this. However, it is this size which typically affects the performance of the comminution steps. The JKMRC has developed further a number of blast models, which aim to address this deficiency. Based on studies at a number of mines these models have shown to be very accurate. This paper describes the application of one of these blast models, in conjunction with models of crushing, screening, and SAG milling, to illustrate the potential of this technique in determining changes in blast design which may lead to significant increases in lump:fines ratio and mill throughput. Hamersley Iron's Marandoo (Kojovic et al, 1998) and KCGM's Fimiston (Kanchibotla et al, 1998) operations have been used for these demonstrations.

MODELLING

Blasting

Model Structure

The blast model used for this exercise uses a modified Kuz-Ram approach to predict the coarse end of the ROM size distribution (Kuznetsov, 1973; Cunningham, 1987). In this model the size distribution of blasted rock is represented by the Rosin-Rammler distribution:

$$R = 100 - e^{-0.693(x/\bar{x})^n} \quad (1)$$

where

R	=	percentage smaller than x
x	=	size of rock
$\bar{x}$	=	median rock size
n	=	uniformity exponent.

Using Cunningham's equations the median rock size is related to the type and amount of explosive plus a rock factor. The rock factor is influenced by the UCS, Young's Modulus, in-situ block size and joint spacing. Cunningham also related the uniformity exponent to the blast design.

In the case of the finer fractions it is hypothesized that they are produced by the pulverizing or crushing action of the explosive adjacent to the blast holes. A cylinder of rock around each hole is therefore defined within which crushing takes place. The radius of the cylinder, and hence its volume, is determined by calculating the point at which the radial stress around the blast hole exceeds the dynamic compressive strength of the rock. For this purpose Jaeger and Cook's equation (1979) is used. Currently a size of 1mm is used to define the coarsest particle that results from crushing.

Having defined the volume of the crushing zone around each blast hole and knowing the number of blast holes the volume of crushed material (-1mm) can be calculated (V_{crush}). As the volume of rock blasted (V_{br}) is also known the % of blasted rock smaller than 1mm can be estimated from:

$$\% \text{ -1mm} = 100 \text{ x } V_{crush}/V_{br} \quad (2)$$

The Rosin-Rammler size distribution is also used to describe the finer fractions but with a different uniformity exponent (n). This is calculated from equations 1 and 2, as the % -1mm from equation 2 is the value of R at 1mm in equation 1.

Characterisation

For the crushed zone model information is required about the rock strength and its structure as follows:

Young's Modulus
UCS
Mean *in situ* block size
Joint spacing

Comminution

Characterisation

Rock breakage characteristics are determined by using a drop-weight device. This is used to break rocks in a range of sizes under a range of energies. The results are condensed in a relationship between the T10 and the specific breakage energy as follows:

$$T10 = A(1 - e^{-bEcs}) \quad (3)$$

where
A, b = ore specific parameters
Ecs = specific breakage energy (kWh/t)
T10 = % passing 1/10th original particle size.

By convention the T10 is the % passing 1/10th of the original particle size, whilst the T50 is the % passing 1/50th etc. The T10 relationship with respect to the rest of the product size curve is therefore expressed as a matrix of Tn values where n = 2, 4, 25, 50, 75.

In the case of the sag mill model the parameters A and b are required. The model then uses these to reconstitute product size distributions from breakage events. In the case of the crusher model a matrix such as described above is required, with required values being determined by spline interpolation.

Model Structure

Crushing

The model used is that developed by Whiten (1974) and subsequently modified by Andersen (1988). Conceptually it is described in Figure 1 and, given that the crushing action of jaw and gyratory crushers is similar (Figure 2), can be used for both devices. Feed is considered to undergo a series of breakage and classification stages as it passes down the crushing chamber, reducing in size as it does so. Each breakage stage is assumed to produce the same geometric size reduction. This is modelled through the use of the T10 parameter, which in turn is related to the product size distribution resulting from breakage. The relationship between T10 and the breakage size distribution is determined experimentally by breaking representative rock specimens using the JKMRC's drop-weight tester.

