Driving Productivity by Increasing Feed Quality Through Application of Innovative Grade Engineering® Technologies

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ABSTRACT

The minerals industry is facing a productivity and investment crisis. The 'Millennium Super Cycle' from 2003-11 was an unprecedented period of growth and investment resulting in increased throughput and development of lower grade resources to meet demand. During the boom quantity became more important than quality with throughput the key metric. This was accompanied by a general trend of decreasing feed grades across all commodities which was offset with higher production volumes.

Current industry perception is that declining feed grade is an unavoidable consequence of ore deposit geology and mass mining technologies for increasingly mature mining operations. In typical crush-grind-float operations value recovery only takes place at ~100 micron particle size involving 3-4 orders of magnitude size reduction compared to run of mine feed. For increasingly low grade deposits the cost of energy and capital intensity required to process and reject worthless material at micron scale drives poor productivity. An alternative is to deploy a range of coarse rejection technologies.

Grade Engineering® is an integrated approach to coarse rejection that matches a suite of separation technologies to ore specific characteristics and compares the net value of rejecting low value components in current feed streams to existing mine plans as part of a system-view.

Coarse rejection (>>10 mm) can be used on size distributions ranging from run of mine to comminution mill discharge. Opportunity for Grade Engineering® involves five rock based 'levers' linked to combinations of screening, sensor-based sorting and heavy media separation. These involve exploitation of preferential grade deportment to specific size fractions during breakage; differential blasting design to size condition grade heterogeneity at bench scale; bulk sensor based sorting at truck and conveyor scale; sensor based sorting of separated streams; and differential particle density.

Grade Engineering® is being developed and implemented by a consortium of over 30 mining companies, equipment suppliers and research organisations. Emerging results from collaborative site activities demonstrate potential for generating significant value which can reverse the trend of declining productivity due to declining feed grades.

INTRODUCTION

The 'Millennium Super Cycle' from 2003-11 was an unprecedented period of growth and investment resulting in increased throughput and development of lower grade resources to meet demand (Downes et al, 2014; Sheehan, 2015). The urgency to bring production to market quickly stretched people, project and management resources.

Now prices have declined the industry is left with a legacy of high costs, declining ore quality and less efficient operating practices (Pease et al, 2015). For example, the average grade of copper ore mined in 2020 will be half what it was in 1990. Along with other challenges (less efficient site logistics, higher stripping ratio, treating more complex ores, etc.) it will take more than twice the activity to produce each tonne of metal (Pease et al, 2015). This is particularly evident in Australia where multi-factor mining productivity has dropped 50% over the last decade (Syed et al, 2015).

The overall trend of decreasing feed grades is shown in a comparison of normalised Cu grades for a selection of world-class Chilean Porphyry Cu operations between 1999 and 2012 (Figure 1). This shows relative feed grade decline of 25-50% over the last decade which is projected to continue over time under current mine planning and scheduling concepts. Over the last 20 years the average head grade for Anglo American platinum operations has decreased from ~5.5 g/t to just below 3 g/t (Rule et al, 2015 – Figure 2).

There are many factors contributing to overall productivity on large mining operations. These can be divided up into supply chain and value chain influences. The supply chain represents the costs of goods and services. During the boom cycle hyperinflation contributed to a significant loss in productivity. This has been addressed by a return to more normal pricing and by structural reforms in major mining companies often involving reduction of skilled workforce. Value-chain factors relate to the quality of ore mined and the overall efficiency of mining and mineral extraction in generating a saleable product. Increasing scale of operation is widely regarded as a key driver of productivity (Mudd, 2004; 2009). While this generated significant benefits in the 1990's as the size of individual units such as trucks, SAG mills and overall material movement increased, the benefits diminished during the boom.

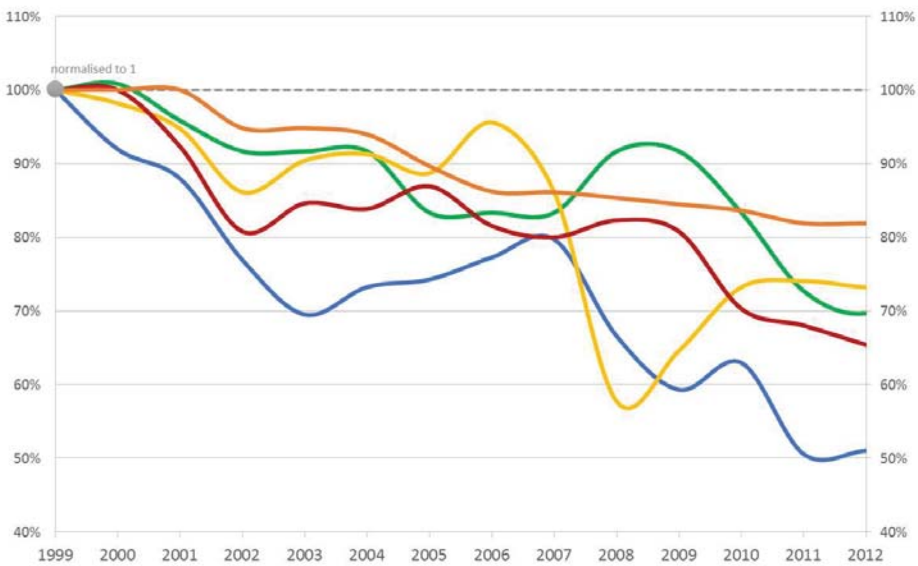

FIG 1 - Comparison of normalised Cu feed grades to the concentrator for a selection of world-class Chilean Porphyry Cu operations.

This reflects a reliance on multiple rather than larger units (more trucks, additional concentrators, etc.); Increased complexity; reduced operator skills; and poor integration across unit operations which has resulted in declining equipment productivity indices. During the boom quantity became more important than quality with throughput the key metric. This was accompanied by a general trend of decreasing feed grades across all commodities which was offset with higher production volumes. Increasing scale of operation resulted in which in turn negatively impacted the feasibility of many projects.

Current industry perception is that declining feed grades are an unavoidable consequence of ore deposit geology and mass mining technologies for increasingly mature mining operations (West, 2011). In typical crush-grind-float operations value recovery only takes place at ~100micron particle size involving 3-4 orders of magnitude size reduction compared to primary feed. For increasingly low grade deposits the cost of energy and capital intensity required to process and reject worthless material at micron scale drives poor productivity.

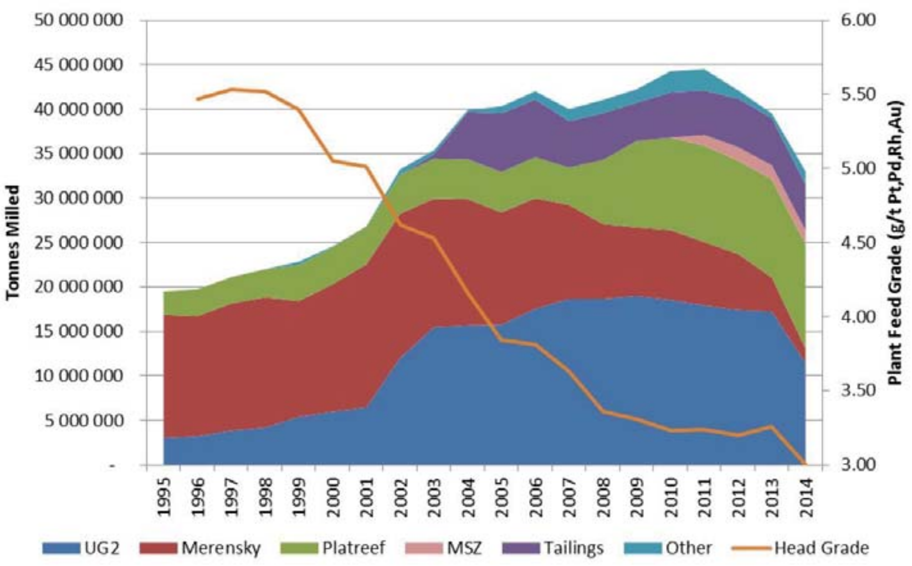

Fig 2 - Average head grade and tonnages for Anglo American platinum operations over the last 20 years (after Rule et al, 215).

An alternative is to deploy a range of coarse rejection technologies. Grade Engineering® is an integrated approach to coarse rejection (~10-100 mm) that matches a suite of separation technologies to ore specific characteristics and compares the net value of rejecting low value components in current feed streams to existing mine plans. The outcome for many base and precious metal operations is a significant increase in ROM feed grades that can be used to counter over reliance on throughput as the only available option to drive value.

CONCEPT OF GRADE ENGINEERING®

Overview

A focus on throughput as the main driver of revenue has led to a bulk average grade mentality around minimum mining units. In many cases average grades used to define bench or stope scale processing destination decisions such as mill, dump leach, waste, etc. include significant sub-volumes of material outside cut-off specifications. An averaging approach ignores potentially exploitable grade heterogeneity below the scale of minimum mining unit even though significant localized grade heterogeneity is a dominant characteristic of many base and metal deposit styles and ore types.

Localized grade heterogeneity is typically overlooked in favor of maximizing extraction rates and loading efficiency. This is coupled with a desire to blend ROM and produce steady state feed in terms of grade and physical properties to optimize and maximize recovery of saleable product particularly in crush-grind-float operations. Where blended supply of 'averaged' feed struggles to achieve steady state processing stability, this is a first order indication that significant heterogeneity exists within a resource that could be exploited rather than suppressed.

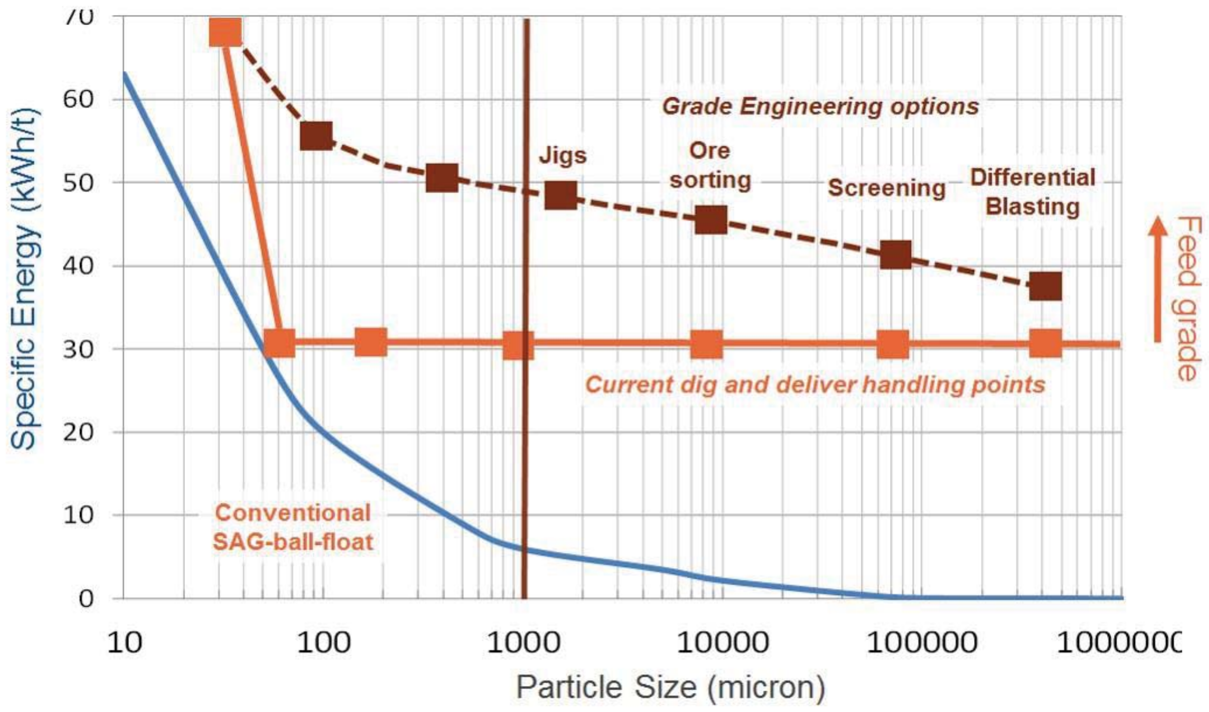

FIG 3 – Schematic illustration of opportunity for Grade Engineering® intervention across all handling and feed transformation point in the current dig and deliver cycle relative to average particle size and energy required to generate the size distribution.

Grade Engineering® recognizes that in many cases out of specification sub-volumes assigned to destinations based on bulk averages can be removed using efficient coarse separation techniques in the 'dig and deliver' interface. Coarse separation can be used on a range of particle size distributions ranging from ROM to SAG discharge (Bearman, 2013). The earlier this occurs in the conventional dig and deliver mining cycle the higher the potential net value of removing uneconomic material (Bamber et al, 2006 a and b; 2008).

