Scenario-based Project Evaluation – Full Mineral Value Chain Stochastic Simulation to Evaluate Development and Operational Alternatives

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ABSTRACT

The variability and uncertainty of mineralisation, coupled with subsequent uncertainty in mining and processing, is often paid scant regard or overlooked during the evaluation of mining projects. In many instances, when the project transitions to the operational phase, the reality of feed or product variability and the consequences of unquantified uncertainties throughout the value chain become obvious. The outcome is the familiar picture of frequent ramp-up underperformance and failure to deliver on planned targets and objectives.

Both mine and exploration geologists are expected to generate mineral deposit models that are based on an integration of diverse sources of data. These multifaceted deposit models already play a pivotal role in the design, development and optimisation of mining project value, and the trend to a fully digitally engineered future means that this importance is increasing. It is therefore vitally important that tools be made available to the geologist (as well as mining engineers and metallurgists) that enable them to characterise and assess variability and uncertainty via appropriate deposit models and thus articulate their impact on potential project configurations and decisions. Scenario-based project evaluation (SBPE) provides a framework for full and proper analysis of the downstream impacts of inherent deposit variability and uncertainty on project performance.

SBPE has been developed by the authors over several years and aims to propagate geological uncertainty and variability through the mining value chain. The outcomes of SBPE can be tested against future external scenarios capturing financial, economic and socio-political factors that also drive project performance. Stochastic representations of the orebody (via conditional simulation (see Chilès and Delfiner, 1999)) that explicitly incorporate variability and represent uncertainty are propagated through the value chain on a block-by-block basis (ie on a much more granular basis than traditional project evaluation approaches).

Conventionally, metallurgical processes are modelled with deterministic equations (eg regression models) based on limited data. The SBPE approach allows for the modelling of process performance uncertainty using geometallurgical sampling fully. Multiple outcomes of SBPE are passed through financial modelling, which can also incorporate stochastic components, thus allowing full quantification of the risks and opportunities of a set of project alternatives. The value of the SBPE system is that once a base case has been established, multiple engineered alternatives coupled with external scenarios are easily evaluated and compared in terms of incremental value.

A new case study of SBPE is presented that shows how, by analysis of the various aspects of variability and uncertainty, project managers are able to focus on the areas that have the greatest ability to reduce risk and/or add significant value. This can lead to sufficient flexibility being built into operations that allow operators to cope with the real orebody delivered to the plant.

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INTRODUCTION

In the past two decades or more, many mineral project start-ups have failed to meet metrics set during the project evaluation and construction phase (Mackey and Nesset, 2003). This underperformance and misspecification of capital for mining projects can be at least partly attributed to failure to take full account of orebody variability and uncertainty related to sparse drilling and sampling information. Often, a single static view of the project is presented and subsequently 'taken as gospel'. For example, evaluations are commonly based on singular, smoothed orebody estimates that ignore the inherent variability and uncertainty of mineralisation and the effect that this may have on subsequent processes. This understatement of spatial variability and uncertainty of mineralisation (Bye, 2011) may have critical negative impacts on the mining, blending and processing steps. In addition, many steps in project evaluation involve further averaging of values over time (eg averaging mine planning or processing steps over annual or, at best, quarterly increments), which leads to additional smoothing and can further distort predicted engineering and financial project performance.

Previous publications by the authors (eg Vann and Bye, 2012; Vann *et al*, 2012, 2014) have argued that a change in thinking and the approach to project evaluation in the mining industry is necessary to improve value delivery, and that this necessitates proper characterisation of uncertainty and spatial variability of the mineralisation. Doing so will keep these critical aspects 'on the agenda' throughout the project evaluation process in contrast to most current processes, which explicitly and erroneously assume that there is no uncertainty and that variability is far lower than will be encountered in reality.

In the paradigm shift proposed, approaches to project evaluation transform to become fully informed by resource uncertainty and variability.

Project teams are moving from thinking in terms of sensitivity analysis (flexing parameters) to thinking in terms of evaluating multiple project engineering configurations with embedded uncertainty and realistic variability throughout the proposed value chain. We use the term 'value chain' (Porter, 1985) to describe the full mineral project system, from the *in situ* mineralisation through to the product sold and resultant cash flows. The proposed approach has been called scenario-based project evaluation (SBPE) (Vann *et al*, 2014) and it consists of *full mineral value chain stochastic simulation to evaluate development and operational 'alternatives'*. We discuss this concept later in this paper, and the reader is also referred to Vann *et al* (2014) for a complete description of the approach.