(3)

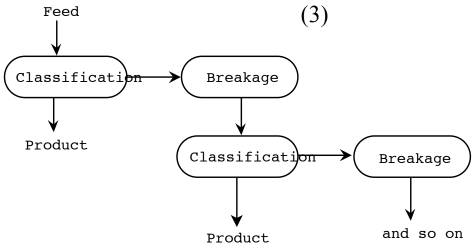

Figure 1 - Concept of classification and breakage in a crusher

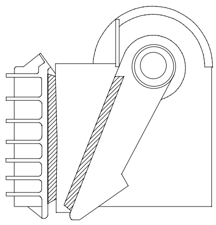

Figure 2a - Schematic of a jaw crusher

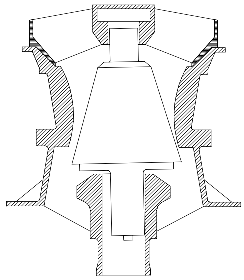

Figure 2b - Schematic of a gyratory crusher

Classification in the chamber of the crusher is controlled by the open and closed side setting. If the rock is larger than the open side setting (oss) then it will remain in the chamber and be broken. Conversely if the rock is smaller than the closed side setting (css) it will fall out of the chamber and not be crushed any further. For rocks which are in between the css and oss in size a probability exists from them to either remain or pass out of the crusher. This probability (classification) function has a shape similar to that shown in Figure 3. It is described by 3 parameters - K_1, K_2, K_3, where K_1 and K_2 ideally should equal the css and oss respectively and K_3 describes the shape of the curve.

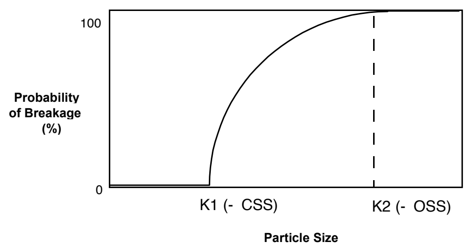

Figure 3 - Classification function for the crusher model

Screening

Screen performance is described using a classification efficiency curve, which is described by Whiten (Napier-Munn *et al*, 1996) as follows:

$$E = C((e^{\alpha}-1)/(e^{\alpha x_i} + e^{\alpha} - 2)) \quad (4)$$

where

α = efficiency sharpness parameter

E_i = fraction to underscreen of size fraction i

C = by-pass fraction

x_i = d_i / d_{50c}

d_i = particle diameter of size fraction i

d_{50c} = corrected cut point

Degradation

Degradation can be viewed as breakage which takes place at low specific energy levels and typically results in the original rock remaining largely intact but with some of its surface features altered. In the case of very friable rock more substantial breakage may occur. The degree of breakage will therefore be strongly ore-strength dependent. To reproduce this type of breakage a model has been introduced to the JKSimMet simulator in which a single breakage step is applied to each size fraction in the feed. The amount of breakage is determined by a user-supplied T10 value. This value is determined from the A and b breakage parameters supplied by the drop weight testing of the ore in question, plus the estimated input energy of the degradation step (eq. 3). This needs to be determined from local geometry eg the height drop in a bin or the speed with which a stream of rock impacts a liner in a conveyor transfer chute.

Semi Autogenous Milling

The most recent version of the sag mill model is based on that originally developed by Leung (1987). This has been subsequently modified to incorporate the effect of ball load, feed size and speed (Morrell and Morrison, 1996) as well as the effects of grate design (Morrell and Stephenson, 1996). In addition a power draw model was also added (Morrell, 1996a, 1996b). Conceptually the model is represented in Figure 4. (5)

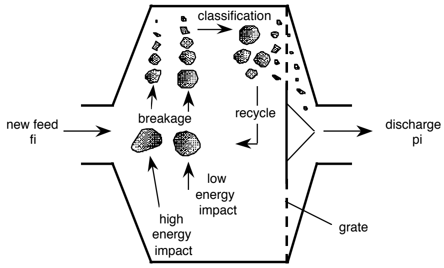

Figure 4 - Conceptual model of a SAG mill

The model utilises the concept that breakage within a mill is dependent upon specific breakage energy. This in turn is related to the mill dimension and a grinding medium size which is a characteristic of the ball charge (if any) and rock charge. The relationship between specific breakage energy and the progeny size distribution is provided by the same drop-weight test that provides data for the crusher model plus a tumbling test both of which are carried out on the ore in question. These generate breakage parameters, which relate to the high energy (impact) and low energy (abrasion) size reduction processes that are believed to take place in AG/SAG mills. Transport of slurry through the mill is described by a function which relates the hold-up of slurry, grate design, grate open area and mill speed to the volumetric discharge rate through the grate.

The model reflects feed size changes by changing the load size distribution and hence rock grinding media size. In addition the size-by-size breakage rate distribution, which is central to the operation of the model, is modified by using an empirical correlation based on a large database of operating mills.