Every handling and size transformation interface in the 'dig and deliver cycle' between extraction of material and arrival at its downstream processing or disposal destination, should be considered an opportunity for applying coarse separation. ROM and post primary crushing are obvious intervention points with opportunity for separation conditioning during modified blast design. This is illustrated schematically in Figure 3. The decision to intervene is a function of the yield-response of a separation device at a specific size reduction point; the ability to change a destination decision for one or more of the new streams following separation; and the net value of the new streams after separation handling costs.

Grade Engineering® outcomes do not create 'new' metal but rather exchange metal from separated components between existing destinations to create improved net value after cost of exchange is taken into account. This involves exchanging a component of separated mill feed with other destinations such as mineralised waste, stockpiles or dump/heap leach with low recovery. The aim is to bring metal forward from destinations that are not delivering maximum current value.

Overall metal exchange balance can be modified to suit operational modes or bottlenecks. This can include keeping the concentrator full with improved grades or deferring the need for expanding installed capacity. Mass pull on separation devices can be used to control accept/reject tonnages and resulting upgrades. While Grade Engineering® does not create 'new metal', outcomes can improve resource to reserve conversion by potentially separating economic parcels of ore from mineralised waste.

The concept of coarse separation or pre-concentration is not new and has been practiced from the beginning of mining as hand picking (Wills and Napier-Munn, 2015; Salter and Wyatt, 1991; Wotruba and Harbeck, 2010). The propensity of some ores to break preferentially during blasting and crushing leading to an increase of valuable phases in finer fractions has also been widely known but rarely exploited at production scale (Bowman and Bearman, 2014). A notable exception was pre-concentration carried out in the 1980's at the Bougainville Copper Limited Panguna Cu-Au mine in Papua New Guinea (Burn and Grimes, 1986; Paki and Koginmo, 1988). This involved a screening plant to upgrade marginal low grade ROM ores (0.22 Cu, 0.18 g/t Au) that exhibited preferential grade deportment into fines. The plant had a capacity of 35 Mt p.a. at a <32mm screening size, which produced a 50% Cu-Au upgrade in 38% retained mass.

Additional examples of production scale pre-concentration include the Dense Media Plant at Mount Isa Mines which removes ~35% of coarse and hardest Pb-Zn feed before the fine grinding treatment process. This increases throughput, reduces capital intensity in the comminution circuit, and reduces energy requirement per unit metal in the concentrator by >40%, together with a 15% improvement of grade in the retained stream (Munro et al, 1982).

While application of sensor-based sorting has found widespread application in industrial recycling and food quality management, there are limited examples of routine application to pre-concentration in the minerals industry. An exception is the Mittersill tungsten mine in Austria where in response to head grades falling from 0.7% to 0.2% since mining commenced in 1976, X-ray Transmission sensor-based particle sorting units were installed in 2008. The results significantly increased effective head grade and reduced energy intensity while allowing rejected waste to be sold as road aggregate (Tomra, 2016).

Although there are global examples of coarse pre-concentration generating value for some base and precious metal mining operations, there is no coherent system-based industry approach or standard methodology to assess optimal configurations for selecting specific technologies or equipment to deliver maximum value for specific ores and operational constraints.

Grade Engineering® is the first large-scale initiative to focus on integrated methodologies to deliver maximum operational value (Pease et al, 2015). Development is being conducted under the auspices of the Australian Government Co-operative Research Centre scheme through CRC ORE (CRC for Optimisation of Resource Extraction) with support from the global minerals industry. CRC ORE was renewed for a further six years in July 2015 with over 30 research, mining equipment and technology services (METS) and end-user miner participants. The prime aim is to deliver Grade Engineering® as an industry standard methodology designed to improve productivity and value to mining operations which includes the ability to filter and rank individual operations for highest opportunity.

Coarse Separation Levers and Response Rankings

Within Grade Engineering® five technology 'levers' are recognized that are capable of delivering coarse separation outcomes (>10mm).

1. *Natural preferential grade by size deportment*: the propensity for some ores to exhibit preferential breakage leading to concentration of minerals into specific size fractions. This typically involves an increase of valuable mineral phases in finer size fractions. Preferential grade deportment is an interaction function of rock mass properties, texture, ore paragenesis and mineralogy at a range of scales.

   There is typically no relationship between magnitude of response and head grade, with the main control being textural rather than absolute abundance. Physical separation is a function of screening employed after blasting or primary crushing.

2. *Differential blasting for grade*: involves conditioning of sub-volumes of material at bench or stope scale using customized blast designs that generate imposed size distributions with higher grade concentrated in finer fractions. Amenability is a function of exploitable grade heterogeneity at blast hole scale linked to the ability to impose and control different energy distributions within a blast design. As for Lever 1 physical separation is a function of screening.

3. *Sensor based bulk sorting*: involves use of a wide variety of electronic sensors capable of providing on-line information on grade in the dig and deliver material handling interface including shovel buckets, trucks and conveyors. There are many technologies capable of coarse rock sensing ranging from surface based to fully penetrative; and providing elemental to mineralogical resolution. Amenability is a function of the resolution and accuracy of individual sensors; rock interaction times and signal acquisition; and selected scale of resulting separation volume.

4. *Sensor based stream sorting*: while sensor based bulk sorting involves full particle size distributions, stream sorting involves a modified particle size distribution. This is driven by the requirements of some sensor technologies for a limited size distribution to improve rock interaction and enable individual particle separation using air jets or mechanical actuators. It is also driven by an option to use sensors as 'cleaners' on lower volume separated streams derived using other levers.

5. *Coarse gravity separation*: involves use of heavy media separation and in-line pressure jigs at coarse scale (>10mm) generating individual particle separations based on density. Amenability and separation outcomes are a function of texture and mineralogy at this scale. Compared to Levers 1 to 3, conditioning feed for coarse gravity separation typically requires secondary crushing and screening to deliver a carefully constrained particle size distribution. For this reason, coarse gravity separation in Grade Engineering® applications primarily operates as a 'cleaner' in combination with streams derived using other levers.

In order to assess relative merits and resulting value of coarse separation outcomes based on applying individual levers or sets of levers for specific ores and operations, it is necessary to define comparative response attributes through a process of physical testing and simulation.

Coarse separation involves generating two or more streams with different grade or physical characteristics. In Grade Engineering® relative difference between separated fractions and feed grade is referred to as a *Response Factor* (Carrasco et al, 2015 and 2016). Response Factor is a function of rock type and its interaction with separation lever technologies. Response Factor varies as a function of mass pull, with a small mass retained (10-30%) typically giving a high Response Factor upgrade while a high mass retained (>70%) gives a lower value.

An example of laboratory scale testing for Response Factor is shown in Figure 4. Data points represent actual test laboratory results in this case for preferential grade deportment by size using crushed drill core at a range of screen sizes (Carrasco et al, 2014). The effect of varying mass retained on Response Factor upgrade is evident. The resulting family of cumulative distributions can be described using a mathematical function irrespective of mass pull referred to as a *Response Ranking* (RR).

Reference RR's are shown as pale grey lines. Response Rankings can be passed into circuit design, simulation and modelling and ultimately drive economic evaluation. In this context Response Rankings and Factors are directly comparable to other rock-based metallurgical performance attributes such as Bond Work Index which can be used for circuit design and equipment selection.

Response Rankings are scaled from 0-200 with 200 the theoretical maximum response and the method can be applied to testing and simulation outcomes for all five levers. The higher the RR the greater the opportunity for producing two or more separated streams with different grades which can alter current economic destination decisions (Carrasco et al, 2014). The ability to place RR's into a global comparative ranking is a key aspect of Grade Engineering® opportunity assessment (). Average deposit scale RR's greater than 70 for specific levers or lever combinations indicate high economic opportunity based on experience to-date, while average RR's greater than 100 represent transformational Grade Engine-ering® opportunity.

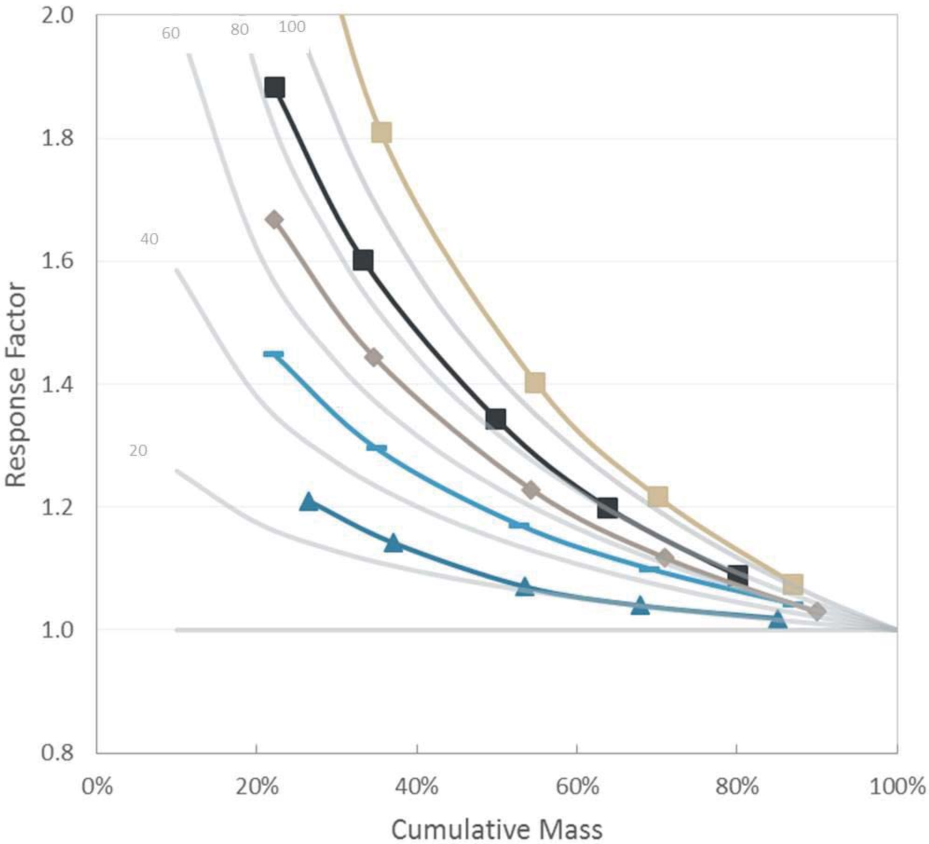

FIG 4 – An example of Response Ranking curves and Response Factor versus retained mass for laboratory testing of preferential grade by size response using drill core. Pale grey lines indicate mathematical Response Rankings. Feed grade is normalised to 1.

Lever Response Rankings can be used in a range of simulation and modelling applications to asses opportunity and net value for producing new separated feed streams. The key outcome is generating separated feed streams that have a new net value which changes existing destin-ation assignment. This could involve exchanging between mill and waste, waste and heap leach, etc. Figure 6 shows the effect modelling three different RR's for opportunity to separate a feed

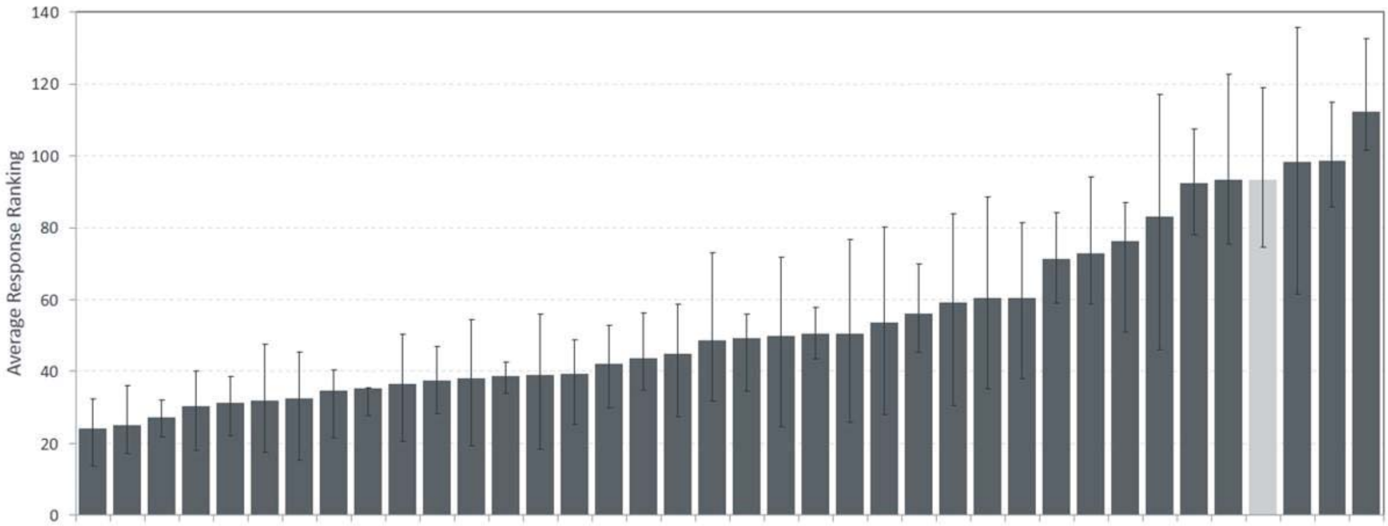

FIG 5 – Comparative ranking of average preferential grade by size Response Rankings for selected deposits. Whiskers show 25th and 75th percentiles.

grade of 0.5% into two new streams across a range of %mass retained using a destination cut-off of 0.4% Cu. At RR100 all mass splits produce a discard below 0.4% with varying upgrades in the retained fraction. At lower RR's the mass split which can generate a feed below destination cut-off progressively decreases. At RR 20 there is no opportunity to generate a stream below destination cut-off. This illustrates the dynamic interplay between RR, mass retention and destination which requires optimisation for highest value operational implementation (Carrasco et al, 2016).