In this updated presentation of SBPE, we focus on several specific benefits of the approach and illustrate these via a case study on a mining project. The case study presented here is from a silver-lead-zinc project in Mexico and highlights that better understanding of uncertainty and variability can have potentially significant impacts on decreasing project risk and thus improving project decision-making.

Full implementation of SBPE ideally includes the consideration of uncertainty associated with external project drivers (or 'externalities'), which are aspects of the future project environment that engineers and planners cannot control. Examples of externalities are economic, market, environmental and social factors. It has been argued previously (Vann *et al*, 2014) that externalities are best captured via scenario planning approaches (see van der Heijden, 2005; van der Heijden *et al*, 2010). This new paper does not deal with externalities and scenario planning *per se*, but rather focuses on aspects of project configuration that can be specified by engineers (eg planning, infrastructure and technology choices etc) and specifically how these are impacted by mineralisation variability. The important link between SBPE and scenario planning (or 'scenario thinking') is that it can be used as a strategic filter to further evaluate the outputs of SBPE.

SCENARIO-BASED PROJECT VALUATION

Conventional evaluation of metalliferous mineral deposits uses estimates of economic and deleterious grades (herein 'attributes') in singular 'orebody models', usually a 3D kriged block model (Chilès and Delfiner, 1999). These models fail to capture two critical aspects that underpin the realised value of mining projects:

1. the inherent *uncertainty* of the estimated attributes and the processes they are subject to
2. the inherent spatial *variability* of attributes, at the scale of mining selection, which impact on downstream processing steps and fundamentally drive realised value (see Figure 1 for a schematic of the conventional approach).

As an aside, it is important to understand that while we discuss SBPE in the context of metalliferous mineral deposits, the ideas are equally applicable to non-metalliferous bulk commodities such as coal and phosphates. The application of SBPE for bulk mining commodities (including iron ore) requires consideration of a different set of constraints and options, and in particular will often utilise different objective functions. For example, in base and precious metals, an objective function might be to maximise grade early in a project through declining cut-off grade strategies. However, in bulk commodities, there is often a multivariate product quality objective function, and the aim is to maximise product that meets these criteria over the longest possible production horizon. To date, there have been applications of SBPE on base metals, precious metals, uranium, coal and iron ore projects.

The first phase of any SBPE project requires the configuration of a 'base case model' that incorporates mineralisation variability and allows block-by-block processing through the value chain. Instead of using a smoothed, kriged model of the

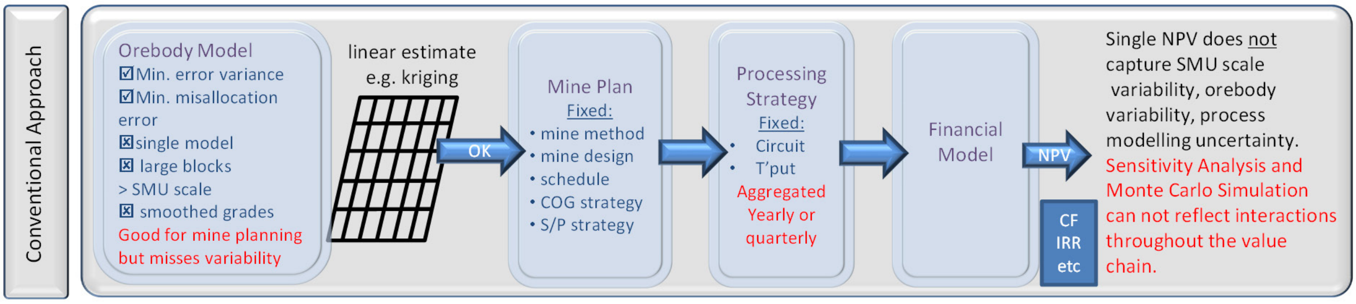


FIG 1 – Schematic of conventional approach to project evaluation.

orebody, a large number (say 50–100) conditional simulation realisations are evaluated (for details on geostatistical simulations, see Chilès and Delfiner, 1999). The final output result of SBPE is a distribution of each of the important project metrics (eg final products, metal, net present value (NPV), annual cash flows etc) that realistically reflects input mineralisation variability and reduces the influences of smoothing due to the aggregation of material to yearly and quarterly volumes (see Figure 2).