Marandoo Case History

Blast Model Validation

Marandoo used ANFO, which has a nominal density of 850 kg/m3 and a VOD of 4000 m/s. Different blast patterns were employed to suit the properties of the different domains within the deposit. The patterns employed in the three of the domains are shown in Table 1.

Table 1 - Blast Design Parameters

Blast Design Parameter	Bench 750/604	Bench 200/227	Bench 300/212
Burden (m)	4.8	5.1	5.6
Spacing (m)	5.5	5.9	6.4
Powder Factor (kg/t)	0.30	0.24	0.22

To realistically simulate the Marandoo operation it was first necessary to characterise the ore body composition in terms of hard and soft ore types and to use the blasting model to predict the ROM from each, independently. Marandoo staff therefore provided initial estimates of the proportions of hard and soft ore based on visual observation of samples. The predicted ROM size distributions from the soft and hard ore types were then combined using proportions which gave the best match to the measured ROM sizings. In all, 3 domains were studied. The Marandoo staff estimates of the proportion of soft and hard in each domain together with the estimates based on the blast model are shown in Table 2. As can be seen the estimates match very well and confirm the validity of the blast model.

Table 2 - Comparison of Fitted (JK) Hard/Soft Ratio and that Estimated by Marandoo Staff (HI)

	Audit 1 (750/604)	Audit 2 (200/227)	Audit 3 (300/212)
	Domain1	Domain2	Domain3
Hard/Soft (%) - HI	60:40	57:43	40:60
Hard/Soft (%) - JK	59:41	61:39	43:57

Comminution Model Validation

The comminution circuit is shown in Figure 5. Surveys were conducted of all of the individual units in the circuit. These data were then used to generate models which were combined into a full flowsheet simulation. The predicted ROM size distributions were then used as feed to the circuit. Hard and soft components were treated separately and combined at the end of the simulation. The resultant final lump:fines ratios predicted from simulation are given in Table 3. These are compared with the DCS data which were collected whilst the ores from each domain were being treated through the plant. Good agreement was found.

Table 3 – Predicted and Measured Lump:Fines Ratios

	Audit 1		Audit 2		Audit 3	
	meas.	sim.	meas.	sim.	meas.	sim.
Lump (Gen + Nat.)	49-51	49	n/a	51	44-47	47
Fines (Gen + Nat.)	51-49	51	n/a	49	56-53	53

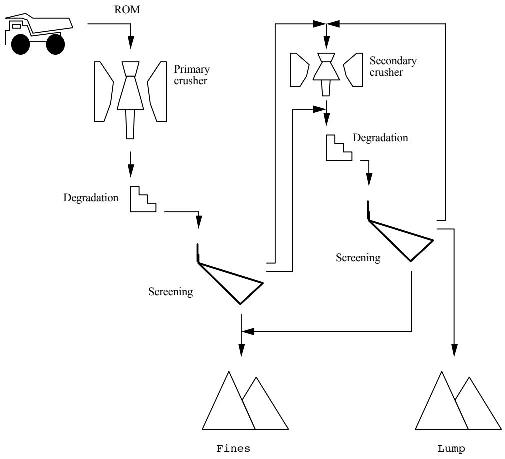

Figure 5 - Flowsheet of Marandoo crushing and screening plant

Simulations of Changing Blasting Practice

Having validated both the blasting and comminution models, simulations were then run to determine whether the blast design could be manipulated to change the final lump:fines ratio.

The influence of the following changes in the blast design on the fragmentation was studied:

- Expansion of pattern.
- Use of low density (700 kg/m^3) and low VOD (3000 m/s) explosive.
- Use of low density/low VOD explosive with expanded pattern.

Expanded Pattern

The pattern was expanded by 16-52%, as summarised in Table 4, to give the same powder factor for all three domains.

Table 4 - Simulated Blast Design Parameters

	Domain					
Blast Design	1		2		3	
Parameter	old	new	old	new	old	new
Burden (m)	4.8	5.9	5.1	5.8	5.6	6.0
Spacing (m)	5.5	6.8	5.9	6.6	6.4	6.9
Powder Factor (kg/t)	0.30	0.19	0.24	0.19	0.22	0.19
Change in Pattern (%)	52		27		16	

The simulation results, summarised in Table 5 by the final lump/fines ratio and secondary crusher circulating load, suggest that expanding the pattern is expected to increase the final lump/fines ratio and the circulating load. The greatest change is seen in Domains 1 and 2 which contain higher proportions of hard ore.