While high RR's drive opportunity, magnitude of RR is only one component in determining if there is improved value in exploiting coarse separation within a mine schedule. As noted the key aspect is that one or more of the separated streams has a new grade value that changes the destination decision and net value of the original bulk volume destination. For this reason maximum economic Grade Engineering® impact occurs through operational application of coarse separation around existing cut-off destination grades. This is illustrated schematically in Figure 7 which shows change of destination opportunity around a given gold cut-off grade as RR values increase (response) and mass retained (yield) is varied based on a simple binary waste or mill decision.

The box and whisker type plots indicate feed grade and resulting separated grades for a range of RR's

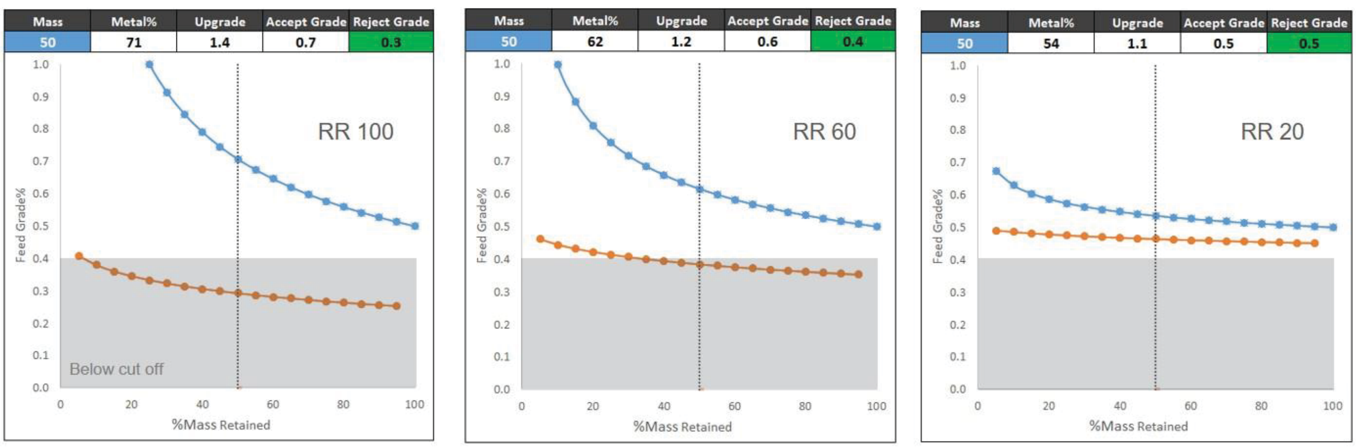

FIG 6 – Modelling of three different RR's on opportunity to separate a feed grade of 0.5% into two new streams across a range of %mass retained using a destination cut-off of 0.4% Cu (see text for explanation).

and the area of opportunity where one of these products is amenable to a different destination. While area of opportunity enlarges with increasing RR there are still defined grade limits which constrain operational decisions. For high grade ores, for example, even with high RR there can be no change

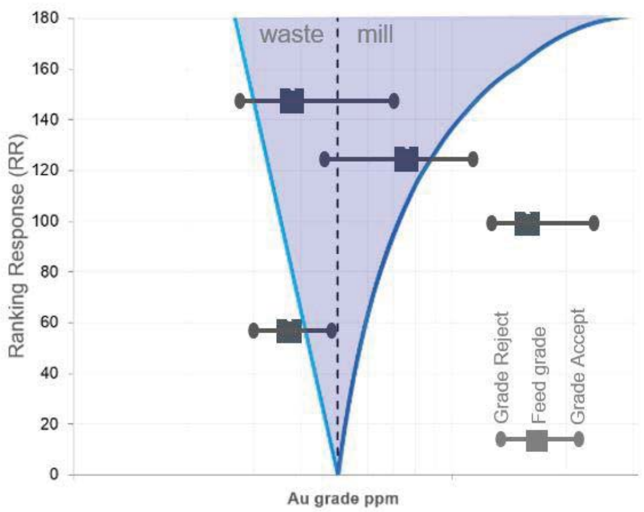

FIG 7 - Change of destination opportunity around a given gold cut-off grade as RR values increase (response) for a set mass yield based on a simple binary waste or mill decision. Whiskers represent the two new stream grades after feed separation.

of destination decision if both separated streams are still mill grade with no economic rationale for intervention. As mass retained is dynamically manipulated this changes grade limits for intervention typically increasing with low yields. Yield manipulation is a function of changing feed conditioning; equipment settings such as screen apertures for levers that generate size differences; or changing sensor activation thresholds. This generates a dynamic interplay between separation functions with implications for advanced process control in Grade Engineering® circuits (Carrasco et al, 2016).

Like other variable rock property attributes, it is important that RR's are populated into the resource block model using a combination of physical laboratory, bulk scale testing and simulation using geometallurgical concepts. This provides an additional set of assigned block values and functions that can be dynamically manipulated for both grade and mass using Grade Engineering® compared to a traditional fixed block grade attribute.

The resulting Grade Engineering® value opportunity is only optimised after rescheduling to exploit new block model attributes linked to user-defined operational constraints such as equipment sizing, dig rates, NPV, etc. Testing programs also need to define how individual lever RR's vary over life of mine generating different operational opportunities and decisions (Figure 8) and what ore types or domains drive highest value. It is also important to define which lever Ranking Responses are additive

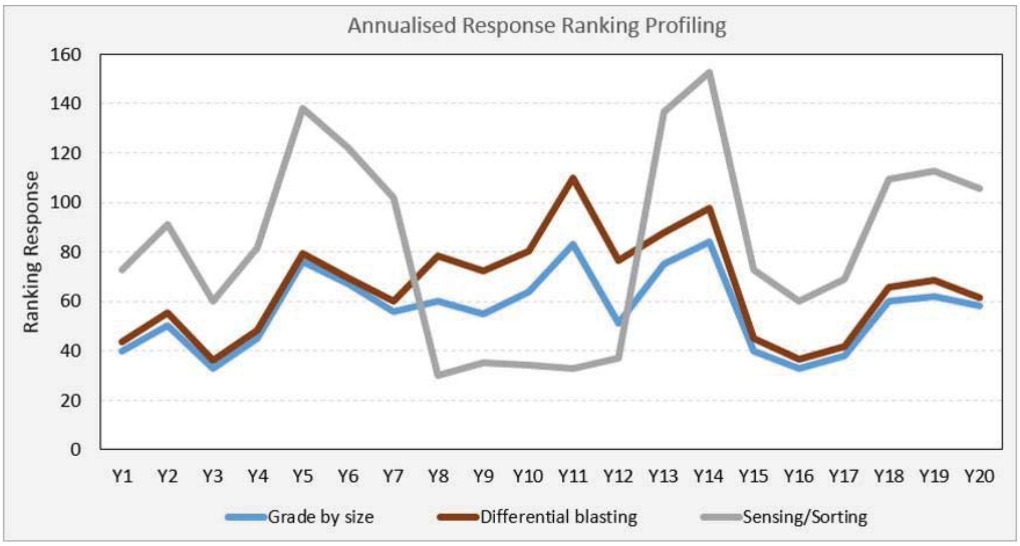

Fig 8 – An example of annualized average Response Rankings for three different separation levers relative the mine schedule. Responses are not necessarily additive and in some cases are mutually competitive.

or in some cases mutually competitive.

For the example shown in Figure 8 grade by size and differential blasting RR's are to an extent additive (although not in a linear fashion) both reporting to the same screen, while the sensor RR operates as an alternative (and competitive) option. In many cases individual levers can be optimised for different domains and the overall objective is design of Grade Engineering® circuits based on minimum number of levers generating the best value proposition without introducing excessive complexity or Capex. For Grade Engineering® assessments to-date maximum value is typically generated by applying outcomes to specific best-response domains rather than entire production (Figures 9 and 10).

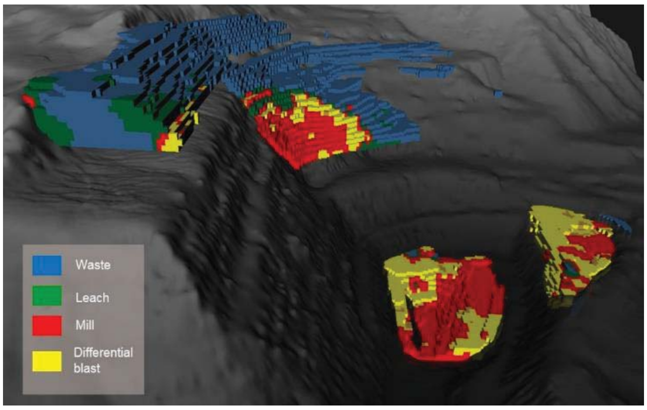

FIG 9 – An example of definition of specific domains in a large open pit operation that drive maximum value in a Grade Engineering® assessment – in this case based on application of differential blasting for conditioning grade by size (yellow blocks).

Examples of Response Rankings and Application

Natural grade by size deportment

the propensity for some mineralised ores to preferentially deport and concentrate specific minerals into different size fractions during coarse breakage (blasting and primary crushing) is well known, what has not been appreciated is the extent and magnitude of response for some ores and resulting production scale economic significance. This can be illustrated using grade by size data from belt cuts of SAG mill feed for the structurally hosted Telfer gold deposit in West Australia (Figure 11). Screening results for the marginal grade and average grade mill feed samples shown indicate around 65-75% of coarse material (>19mm) about to be fed to the SAG mill is below economic cut-off The resulting potential 'retain' mass <19mm has a Response Factor upgrade of 2.4-3.7.

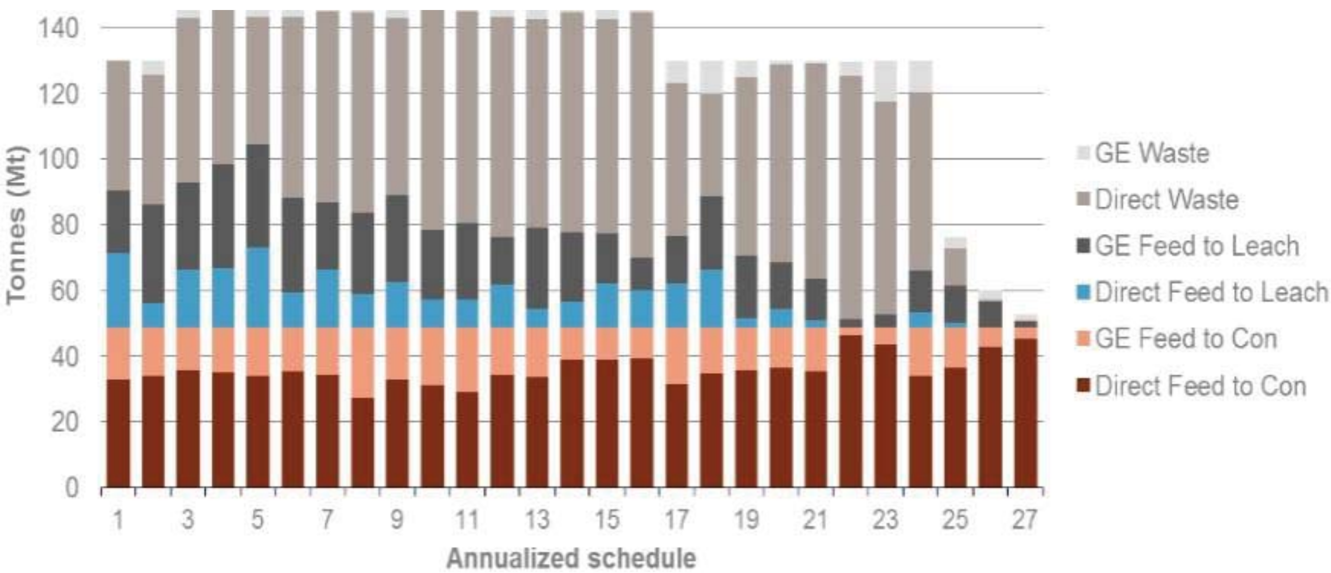

FIG 10 – An example of annualized tonnages of material assigned for Grade Engineering® coarse separation compared to overall material movements solved for maximization of value and fit to operational constraints.