The configuration phase of an SBPE project often requires the most time and effort and provides the project team with a very useful active audit of critical project inputs, such as mine planning.

The final stage of SBPE is where a number of alternatives, iterations and scenarios can be tested. These terms are defined as follows (see also Vann *et al*, 2014):

- *Alternatives* – These are distinctly different configurations of the project that is being evaluated. Differences between alternatives are centred on engineering decisions over which the project team has complete control. Examples include mining method, stockpile configurations, different processing circuits and different throughputs. By carefully choosing a set of alternatives, the successive differences between them allows for the evaluation of incremental value of project options. All engineering alternatives should be properly costed.
- *Realisations* – These are the individual outputs of a conditional simulation. They are unsmoothed and capture realistic variability of the mineralisation, as previously discussed. They are multiple representations of the orebody that quantify the variability and uncertainty and honour the input data and known statistics. A set of realisations (say 50–100) constitutes a conditional simulation model and collectively captures uncertainty.
- *Iterations* – These are multiple representations of metallurgical process modelling, collectively capturing uncertainty on processing steps. Often, process models are single regressions (thus deterministic functions) based on very limited data. Numerous plausible process (mining and plant) functions can be modelled and evaluated in SBPE, allowing stochastic consideration of processing steps.
- *Scenarios* – These are a limited set of future contexts in which the project will operate. The values of external parameters over which the project team has no control are required to be consistent with the scenario logic. Parameters include metal prices, exchange rates, tax regimes, royalties, costs and cost of capital.

The overarching outcome of the SBPE process, as described previously, is a much richer and more realistic understanding of the major risks that impact on the project outcome and the uncovering of opportunities for material improvements in project outcomes. This is because these risks are largely driven by the uncertainties and variability that is explicitly captured by SBPE.

CASE STUDY BACKGROUND

Deposit geology

The case study is based on a silver-lead-zinc (Ag-Pb-Zn) deposit. It is planned to mine this deposit using open cut methods and process it through a plant consisting of a crushing/milling circuit, a lead flotation plant and a leach circuit. The mine will produce a lead concentrate, a zinc concentrate and silver doré. After the feasibility study for the project was completed, the owner's team recognised that the project was sensitive to various inputs and assumptions and sought to quantify the risks to the project. Note that various project metrics (eg grades, tonnages, NPV) have been altered or disguised in this case study for confidentiality reasons.

The Ag-Pb-Zn mineralisation is associated with a felsic igneous complex. The complex is emplaced into a sequence of intermediate felsic volcaniclastic and pyroclastic sediments that are interpreted to have been deposited in a marine sedimentary basin.

Mineralisation is represented by an aerially-restricted but vertically-extensive zone of disseminated sulfides and sulfidic veinlets, as well as strata-bound massive replacement mineralisation.

During weathering, metals of economic interest were variably mobilised and re-distributed into secondary minerals that formed under supergene conditions. The characterisation and spatial mapping of the degree of oxidation impacts significantly on the processing of the ore.

Mining and treatment

The project plans to operate several starter open pits that will, over time, coalesce into one large open pit. Due to topographic constraints, the ability to stockpile subgrade material is limited, and primary crushing will be carried out on a campaign basis to minimise capital cost. As a consequence, the mine plan has been designed to produce sequential batches of material that will either be directly leached or subject to froth flotation prior to leaching. The target grind size will be adjusted for each type of material, which creates different throughput rates for each material type.

The main drivers of metallurgical recovery are the grades of the key metals and the oxidation state.