Table 5 - Effect of Expanded Blast Pattern (Plant treating 1900 tph)

Domain	Blast Design	Lump/Fines %	Circulating Load, tph
1	old	49/51	851
	new	56/44	1028
2	old	51/49	823
	new	55/45	923
3	old	47/53	651
	new	49/51	705

Low Density/Low VOD Explosive

Based purely on the manner in which commercial explosives deliver energy into rock, the general explosive/rock interaction criteria would suggest that Marandoo, with predominantly soft rock, should be using diluted ANFOs which have a very low VOD. The usage of low VOD explosive with the same patterns, will alter the partition of explosive energy to reduce the percentage of shock energy whilst maintaining the heave energy. Therefore the usage of low VOD explosive is aimed not only at increasing the lump to fine ratio but also improving muckpile looseness. However, these aspects should be investigated further. The terms hard and soft rock relate not only to the intact rock strengths and mode of failure but also to the spacing and condition of the jointing. To test this hypothesis an explosive with a nominal density of 700 kg/m^3 and 3000 m/s VOD (Relative Weight Strength of 98) was simulated.

The simulation results suggest that the low density/low VOD explosive has a much more pronounced effect on the lump/fines ratio, as shown in Table 6, compared to the pattern expansion. The change in explosive type represents an eight percent improvement in lump production, for a moderate increase in circulating load. The reason why the change in explosive type makes such a large difference is that the ROM size distribution is coarser by virtue of a reduction in fines (<6.3mm), whilst the natural lump has increased a few percent. The benefit of lower fines therefore translated almost directly to higher lump/fines ratio.

Expanded Pattern & Low Density/Low VOD Explosive

Simulations were also carried out on the combined effect of expanding the pattern whilst using the low density/low VOD explosive. Figure 6 illustrates the effect on the ROM. The results showed that there would be a further improvement in lump/fines ratio over that already achieved in just changing the explosive type or pattern, at the expense of a major increase in crusher circulating load. Domain 1 would yield 62/38 at 1210 tph, Domain 2 61/39 at 1082 tph and Lower Flats 56/44 at 904 tph. Note that the greatest change is in the hardest ore type. The increased circulating load would require the use of both secondary crushers in production.

Table 6 - Effect of Low Density/Low VOD Explosive

Bench	Domain	Blast Design	Lump/ Fines, %	Circulating Load, tph
750/604	1	old	49/51	851
		new	58/42	1008
200/227	Flats Upper 2	old	51/49	823
		new	59/41	988
300/212	Flats Lower 3	old	47/53	651
		new	55/45	818

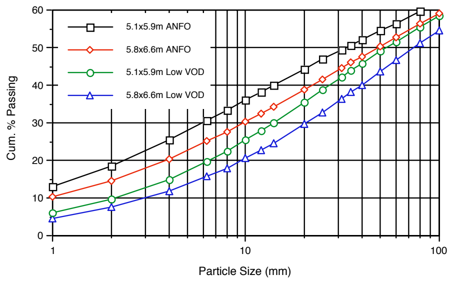

Figure 6 - Effect of explosive type and pattern expansion on ROM blast fragmentation, based on 200/227 bench

The simulations of blasting, crushing and screening using a dual circuit approach to represent the soft and hard ore separately give realistic results and confirm the trend with ore hardness as expected from geologists logging.

On the basis of simulations, there is scope to improve the lump/fines ratio by changing the blast pattern. Alternatively, the use of a low density low VOD explosive should significantly reduce the fines in the ROM which represents an eight percent improvement in the lump/fines ratio. The impact of the changes in ROM size distribution on excavation and productivity will need to be considered.

KCGM Case History

Model Parameters

Blasting

Ore Characteristics

The blast model requires the UCS, Young's modulus, in-situ block size and joint spacing of the rock. For the domain used for this study rock samples were taken to determine the first two parameters at the JKMRC. In-situ block size and joint spacing were provided by mine staff. The resulting values were:

Young's Modulus	80 GPa
UCS	100 MPa
Joint Spacing	0.8 m
In situ Block Size	1.103 m

Blast Model Calibration

The blast design details used by the company were provided by mine staff (Table 7) and were put into the blast model. The model was then run and a ROM size distribution predicted. This was compared to that provided by Split analysis of images of ROM on the back of haul trucks. Reasonable correspondence was obtained (Atasoy et al., 1998, Kanchibotla et al, 1998 and Valery et al., 1999).