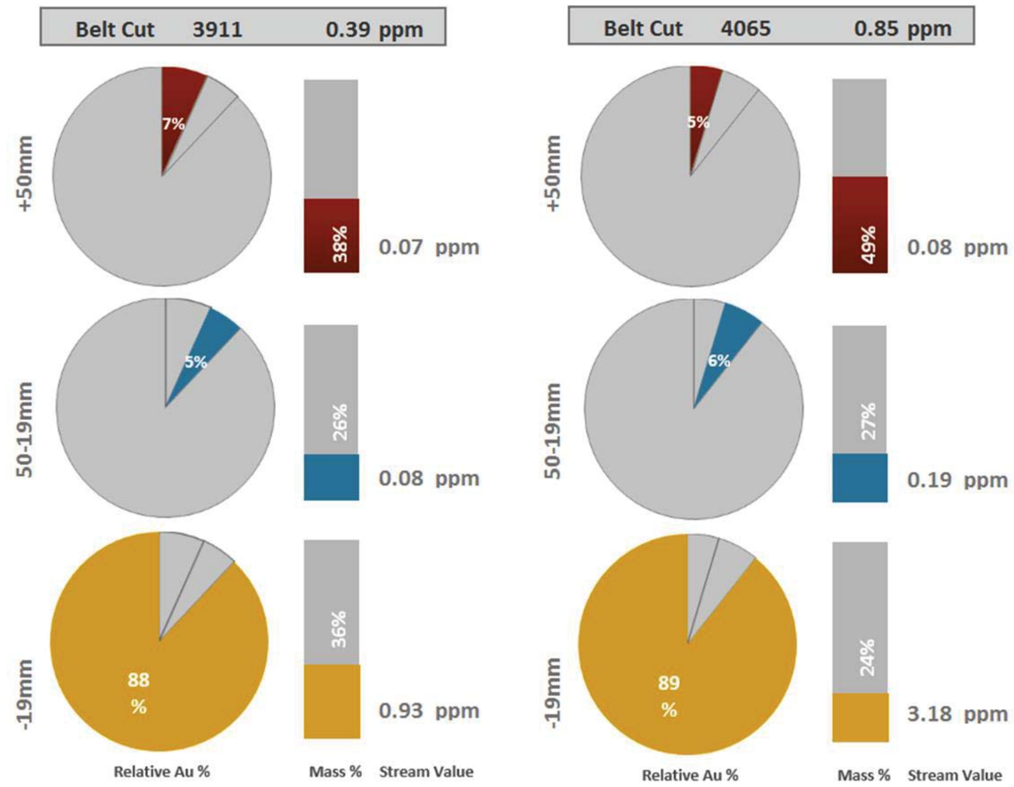

FIG 11 – Representative Au preferential grade by size belt cut responses for the Telfer Au-Cu mine. Pie charts represent proportion of contained gold and bar charts represent mass. maximization of value and fit to operational constraints.

While In addition, the low grade coarse fractions involve hard material which consumes over 80% of energy in the SAG mill.

If the coarse fractions were separated out and rejected prior to SAG milling this would result in 'loss' of around 11-12% of contained gold compared to processing the entire ROM feed stream. This should not be viewed or valued in traditional terms of lost recovery in a processing plant. A more appropriate consideration is that this represents a resource to reserve conversion function specific to Grade Engineering® which needs to be applied in the mining not processing interface. The low-grade, energy- intensive coarse size fractions would not generate net revenue during processing and should be viewed as unprofitable. There is also no implication that these low grade fractions are related to dilution during mining, with head grades representing statistically correct average values in the mined bench. The clear indication is that the mineralisation is not uniformly hosted throughout the mined rock volume and (as observed in geological logging) is focused into specific structures and mineral associations. The results shown are also typical of the larger scale resource and confirmed by a much more extensive set of data (Bowman and Bearman, 2014; Carrasco et al, 2014).

In this case the magnitude of the Response Ranking and opportunity to reject the bulk of coarse material prior to the mill would have profound negative implications for trying to maintain stable and effective SAG mill performance. A requirement to use existing installed milling infrastructure and capacity can be a problem for retrofitting transformational Grade Engineering® opportunities involving modified particle size distributions. Conversely exploiting this type of response would enable radically different circuit designs involving lower Capex and improved productivity capable of unlocking stalled feasibility projects.

In existing operations and circuits this type of Grade Engineering outcome is typically used to incrementally improve current feed grades and metal production by bringing forward metal separated from deferred lower grade stockpiles and blending this into current feed. This is exemplified by current operations at the Detour Lake mine in Canada where

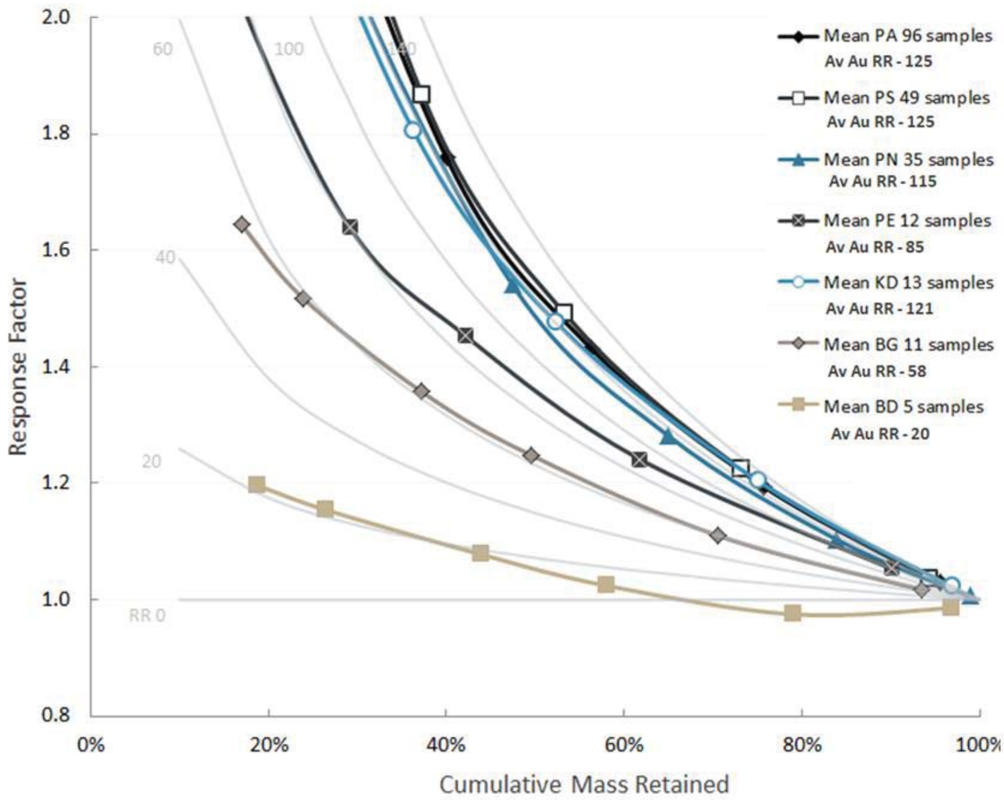

FIG 12 – Grade Engineering® Cu Response Rankings applied to bulk testing results for preferential grade by size deportment from the Panguna Cu-Au operation on Bougainville Island.

higher grade -1 inch fines flitched from existing low grade stockpiles aver-aged 1.6 g/t Au compared to 0.3 g/t Au for +1-inch material (Dupont, 2016).

Application of Response Factor analysis to preferential grade by size data from the Panguna Cu-Au on Bougainville Island noted previously, are shown in Figure 12.

Average Au RR responses for the main ore types indicate values around 120 capable of driving the significant production scale outcomes evident in the screening plant. The result also indicate two ore types are associated with much lower RR's that would not generate value after the costs of handling were taken into account. This is a typical domain-based opportunity assessment outcome from deposit scale Grade Engineering® testing programs.

Differential blasting for grade

Where preferential grade deportment by size testing outcomes from individual operations show lower Response Rankings, it is possible to supplement or replace this with Response Rankings related to differential blasting. Differential blasting involves changing energy design for blast blocks to create different fragmentation profiles. The aim is to condition in situ grade using blasting to create different size fractions which can be recovered by screening. This requires definition of in situ grade heterogeneity at blast block scale which can be exploited by blast conditioning of higher grade fines to upgrade net value of resulting separated streams using coarse screening.

Reducing top size and increasing fines production in blasting can also improve throughput and reduce energy for SAG and ball milling. This approach to 'Throughput Engineering' was the basis of Mine to Mill™ initiatives during the 1990's (McKee, 2013). While benefits were delivered on many operations Mine to Mill is not a universally accepted operating practice in base and precious metal mining. This was

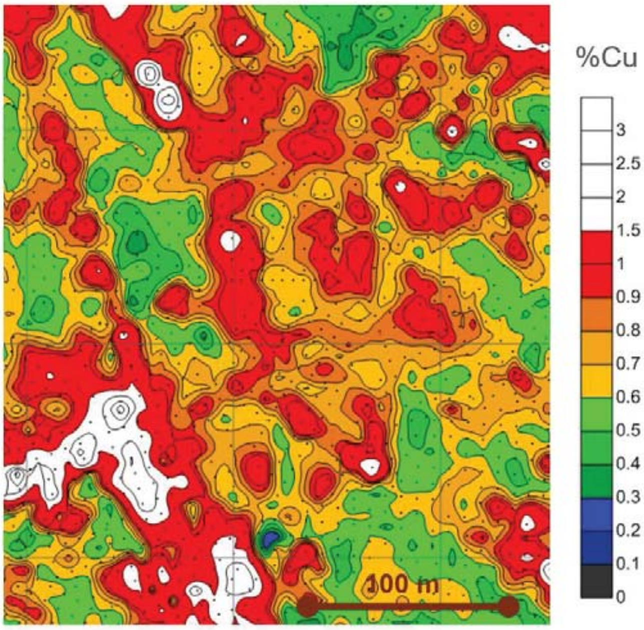

FIG 13 - plan view of contoured blast hole Cu grades for a set of mining benches assigned to mill based on average cut-off grades. Ideally zones shown in green are below mill cut-off grade and represent coarse separation opportunity.

due to perceived complexity for blast design execution and failure to articulate a shared value proposition across the entire system. Increased costs against blasting department budgets were typically not discounted against whole of system cost and reduced energy intensity benefits.

Differential blasting for grade as part of Grade Engineering® incorporates many aspects of Mine to Mill but adds significant additional value. Improvement in size conditioned feed grade can be added to improved throughput delivering greater benefits. Use of integrated Grade Engineering® methodologies also ensures that net economic benefits from differential blasting are clearly identified and optimised as part of overall system-value.