Financial model

The financial model was based on a feasibility study that included numerous inputs and forecasts for costs and revenues. Importantly, this model used an activity-based costing model to derive a net smelter return (NSR) for each block. The details of this approach are similar to those

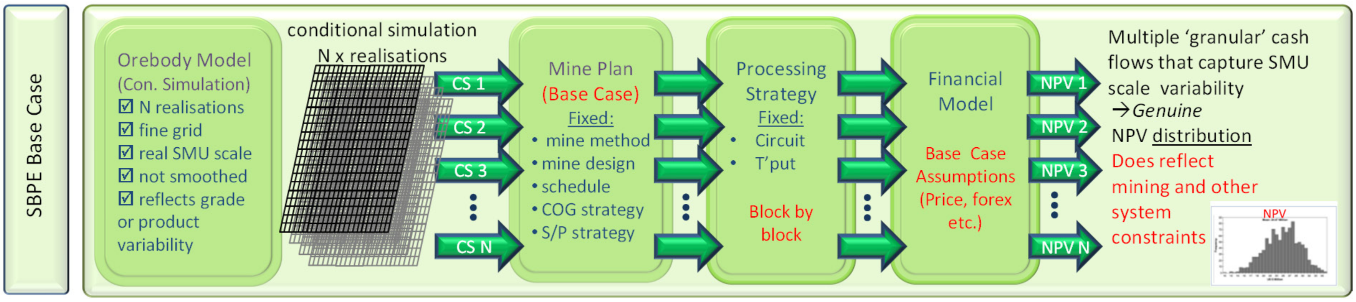
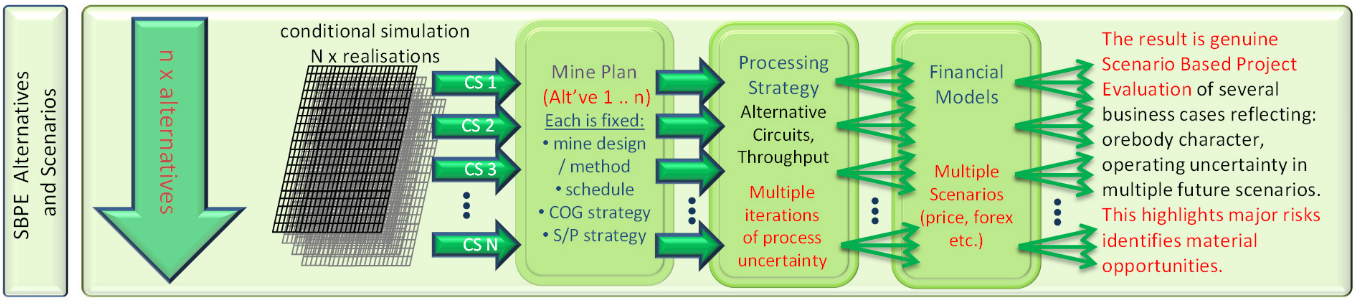


FIG 2 – Schematic of base case of the scenario-based project evaluation approach to project evaluation.



The result is genuine Scenario Based Project Evaluation of several business cases reflecting: orebody character, operating uncertainty in multiple future scenarios. This highlights major risks identifies material opportunities.

FIG 3 – Schematic of alternatives, iterations and scenarios applied to scenario-based project evaluation base case.

described in Goldie and Tredger (1991), and it assigned a $/t contribution to *in situ* material based on all of the on-mine and off-mine metal realisation costs, as well as the expected recovery of the multiple metals to multiple products.

In implementation for the case study presented here, the NSR calculation was used to allocate the ideal mining destination for each block (direct leach, two product flotation, two product flotation followed by leaching or waste). This required that the net contribution for each block be calculated for each potential processing pathway, with the assigned 'desired' route based on the route that returns the highest net contribution. When the value chain is simulated using SBPE, the actual processing route may, in some cases, differ from the ideal route due to dynamic process plant constraints (availability, mass balance, batch process time etc).

SMOOTHING THROUGH THE VALUE CHAIN

One of the pitfalls of the conventional approach to project evaluation is 'double smoothing'. Vann *et al* (2012) defined 'double smoothing' as the use of smoothed resource models (ie singular kriged block models as previously discussed), combined with the industry standard practice of averaging processing inputs into annualised (or, at best, quarterly) increments for evaluation purposes.