Table 7 - Blast Design Details

Burden (m)	5
Spacing (m)	5.8
Hole depth (m)	11.3
Hole diameter (mm)	165
Column charge length (m)	7.2
Explosive	Energan2620
Density (kg/m3)	1100
VOD (m/s)	4550
Powder factor (kg/t)	0.58

Crusher and Mill Model Validation

The comminution circuit at Fimiston is shown in Figure 7.

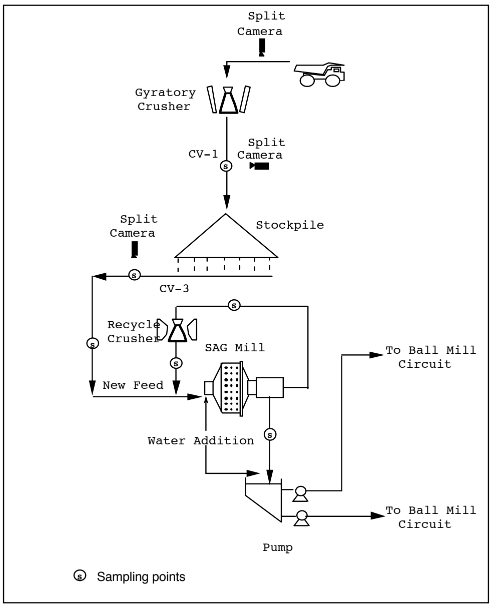

Figure 7 - Schematic of crushing/SAG mill circuit

The primary crusher, mill and recycle crusher models were developed from real plant data. During the last 5 years these models have been successfully applied at KCGM to optimise their grinding circuit and hence there is a high degree of confidence that they do mimic the general performance characteristics of the comminution circuit (Nelson et al., 1996).

If the primary crusher model is accurate, as well as the ROM sizings predicted from the blast model, then it would be expected that if the current comminution circuit were simulated with the SAG mill feed size predicted from the primary crusher model a lifelike throughput should be predicted. To test this the blast and comminution circuit models were combined and such a simulation run. The SAG mill model was set to run with a maximum filling of 30%. The simulation results are shown in Table 8 together with the observed results of industrial survey of the circuit. It can be seen that the results are in good agreement and hence confirm the accuracy of the blast and comminution plant models.

Table 8 - Observed vs Predicted Grinding Circuit Performance

	Observed	Predicted
Feedrate (t/hr)	1250	1250
Feed F80 (mm)	130	118
Trommel undersize P80 (mm)	3.06	3.21
Recycle crusher feedrate (t/hr)	276	345
Recycle crusher F80 (mm)	63.6	60.7
Recycle crusher P80 (mm)	15.0	15.5
Mill filling (%)	29.5	30
Mill power (kW)	12717	12750

Simulations

Having validated the models using the current design, the blasting, crushing and sag mill models were linked together and changes made to the blast design to determine their effect on mill performance.

Blast Design Details

Two different blast designs were chosen to illustrate their effect on mill throughput. Details of these designs (Designs 3 and 9) are given in Table 9. Design 1, which is the mine's current design is also given for comparison. It can be seen that design 3 and 9 use different explosives and powder factors compared to the current situation.

Table 9 - Blast Design Details

	Design1	Design3	Design9
Burden (m)	**5**	5	**4**
Spacing (m)	**5.8**	5.8	**5**
Hole depth (m)	**11.3**	11.3	**11.3**
Hole diameter (mm)	**165**	165	**165**
Column charge length (m)	**7.2**	7.2	**7.2**
Explosive	**Energan26 20**	Powergel gold	**powergel gold**
Density (kg/m3)	1100	1250	1250
VOD (m/s)	4550	6000	6000
Powder factor (kg/t)	0.58	0.66	0.96

Effect on ROM Sizing

The predicted size distributions of the ROM from all 3 designs are shown in Figure 8. It is immediately apparent that the new designs have produced more fines as would be expected from the higher powder factors and higher VOD explosive used. It should be noted that Design 3 has only minimal effect at the coarse end of the distribution whereas Design 9 has a marked one due to the changes in burden and spacing.