Blast designs are modified to condition fragmentation profiles by grade based on aggregates of higher grade blast holes designed to produce more fines. This involves changing powder factors by stemming or using different explosive formulations. Many sites already have different blasting 'recipes' for destinations such as mill versus waste at blast block scale. Differential blasting uses different recipes within individual blast blocks based on blast hole grades. This requires more complex execution but does not involve new technology

Opportunity is driven by bench or stope scale grade heterogeneity at blast hole resolution such that significant sub-volumes below minimum mining unit occur that are outside of the bulk average grades

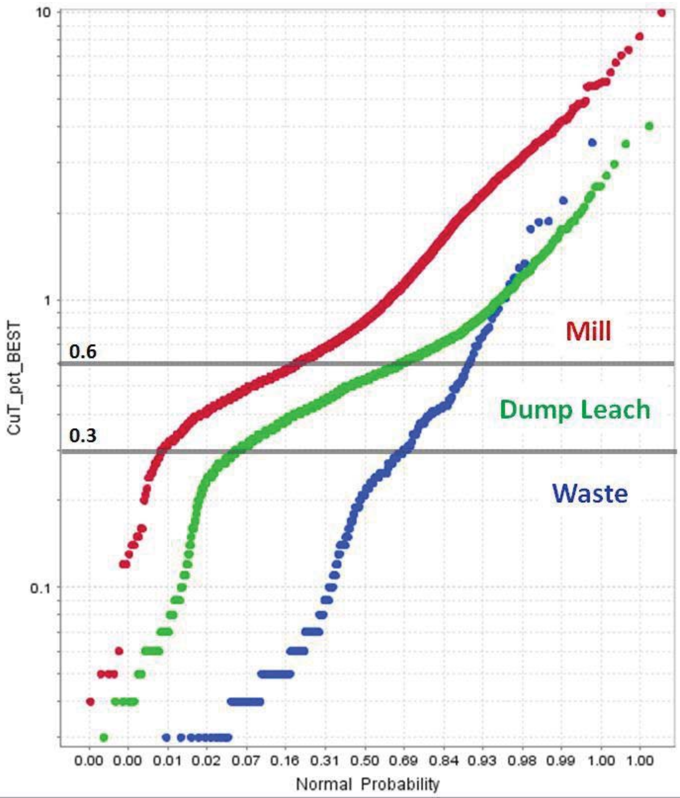

FIG 14 - Probability plot distribution of blast hole Cu grades by destination for an RL slice of a major porphyry Cu mine indicates first order statistical potential for separation (see text for explanation).

used to assign destination.

This is illustrated in Figure 13 for a porphyry Cu operation which represents a plan view of contoured blast hole Cu grades for a set of mining benches assigned to mill based on average cut-off grades. Ideally zones shown in green are below mill cut-off grade and represent coarse separation opportunity.

A probability plot distribution of blast hole Cu grades by destination for an RL slice of a major porphyry Cu mine illustrates a rapid approach for generating first order statistical potential for differential blasting (). This indicates 20% of assigned mill feed based on blast hole grade distribution would ideally have been sent to dump leach; and 33% of dump leach would ideally have been sent to mill. Assuming blast hole volumes could be reassigned would increase effective mill feed Cu grade by 17% at equivalent shipped tonnages. 30% of mineralised waste material could also conceptually be reassigned.

Converting statistical potential to realistic blast designs with imposed grade by size yields involves an iterative process using existing blasting design and simulation tools. The aim is to produce different particle size distributions driven towards conditioning higher grade material in finer fractions while accepting a degree of size overlap and inefficiencies in outcomes.

Blast simulation modelling indicates grade distribution by size for a differential blast design (). Mass distribution histograms show an induced bimodal distribution in the mid to coarse size range with a large proportion of fines <20mm. Size conditioned grade is shown as a solid line relative to an average feed grade of 0.83% Cu. A significant increase in conditioned grade in the finer fractions is evident.

Choice of screening cut size controls mass pull and accept grade, and is an operational decision based

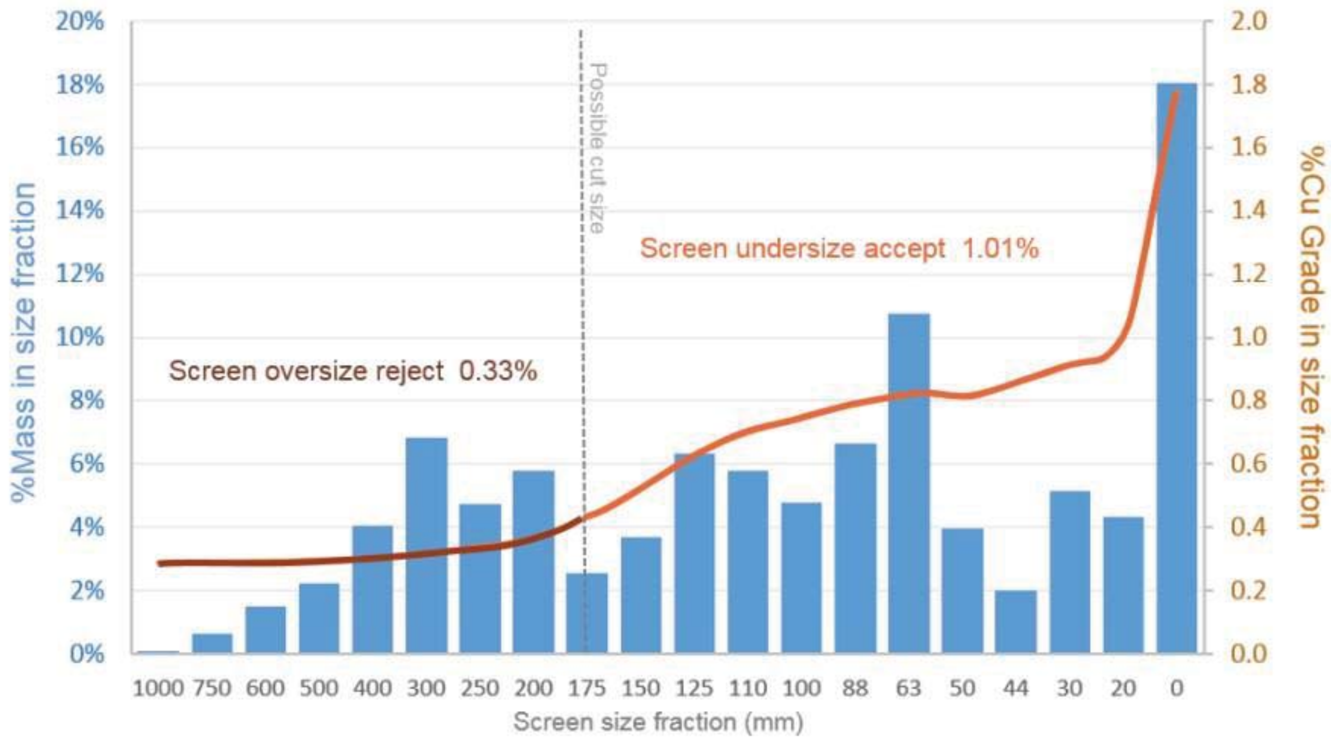

FIG 15 - Blast simulation modelling indicating bimodal grade distribution by size for a differential blast design based on a blast block average head grade of 0.83% Cu assigned to the mill. A screen cut at 175mm generates a reject mass stream of 25% suitable for low grade stockpiling.

on net value and operating constraints or targets. For a user-defined cut size of 175mm the accept fractions would be 1.01% Cu (30% upgrade) with a reject stream value of 0.33% which can be sent to a different destination in this case dump leach. Removal of top size by screening would also increase SAG throughput (Ballantyne et al, 2015).

Outcomes of differential blasting for grade are evident in the results of large scale differential blast trial carried out at an open pit precious metal operation involving narrow reef structures. Resulting grade by size conditioned ROM was screened at 110 mm with the undersize accept sent to the mill for seven days.

Mill sampling results indicated a upgrade factor ~2.0 times above normal average feed grade (Figure 16). While energy intensity increased as a result of the differential blast design involving locally higher powder factors, this was more than compensated by a reduction of energy per unit metal in the comminution circuit. Total energy during the period of the trial reduced from 225 to 111 kWhr/oz.

CRC ORE has developed an integrated calculator that solves net value for differential blasting for defined blast blocks. Site specific costs and blast designs are used as variable inputs together with information on blast blocks and blast hole grades. Outputs include selection of holes for differential blasting and target fragmentation profiles. This delivers an optimised and benchmarked solution to maximize net value based on a range of different end user constraints. Typical operational constraints include maintaining mill feed tonnages versus maximizing metal with reduced installed mill capacity.

Outcomes of optimised differential blast modelling can be reported in many different ways such as feed grade improvement; energy savings per unit metal through the comminution circuit; changes to mining rate, etc. Figure 17 shows calculated net $/t gained for selected blast blocks after costs are included compared to a base case of current practice for three production RL's in a pit.

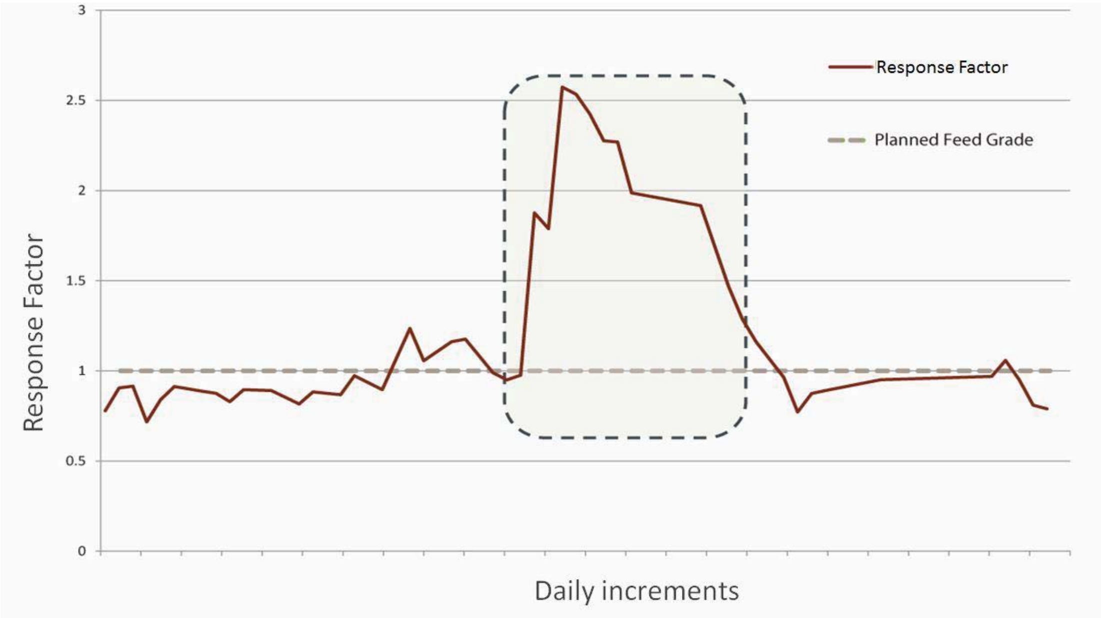

FIG 16 – Normalized Response Factors for differentially blasted and screened ores based on daily mill sampling for a precious metal operation.

This shows there is no significant net value for some blast blocks. Highest net value outcomes occur in the south eastern corner of the production area with a high degree of spatial consistency between RL's. This type of outcome starts to map zones of highest value opportunity into a resource model. As for other levers typical differential blasting assessment outcomes involve identification of specific highest value domains within a resource that delivers the majority of Grade Engineering® value. In this context

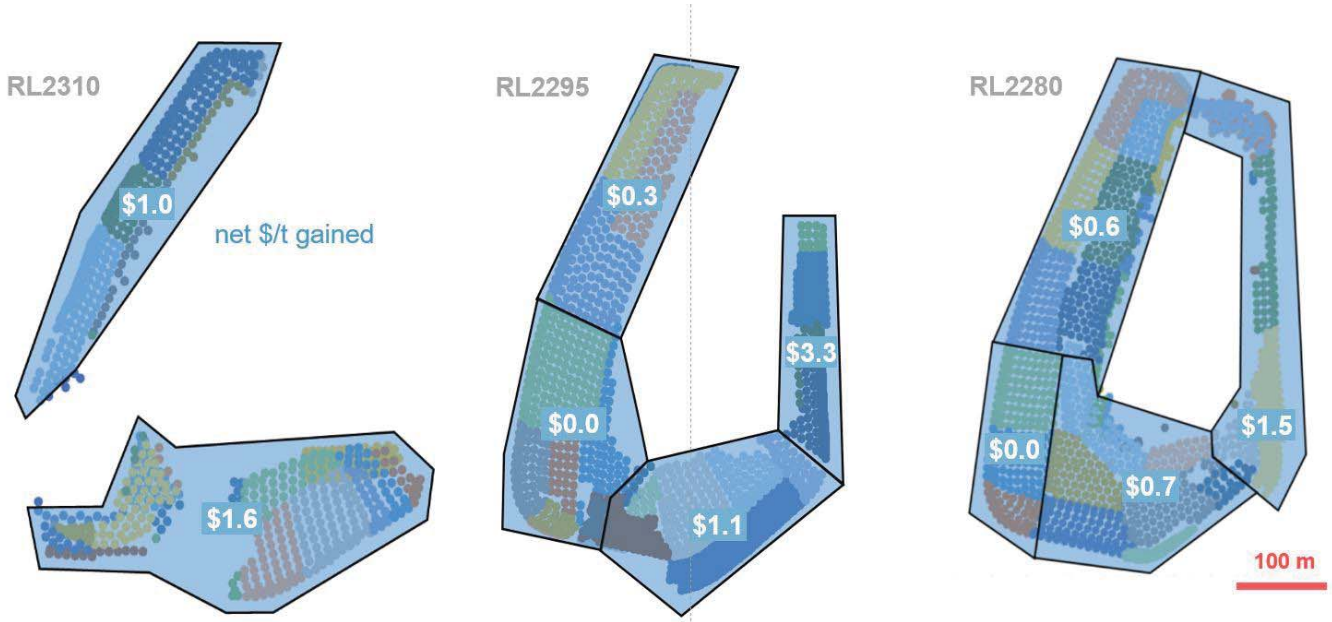

FIG 17 - Calculated net $/t gained for selected blast blocks after costs are included compared to a base case of current practice for three production RL's in a large open pit

Grade Engineering® should always be regarded as supplementary to current production options rather than a total replacement with opportunity driven by net value.