Double smoothing will impact on subsequent mine scheduling and the prediction of actual processing performance. Over relevant shorter time periods (eg quarters, months or weeks), such double smoothing can produce knock-on effects on the overall achievability of the mine schedule. The end result is that projects evaluated using conventional approaches, which are based on such double smoothing, will have operational ore grades, material type attributes (eg ore hardness or deleterious clays), product quality attributes and ultimately cash flows that fluctuate more appreciably than predicted. The predictions of ore grades, material type attributes, product quality attributes and cash flows may also be materially biased when built on such 'doubly-smoothed models'.

Double smoothing has impacts for variables other than the key economic grades. The variability of non-revenue attributes can also have very significant operational and financial implications that can be captured in SBPE. Take the example of highly spatially-variable deleterious content of base metal mineralisation, which could cause reduced fluid percolation in a heap leach operation, suppress flotation performance or negatively impact the quality of shipped concentrate. Being unaware of these impacts could severely bias evaluation. There are many examples of this happening in the mining industry. For example, base metal mines where deleterious components of concentrates are out of specification periodically (but were predicted to be consistently 'in control' by the evaluation study). This may require accumulation and blending of concentrates over lengthy periods and thus delay cash flows. The impacts can be severely stressful, especially in the ramp up phase of projects.

The dampening of predicted variability due to double smoothing will necessarily impact on the choice and design of capital infrastructure such as mining fleet, stockpile capacity, screening and blending systems and processing technologies. Many billions of dollars are tied up in such decisions, and making them on the basis of project evaluations that are devoid of realistic variability assumptions is arguably negligent.

The ultimate consequence of double smoothing is that the risk of project underperformance or failure is much higher than was perceived during the evaluation phase. This is often not fully communicated to managers and executives evaluating the performance of potential mining projects, and, where variability is high, may have material financial and operational impacts. Now that the means for better evaluation are available, it is incumbent upon the project team to ensure that these aspects are properly evaluated and communicated up and across the organisation.

Importantly, the understatement of deposit variability and its impacts through the value chain not only exposes us to downside risks, it also increases the chances of missing important upside opportunities. For example, the opportunity to increase cash flow by exploiting the aforementioned variability of deleterious grades in a base metal mine to change mine planning strategies such that concentrates can be shipped within specifications without value-destructive blending (Bye, 2011).

An example of double smoothing on the Ag-Pb-Zn case study

In the case study, the original project evaluation was carried out by calculating a NSR for each block. The NSR takes into account costs, prices and metallurgical recoveries for each stage of flotation (roughers and cleaners etc). To demonstrate the impact of aggregating large volumes equating to annual or quarterly production periods on the project outcome (ie double smoothing), deliberately smoothed cases were generated using the original 3D block model data. Note that the comparison here is between a kriged block model (ie smoothed) and aggregations of these kriged blocks into quarterly and annual increments. This process is testing only the second part of the double smoothing (the step typical in evaluation of mineral processing responses for example). The impact would be more severe if we compared the aggregated quarterly and annual increments to blocks from a conditional simulation (ie to unsmoothed deposit modelling at block scale).

The exercise involved the following steps:

- Calculate the average grade of each revenue metal (Ag, Pb, Zn) from the kriged block model over annual and quarterly volumes in the schedule. So now, each block in a given year or quarter has the same grade (ie the average annual or quarterly grade).

- Recalculate the metal quantities coming out of the plant after using the average annual or quarterly grades through the various process recovery equations (30 equations in total).
- Re-run the financial model for each case.

Figure 4 shows the raw grades of ore mined in year nine of the operations with two distinct grade zones. Figure 4B, with uniform grades is how it is evaluated. This demonstrates the reality of the double smoothing step and that the impact of such an aggregating decision cannot be ignored.

Table 1 summarises the result of SBPE with financial modelling for the three models, ie:

1. granular kriged model
2. aggregated to quarterly increments
3. aggregated to annual increments.

Overall, the difference in NPV between these models is less than ten per cent. However, period-by-period analysis shows that there are some very significant differences between the financial predictions of a kriged model (recall that this is 'single smoothed') and a double-smoothed (quarterly or annual) model. For example, in year nine, the quantity of silver from the plant (float leach and also direct leach in total) went from 7.76 Moz in the block-by-block analysis to 5.78 Moz (-26 per cent) when aggregated quarterly and 5.46 Moz (-30 per cent) when aggregated annually. Interestingly (and logically when the impact of the geostatistical notion of volume-variance effect is considered), the first step of double smoothing – from kriged blocks to aggregated quarters – reduces the variability far more than the step from quarters to annual increments. Note also that the effect does not necessarily lead to underestimation. We may overestimate metal delivery and thus project economics in some cases in other years (see period 16 in Figure 5). It is important to understand that the periods with the greatest variability are more likely to generate a bias during the averaging process due to the non-linear nature of the recovery functions applied.