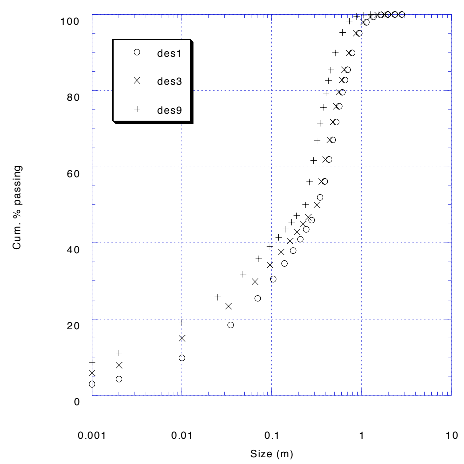

Figure 8 - ROM size distributions from 3 different blast designs

Effect on Crusher Product

The results of simulating the various ROM distributions after they have passed through the primary crusher are shown in Figure 9. Interestingly the differences between the ROM distributions are significantly reduced post crusher, particularly in the +100 mm fraction. This is due to the typical action of primary crushers which generate very little fines but tend to crush oversize rocks into 2-3 size fractions immediately below the closed side setting. However, despite the reduction in the differences between the ROM distributions that result from primary crushing, there still exist some significant differences in the crusher product distributions. Notably there is an increase in the amount of -10mm with the new designs, a steepening of the distribution in the +100mm fraction and a reduction in the gradient in the -100+25mm size range.

In addition to the effect on product size it is also noteworthy that due to the reduction in top size in Design 9, primary crusher throughput capacity will increase. Alternatively, the primary crusher gap could be reduced with this design.

Effect on Mill Performance

Mill performance is usually evaluated in terms of throughput, specific energy (kWh/t) and final grind size. For these simulations the mill was run at a constant mill filling and speed, and hence constant power, so that the effect on throughput could be gauged. The results are shown in Table 10 for the 2 new designs (3 & 9) together with the current design (1).

Table 10 - Simulation Summary

Design	Feedrate (t/hr)	P80 (mm)	P50 (mm)	Power (kW)	kWh/t
1	1250	3.21	0.69	12750	10.2
3	1420	3.13	0.65	12755	9.0
9	1480	3.11	0.63	12749	8.6

As can be seen a significant increase in throughput is obtained with Design 3 with further, though proportionately much less improvement with Design 9. This is despite the 50% increase in powder factor in Design 9 compared with Design 3. The reasons for the increased throughput are twofold. Firstly both new designs generate more -10mm material which does not need to be ground and is essentially "free" throughput for the mill. Secondly the changes in the +50mm size range lead to marginally lower amounts of so-called "critical" size in the feed and a narrower distribution in the +100mm media size range, with less unnecessary oversize.

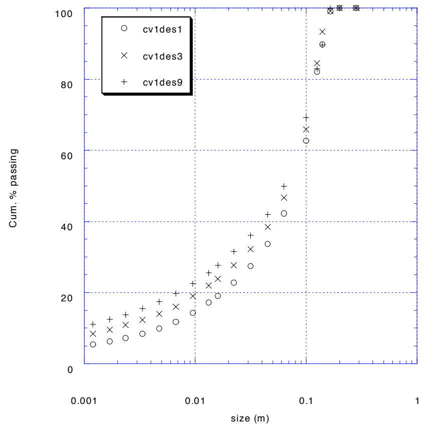

Figure 9 - Crusher product size distributions from 3 blast designs

An increase in powder factor to 0.75 was implemented by KCGM and throughput rates were increased to 1350 – 1400 t/h. Experience has shown that feed size distribution is one of the main factors in affecting the performance of ag and sag mill circuits (Valery and Morrell, 1997). It is also clear that blasting can affect the ROM size distribution. Although the primary crusher tends to limit the effect of a change in the ROM distribution this simulation study has indicated that enough remains to significantly affect the performance of the mill.

CONCLUSIONS

Whether mining is followed by crushing and screening steps or SAG milling, simulations indicate that considerable potential exists for increasing throughput or improving product quality by modifying blast design. The JKMRC models are relatively simple to calibrate and good enough to reproduce the observed performance trends and interaction between the mine and subsequent comminution steps. These models have been successfully used in mine to mill optimisation projects at several mine sites such as Minera Alumbrera (Argentina), BHP Newman (Australia), Cadia Mine (Australia), Century Zinc (Australia), Ernest Henry Mining (Australia), Highland Valley Copper (Canada), Cerro Colorado (Chile), Escondida (Chile), OKTedi Mining (Papua New Guniea), Porgera Joint Venture (Papua New Guniea), and others.

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