While this type of modelling using blast hole drilling grades informs short term resource models and operational decisions, opportunity and value for differential blasting need to be propagated into the long term model using much more widely spaced resource drilling. Unlike preferential grade deportment by size there is no small scale blasting test that can be performed using drill core and alternative modelling methods need to be used. While resource drilling is more widely spaced than blast holes the down hole frequency of assay data is typically much higher.

A range of statistical methods have been developed and evaluated to relate different data support scales to predict bench scale heterogeneity. This includes use of Response Factors based on analysis of

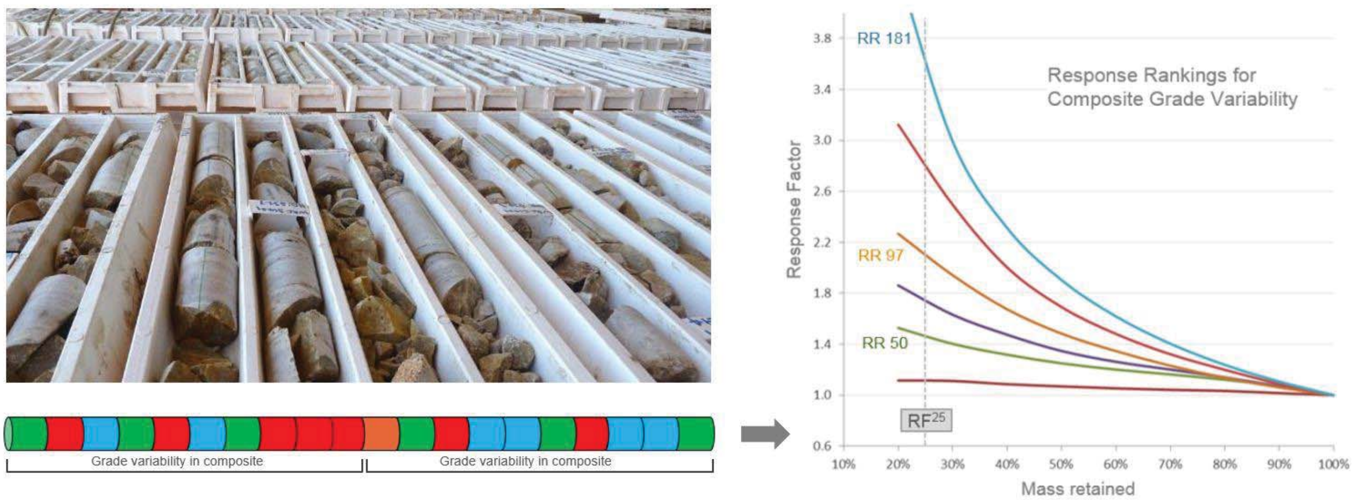

FIG 18 – Illustration of Response Factor curves for analyzing grade composites typically at ~15 meter assay composite scale to represent bench scale heterogeneity. A standardized RF^{25} Response Factor value taken at an arbitrary yield of 25% mass retained is also shown.

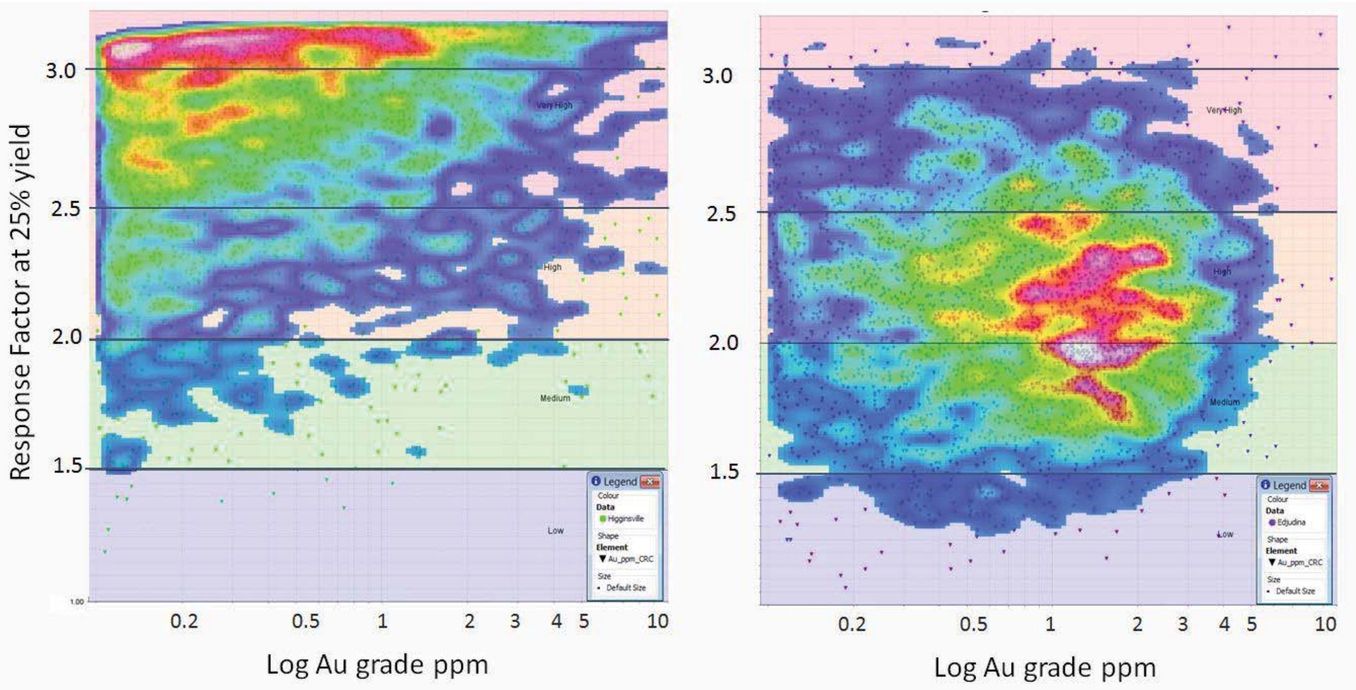

FIG 19 – Example of as a colour data density plot of composite grade versus Response Factor at a standardized yield of RF^{25} for two structurally controlled Au deposits.

resource drilling assay composites typically at ~15 meter composite scale to represent bench scale heterogeneity. Individual assays are ranked from highest to lowest to generate a Response Factor curve with a Response Factor value taken at an arbitrary yield of 25% mass retained (Figure 18). This is not meant imply an actual mass yield but serves as a useful reference point analogous to a P^{80} for describing particle size distributions. Outcomes can be rapidly applied to existing resource drilling to provide comparative benchmarking of grade heterogeneity within and between individual deposits.

An example of comparative grade heterogeneity for two Au deposits is shown in Figure 19 as a colour data density plot of composite grade versus Response Factor at a standardized yield of RF^{25}. High RF^{25} values at site specific cut-off grades is a first order local heterogeneity indicator for consideration of both differential blasting for grade and also bulk sensor based sorting. The example in Figure 19 showing much lower RF^{25} responses mainly well above cut-off grade is conceptually a less

FIG 20 – Comparative ranking of Au RF^{25} for resource drilling assay composites from a wide range of different deposits and prospects.

attractive differential blasting (and bulk sorting) opportunity.

While composite RF25 plots are a useful visualisation tool more detailed spatial analysis is undertaken to determine if exploitable heterogeneity occurs in grade ranges that can improve destination assignments based on local cut-offs and constraints. The RF25 approach is useful in enabling rapid comparative ranking that can be used to filter and prioritize operations or prospects with comparatively high responses (Figure 20).

Sensor based bulk and stream sorting

Sensor based sorting involves a wide range of potential technologies that can remotely analyze coarse material for elements and minerals of interest at detection levels and resolutions relevant to operational decision making. These include sophisticated technologies that can scan and sense surface properties in real time as well as technologies capable of rapid penetration into rock mass volumes such as shovel buckets, trucks or conveyor belts (Bamber et al, 2006a and b; Buxton and Benndorf, 2013; Cutmore et al, 1998; De Jong and Harbeck, 2005; Morrison et al, 2013; Salter and Wyatt, 1991; Wills and Napier-Munn, 2015; Wotruba, 2006).

Coarse (>10mm) bulk sorting can be defined as the ability to identify and separate pods (50-500 tons) of material involving the full ROM particle size distribution. Coarse stream sorting can be defined as the ability to identify and separate components from within a feed particle size distribution typically involving a screened fraction. A common engineering application of stream sorting involves ejection of individual particles using air jets or mechanical activators (Fickling, 2011; Kleine and Wotruba, 2010; Robben et al, 2013). Particle ejection stream sorting ideally requires a monolayer presented to the sensor, which can result in high separation efficiency but with much lower throughput compared to bulk sensor-based sorting.

The majority of innovation and market pull for on-line sensors and sorting development has been driven by the industrial recycling and food processing industry especially in Europe. This involves particle ejection of materials such as electronic scrap, plastic bottles, demolition debris and paper (Wortruba and Harbeck, 2010). The sector specific scale, volumes and mass of industrial recycling means that many of these engineering applications and capabilities have proven difficult to translate into the bulk mining industry.

Although bulk sensor based sorting is seen as a key future technology for the global base and precious metal industry (Bamber et al, 2008; Bennet et al, 2009; De Jong and Harbeck, 2005; Duffy et al, 2015) despite extensive technology development and evaluation there has been little emergence to-date of routine site implementation in the base and precious metal mining industry. More significant adoption has occurred in bulk commodities such as iron ore and cement manufacturing mainly involving on line detection of major element components for blending purposes typically implemented on feed conveyors (Kurth, 2015; Matthews and du Toit, 2014; Kruukka and Broicher, 2002).

More limited examples of routine application to base and precious metal operations include on belt analysis of Cu using Prompt Gamma Neutron Activation Analysis (PGNAA) techniques at the Sepon mine (Arena and McTiernan, 2011), on-belt sensing of Pb-Zn feed grades using PGNAA at the Mount Isa Pb-Zn-Ag mine (Patel, 2014), on-belt use of XRF for sorting Cu-PGE ores at the Mogalakwena Mine (Rule et al, 2015), use of magnetics to sort Ni-Cu ores at the Whistle Mine, Sudbury (Vatcha et al, 2000), and use of optical sorting to rework waste rock dumps on the Witwatersrand goldfield (Von Keteholdt, 2009).

Routine bulk sensor-based grade telemetry at shovel, truck or conveyor scale is conspicuously absent on the vast majority of base and precious metal bulk mining operations (Pease et al, 2015). A typical haul truck streams or displays over 200 performance attributes such as engine component wear, operator fatigue or positioning, while sophisticated dispatch systems are used to optimise dig, load and delivery cycles. However, none of these equipment performance attributes include information or related to on-line quality of payload and confirmation of grade relative to assigned delivery destination.

There is a fundamental information gap in current mining practice between shipped grade defined in the short term mine schedule and confirmed grade as received in the mill or sent elsewhere. This leads to a ‘dig and deliver’ mining culture whereby tonnage is the only measurable information attribute that can be optimised (and rewarded).

There are a wide range of existing and emerging sensor technologies that have different rock interactions and detection characteristics (Figure 21). This can result in competing vendor claims and confusion regarding optimisation for specific applications. In some cases, sensors provide proxies for the element or phase of interest such as colour or magnetics; or in other cases a direct measure of a phase of interest. Technologies capable of penetrating into rock volumes such as shovel buckets, conveyor belts or ultimately truck payloads with direct detection of the element or phase of interest represent the preferred outcome.