TABLE 1

Summary of Ag production and impact on net present value for kriged model versus quarterly and annual ('double smoothed') aggregated models.

	Kriged	Quarterly	Annual
Reserved mined (mt)	118.7	118.7	118.7
Doré from plant (Moz)	93.4	91.2	91.2
Net present value ($M)	1092	966	954

THE IMPACT OF VARIABILITY

The concept of variability is critical in the rationale for adopting an SBPE approach and thus warrants further discussion. 'Variability' denotes fluctuations in successive values either in space ('spatial variability') or time ('temporal variability'). In SBPE, spatial variability in the mineral deposit models is transferred to variability in subsequent steps of the value chain via 'transfer functions'.

Variability must be contrasted with the concept of uncertainty, which denotes any situation or value for which there is incomplete knowledge, and therefore where there is a requirement to use distributions rather than single point values. The contrast between variability and uncertainty can be summed up thus:

> *…variability is a phenomenon in the physical world to be measured, analysed and where appropriate explained. By contrast, uncertainty is an aspect of knowledge.* (Sir David Cox, quoted in Vose, 2008, p 47.)

As previously discussed, the conventional input for the evaluation of mineral projects has been a kriged estimate of grades (and possibly other attributes) in a singular 3D block model. Such models, even when estimated using best-practice kriging approaches, fail to capture the two aspects

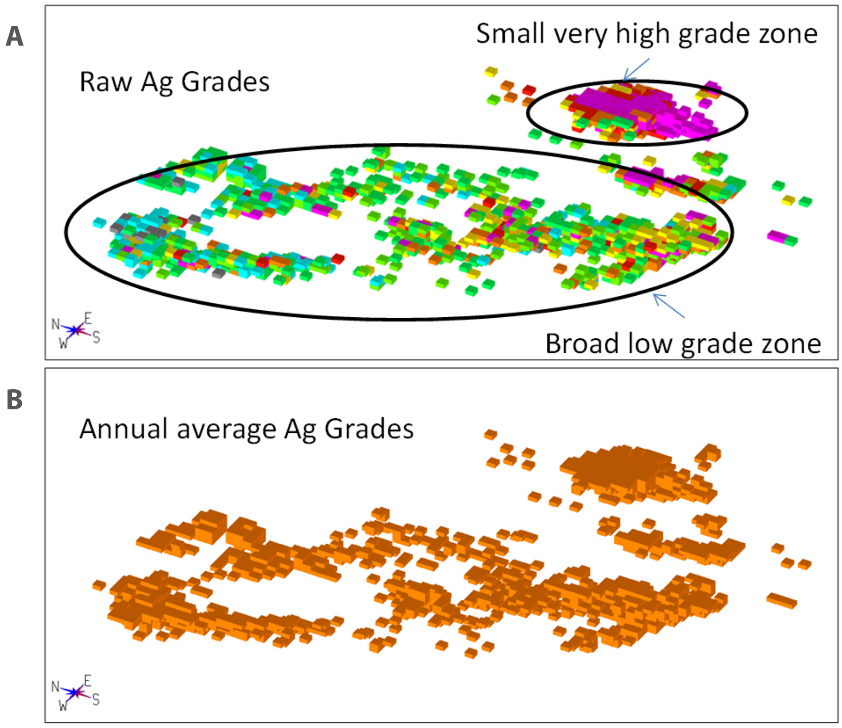


FIG 4 – Oblique view of (A) raw Ag grades for ore mined in year nine compared to (B) what the evaluation sees if annual increments are used.