There are many variables involved in determining what sensor or combination of sensors can add value to Grade Engineering® coarse separation. This is a function of the nature of on-line sensor-rock interactions; designing measurement geometries for optimal sampling statistics; short time to decision; low operational detection limits: and defining net value propositions for coarse separation options (Iyakwari and Glass, 2014; Lessard et al, 2014; Nayak, 2015). Detecting pods of waste in otherwise

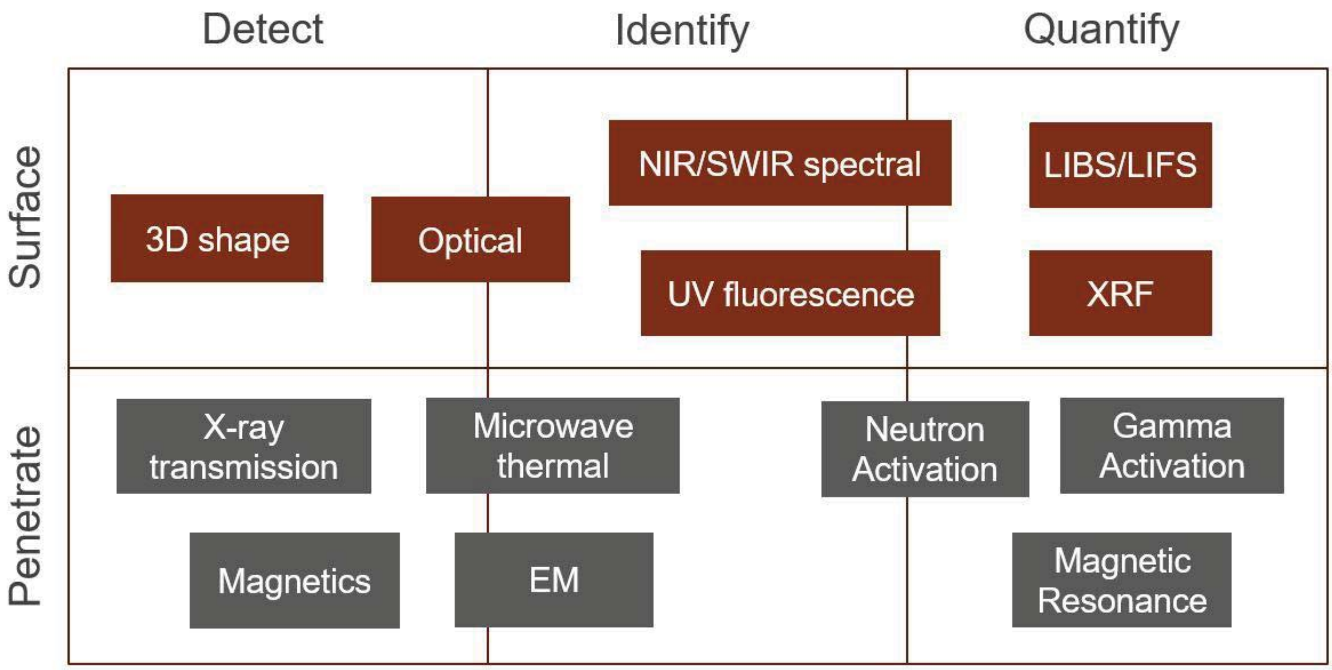

FIG 21 – Summary of main coarse rock-based sensor technologies and type of resolution.

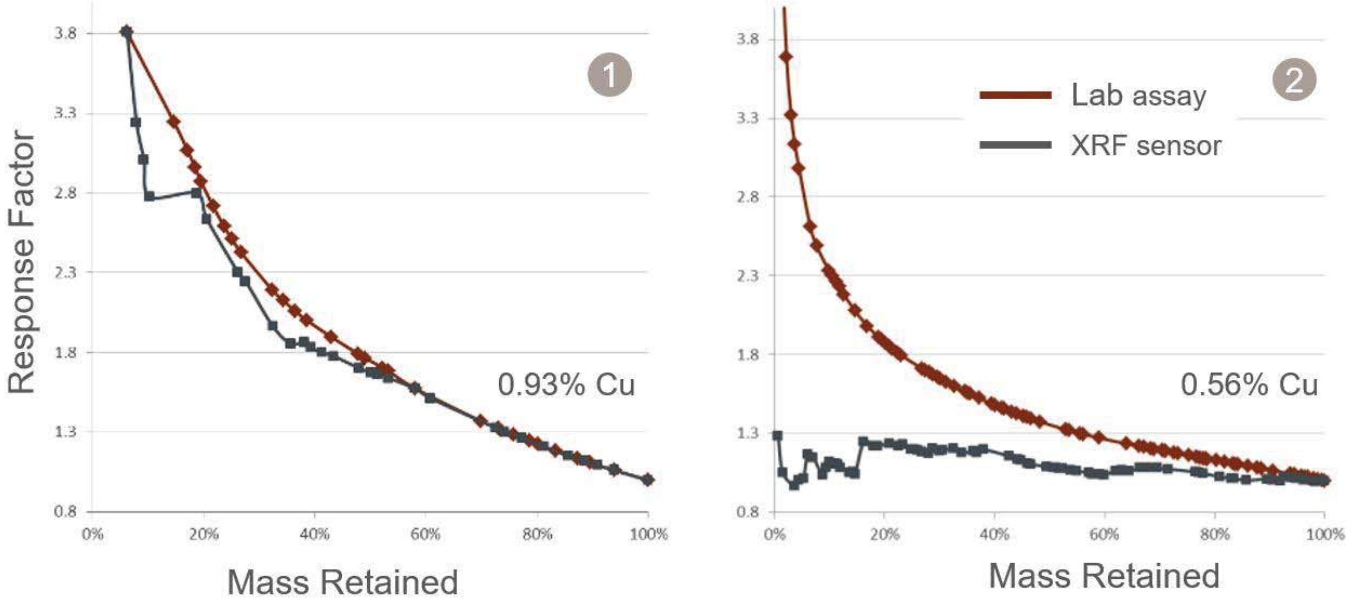

FIG 22 - Laboratory assessment of XRF particulate sorting potential for porphyry Cu ores using a screened 7.6-2.5 cm fraction. Ranked Cu grade from laboratory ICP-MS assays is compared against surface based XRF measurements of the same particles.

high grade mill feed is a different technical sensor issue from detecting pods of low versus medium grade.

Surface based sensor technologies with elemental resolution include XRF, LIFS and LIBS (Fickling, 2011; Hussain and Gondal, 2013; Lee et al, 2004; Noll, 2012; Porizka er al, 2014; Rosenwasser et al, 2001; Gaft et al, 2009). All surface based sensing techniques are strongly influenced by sampling statistics where surface responses may not be indicative of bulk composition (Iyakwari and Glass, 2014). Sampling problems are exacerbated by sensing a phase of interest with low abundance, and if there is size segregation on exposed surfaces for ores that exhibit significant preferential grade by size responses such as a concentration of fines at the bottom of conveyor belt loads.

Figure 22 show laboratory assessment of XRF particulate sorting potential for porphyry Cu ores using a screened 7.6-2.5 cm fraction. Ranked Cu grade from laboratory ICP-MS assays shows significant Response Factor curves that indicate significant opportunity for removing low grade particles if a suitable sensor based separation technology was available. The XRF curve shows Cu values determined using a hand held XRF with 4-6 spots per particle. While Sample 1 shows close correspondence indicating surface based sensing is likely to be representative, Sample 2 indicates poor correspondence indicating that surface based sensing would introduce significant decision bias.

This type of initial testing is a prerequisite for selecting surface-based techniques. However, it should be emphasized that the intent is not to replicate the precision of a laboratory analysis bur rather to determine if decision points can be created that on-average can be used to reject/accept material with a higher net value than not intervening.

More penetrative rock sensing techniques (Figure 21) capable of generating real-time information at belt or shovel scale provide improved sampling statistics. The most common sensing technology capable of providing bulk elemental analysis involves Prompt Gamma Neutron Activation Analysis (PGNAA) techniques. This can be used for both sensing of bulk fragmented volumes typically at feed belt scale (Patel, 2014; Kurth, 2015), but is also suitable for down-hole logging of in-situ rock volumes.

The most significant example of down-hole PGNAA-based logging is in routine reservoir engineering application in the petroleum industry with sophisticated mineralogy from assay calculations, and direct measurement of organic carbon and porosity (Schlumberger, 2014; Borsaru et al, 2006). Applications of down-hole PGNAA in the base metal mining industry are much more limited and generally involve demonstration of opportunity at blast hole logging scale (Charbucinski et., 2003; Charbucinski et., 2004; Trofimczyk et al, 2009).

While this work shows the technical feasibility of down hole PGNAA logging for assay, what has been lacking to-date is a clear value proposition for undertaking logging as an addition to current practice; and what decision purpose this additional higher resolution information would address. The use of higher resolution in-situ sensor-based assays at blast hole scale for enabling Grade Engineering® decisions related to amenability to bulk sorting and differential blast design based on heterogeneity indices provides a new value proposition.

Bulk sensors capable of providing direct on-line mineralogical discrimination rather than derived elemental signatures are of particular interest for advanced sensor-based separation. These include surface based near infra-red (NIR) and short-wave length infra-red (SWIR) spectral scanners that are sensitive to many mineral species such as clays, carbonates and oxides using SWIR (Dalm et al, 2014; Goetz et al, 2009; Robben et al, 2013). Accurate quantification of on-line IR-sensing data is difficult and in the majority of cases resulting sensor information is used to define comparative assemblage signatures as proxies for associated phases of direct interest, such as IR-based alteration assemblages as a guide to Cu grade in Porphyry deposits (Dalm et al, 2014).

Techniques capable of providing quantitative and penetrative discrimination of phases of direct interest represent the ultimate objective for next generation on-line bulk sensors. Use of mineral phase-specific Magnetic Resonance (MR) is an emerging sensor technology that is responsive to a range of economic sulphide species. MR response is a function of mineral lattice bonding vibrations that can provide diagnostic signatures for a range of minerals. Examples of use of MR to detect and quantify chalcopyrite in coarse bulk material and slurries (Bennet et al, 2007 and 2009), provides an indication for the emergence of next generation bulk sensing capabilities.

The wide variety of potential coarse sensor technologies and variable interaction with specific ores and mineral assemblages, coupled with potentially poor sampling issues and highly variable separation efficiencies makes comparative and cost-effective laboratory testing of yield-response challenging. This is exacerbated in Grade Engineering® where sensor-based bulk sorting is regarded as only one of a number of potential separation levers.

Selection of final coarse separation levers and circuit engineering design is a function of comparative yield-response functions for potential levers; net value after separation and handling costs are considered; a desire to reduce complexity by only selecting the minimum set of lever technologies; reduction of Capex and Opex costs for different coarse separation circuit designs; and the need to map variable yield-responses into the resource block model and resulting optimised mine schedule to determine economic parameters such as NPV and IRR (Buxton and Benndorf, 2013; Duffy et al, 2015; Lessard et al, 2014). The impact of early coarse separation on downstream processing operations also needs to be considered (Ballantyne et al, 2015). Experience of undertaking Grade Engineering® assessments to-date indicates that it should not be viewed as a ‘one size fits all’ approach with highly variable opportunities and net value related to specific ores and domains.

XRT attenuation as an indicator of mineral density - Robben et al, 2013).

In order to facilitate comparative ranking of yield-response functions across all Grade Engineering® lever assessments, the Response Factor and Response Ranking approach outlined in previous sections (Carrasco et al, 2016) can be used to visualize and analyze sensor-based sorting response (Figure 22). The RF[25] approach used to define in-situ grade heterogeneity described previously for assessing amenability for differential blasting (Figure

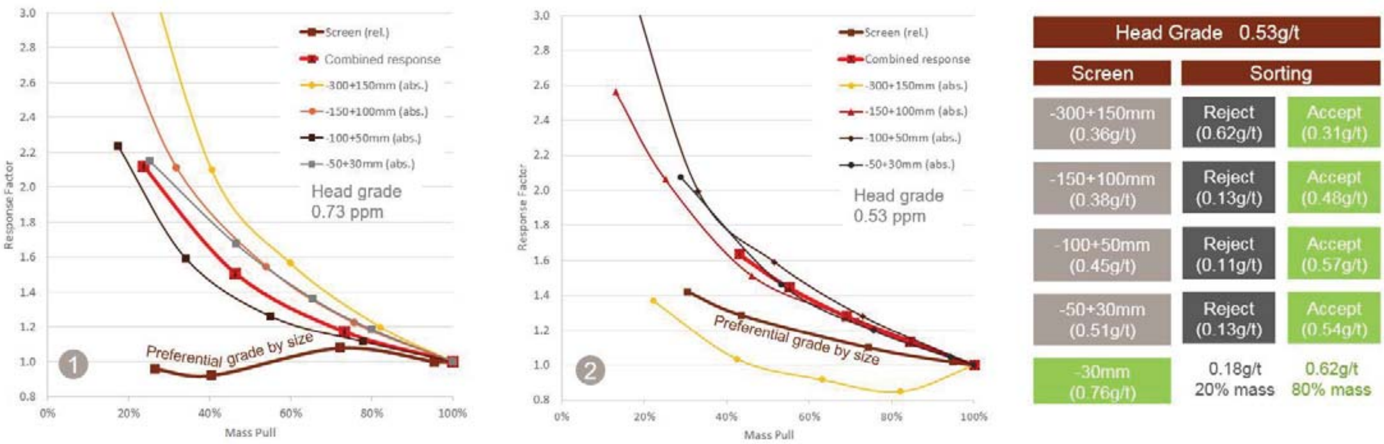

FIG 23 – An example of use of Response Factor diagrams for displaying mass balanced outcomes of multiple coarse separation levers combining XRF particulate sorting and preferential grade by size responses. Bold red line represents mass balanced combination.

Meeting this objective requires comparative yield-response functions for all coarse separation levers including sensor-based sorting that can be passed forward into simulation, modelling and design. A range of yield-response functions for sensor-based sorting laboratory and bulk-scale testing outcomes have been developed (Fourie, 2007; Altun et al, 2015; Bamber et al, 2006b; Hitch et al, 2015; Tucker et al, 2013, Wills and Napier-Munn, 2015). Variable accept/reject yields in sensor-based sorting are a function of user-defined signal thresholds or a multi-component signal algorithm. This can be a direct measure such as a primary XRF spectral peak for Cu or a discriminant function based on proxies that correlate with the element or phase of interest (e.g.

19) is also applicable to defining opportunity for applying bulk sensor-based sorting by highlighting domains of significant grade ‘mixing’ at sub-bench pod scale. In this context sensor-based bulk pod sorting using diversion and differential blasting using size induced screening are to an extent mutually competitive. Selecting the optimum lever is a function of the overall net value proposition linked to a desire to reduce complexity and Capex wherever possible.

Adoption of a routine Response Factor/Response Ranking approach also allows combinations of levers to be assessed together with mass balanced interactions. This is particularly important for stream based sorting options applied to specific screened size fractions with finer grained fractions typically bypassing sorting. As noted previously, preferential grade deportment by size attributes means that finer fractions can show significant upgrades for some ores which can be represented using Response Factors.

Figure 23 illustrates use of Response Factor for mass balancing outcomes of multiple levers. Response Factor curves are shown for two bulk samples of Cu ores tested for particulate XRF stream based sorting. After crushing ROM to 100% <300mm five size fractions were prepared to optimise XRF sorting outcomes. The <30 mm fines fraction is not suitable for particulate sorting and bypassed into a retained stream.

Particulate sensor based sorting of the four remaining size fractions results in a complex combination of accept/reject streams with accept streams combined with the fines to produce a composite accept product. Individual Response Ranking curves for each size fraction are shown together with the preferential grade by size related Response Ranking for the fines. Individual size fraction Response Ranking curves are not mass balanced and a combined response needs to be calculated to show the net benefit (bold red line). Sample 1 shows no significant preferential grade by size response whereas Sample 2 shows a moderate response. This moderate response combines with the sorting accepts to enhance final response.

Coarse gravity separation

Gravity separation involving dense media or jigging is well known and proven in the minerals industry (Abols and Grady, 2006; Murphy et al, 2013; Wallace et al, 2015; Denysschen and Wagner, 2009; Walker, 2012). One of the most significant examples is use of dense media to ‘wash’ coal and remove noncombustible impurities (Meyer and Craig, 2010). The use of coal washability curves to represent and value this upgrading approach is also well documented (e.g. Majumder and Barnwall, 2004).

Dense media separation has been applied to a wide range of applications involving precious and base metals, diamonds, coal and bulk minerals. The current four module Dense Media Plant at Mount Isa Mines (Munro et al, 1982) removes about 35 per cent of coarse and hardest Pb-Zn feed before the fine grinding treatment process. This increases throughput, reduces capital intensity in the comminution circuit, and reduces energy requirement by >40 per cent. Retained mass has a 15% upgrade. A similar one module 4 Mt/y Dense Media plant with a 30% reject rate was installed in 2012 at the McArthur River Pb-Zn mine (Wallace et al, 2015).

In Line Pressure Jig (IPJ) technology efficiently pre-concentrates ore particles using gravity separation, mechanics and fluid dynamics (Grigg and Delemontex, 2014; Murphy et al, 2013). IPJ uses less power and lower water than traditional jigs. The technology has been successfully employed on a number of diamond, base and precious metal operations and typically generates up to 30% of feed mass as a concentrate. IPJ can handle a top size up to 30mm and operates optimally between 10 mm and 200 microns. Use of IPJ requires secondary and tertiary crushing to prepare feed with a fines bypass, and relies on gangue density differential and liberation of some clean gangue at coarse size. A range of operating parameters can be used to change or fine tune performance in response to ore type variation.

Gravity separation requires tertiary crushing and screening to generate a suitable feed stream with fine fractions typically bypassing separation. This introduces a similar dynamic to stream based sensor sorting where the mass balance of all the streams and separations needs to be considered to define overall benefit. Grigg and Delemontex (2014) and

Gray et al (2011) outline the application of IPJ to the Pirquitas Ag-Zn mine in Argentina.

Ore is crushed to 100% passing -11mm with a -11+2 mm screened of as IPJ feed. The -2mm fraction shows a highly significant preferential grade by size deportment response with a Response Factor upgrade of 2.0 in 25% bypass mass equating to a Response Ranking of 100 (Figure 4) which can be fed direct to ball mill. This is combined with the upgrade related to IPJ in the coarser fraction to give an overall combined mass balanced outcome generating a Response Factor of 1.5 in 67% mass retained. Advantages included increased metal production, improved flotation recovery and lower energy intensity per unit metal produced (Gray et al, 2011).

As for sensor based stream sorting the key is to view gravity separation as one potential coarse separation lever rather than an isolated point solution and to develop an integrated approach which compares a range of possible separation fitted for specific ores and solved for value.

Delivering Integrated Grade Engineering® Solutions

Comparative Response Factors and Response Rankings for specific ores and specific separation lever technologies are key inputs into integrated Grade Engineering® assessment. These can be generated from small-scale laboratory testing using drill core, bulk testing of ores for current operations, or from modelling of existing data such as long and short-term drilling information. As for all laboratory testing protocols, scale-up factors are required to transform Grade Engineering® testing results into production scale Response (Carrasco et al, 2015 and 2016).

Resulting coarse separation Response Factors and Response Rankings need to be treated like geometallurgical attributes and interpolated into the resource block model to enable use in scheduling and optimisation (Bye, 2011; Keeney and Walters, 2011, Walters, 2009 and 2011). This can then be mapped into production schedules and operating scenarios linked to value drivers.

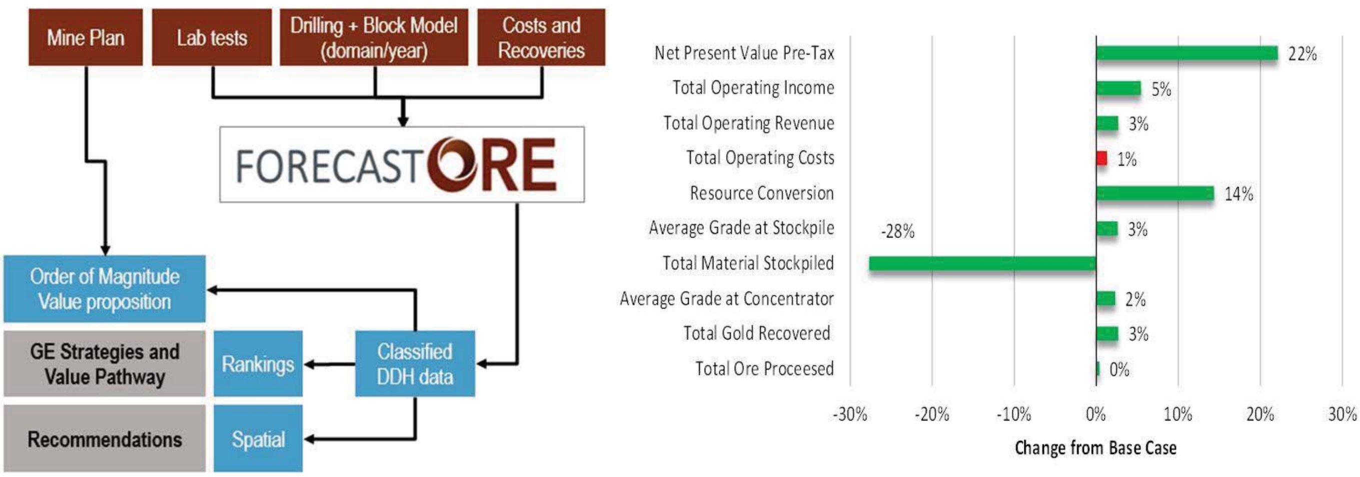

FIG 24 – Flow chart summary of initial Grade Engineering® Opportunity Assessment methodology and typical reporting of outcomes as key operational metrics.

The dynamic nature of embedding Grade Engineering® Response Rankings into resource block models, challenges current operating practice and culture. While many operations embed integrated economic value algorithms in resource models such as Net Smelter Return this is typically not dynamically manipulated, with interpolated block grade viewed as a static attribute. The tendency to smooth out grade heterogeneity in spatial interpolation statistical methodologies and use of bulk average mentalities at mining scale disguises Grade Engineering® opportunity and needs to be reinstated for integrated opportunity assessment.

The ability to generate two or more new streams at sub-block or minimum mining unit scale, with different stream destination assignments from what was previously a single destination, provides a new type of flexibility and user-defined optionality. As well as maximizing net value of resulting metal these options include addressing other production requirements such as controlling bottlenecks, maximizing use of installed capacity or reducing energy intensity.

Solving Grade Engineering® options for value over life of mine provides a business case. This is based on an updated schedule that identifies maximum value (Figure 24). Optimised outcomes are reported in standard project assessment terms such as net revenue, NPV or capital intensity. Grade Engineering® solutions should not be treated as a ‘one size fits all’ approach and need to be carefully fitted for value around individual operations and ores. The integrated and standardized approach developed by the CRC ORE consortium is designed to support fitting for value.

CONCLUSIONS

The concept of using coarse separation or ‘beneficiation’ to improve feed grades and capital intensity in the mine to mill ‘dig and deliver’ interface is not new but requires next generation innovation and disruptive thinking to become a routine industry approach.

Grade Engineering® is an emerging integrated approach to coarse rejection that matches a suite of separation technologies to ore specific characteristics and compares the net value of rejecting low value components in current feed streams to existing mine plans as part of a system-view. It has been designed in collaboration with a consortium of miners, METS and research associations to counter over reliance on throughput which became the dominant operating culture during the Millennium Super-Cycle of commodity pricing. This contributed to a decline in productivity and return on investment which challenges the minerals industry in the current price cycle. Grade Engineering® represents a return to feed Quality in combination with feed Quantity as primary drivers of operational excellence focused on the value-chain,

Standardized Response Rankings based on five rock-based separation levers which drive Grade Engineering® opportunity offer an alternative approach to ‘unpacking’ heterogeneity at block scale. The best analogy for the operational and cultural change required to embrace Grade Engineering® methodologies is a modern containerized freight depot which rival mining operations in terms of volume. Containers with a mixed manifest are sent to intermediate freight depots where they are unpacked and delivered to the appropriate end customers. There is no such thing as an average value in a freight container manifest and unpacking requires sophisticated tracking and dispatch systems.

Grade Engineering® opportunity is a dynamic function with a high level of optionality. Implementation scenarios depend on the maturity and stage of individual operations, with outcomes customized to site and corporate objectives. A key metric is improving net value per unit metal produced rather than simply increasing overall metal production. This can include the need to improve capital intensity or reduce energy and water consumption on a unit metal basis.

Embracing Grade Engineering® opportunities challenges traditional operating concepts and cultures. In many cases the technology required to support Grade Engineering® outcomes already exists in other sectors, or involves point solutions that have not been integrated into overall system-value. While Grade Engineering® represents an emerging approach, the potential benefits identified in site applications to-date indicate significant transformational opportunities for many current operations and stalled feasibility projects.

ACKNOWLEDGEMENTS

The ongoing development of Grade Engineering® within CRC ORE has involved a collaborative team effort across a wide range of disciplines. Inputs and support from Alan Bye, Luke Keeney, Pat Walters, Cristian Carrasco, Michael Scott and Carlos Espejel during initial development are particularly appreciated. CRC ORE is supported by over 30 mining, METS and research organisations (www.crcore.org.au) and approval to publish is gratefully acknowledged. Grade Engineering® has been enabled by unprecedented access to mining operations, production data and constrained sampling programs in collaboration with CRC ORE participants.

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