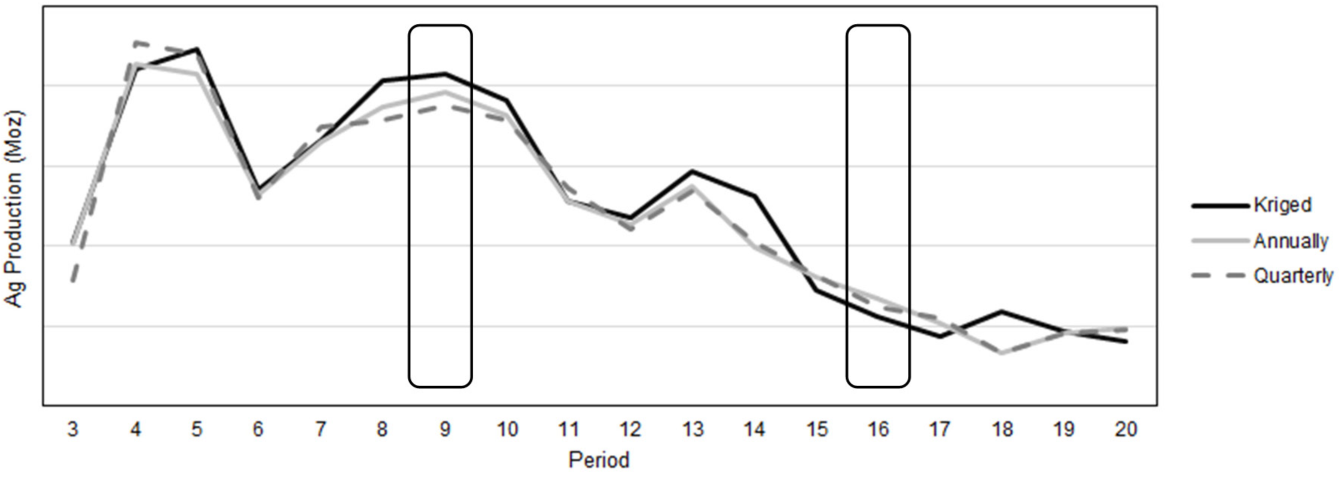


FIG 5 – Annual Ag production profile using raw kriged grades, quarterly averaged grades and annually averaged grades.

of mineralisation attributes critical to evaluation defined previously:

1. Uncertainty on the estimated attributes, which is only reducible to a certain degree (by taking better and closer spaced samples, by improved geological understanding etc). Ultimately, there is always irreducible and non-negligible uncertainty on the estimated variables in a block model (Kleingeld and Nicholas, 2004). This is why it is called 'an estimate'.
2. Spatial variability of attributes at the scale of mining selection (or in geostatistical terminology, at selective mining unit (SMU) scale). The properties of kriged block estimates (especially the lack of conditional bias) that make them suitable for long-term planning are obtained at the expense of unavoidable smoothing. However, these same desirable properties lead to potentially very significant understatement of the impact of spatial variability at shorter time scales.

These two limitations of the usual kriged input models contribute to the distortion of subsequent project evaluation. Note that while the illustration of the impact of smoothing given previously showed material financial bias, it understates the impact because the references that the quarterly and annual increments were compared to were kriged, and thus have the smoothing problem outlined previously.

Kriging models are 'singular' in the sense that they store a single value per block. They do not allow for a range of possible values in each block and therefore do not model uncertainty. In fact, by itself, a kriged model as an input to project evaluation is making an implicit (and utterly unwarranted) assumption that there is no uncertainty. Hence, the traditional approach is to attempt to allow for this uncertainty by 'sensitivity' analysis (ie the flexing of end results in an arbitrary manner).

In conclusion, the use of singular smoothed models as inputs is a potentially severe limitation in the project evaluation process when key attributes have significant uncertainty and/or variability that will interact with constraints in the system. It is further compounded by the double smoothing step of subsequent aggregation in the modelling of processing.

Case study of variability through the value chain

As noted previously, one of the primary drivers of the value of mining projects (and concomitantly, potential source of value destruction) lies in the spatial variability of the input mineralisation and the propagation of this variability through the subsequent steps. Using conditional simulation is an alternative to kriging that generates multiple, stochastic realisations of the grades (and possibly other non-grade attributes) that can be:

- *Considered as a set* – generate plausible distributions of values. This is true at any scale, from an entire domain down to an individual SMU block for which we will have say 50 or 100 values forming a distribution of grades that is consistent with the known input statistical and geostatistical characteristics.
- *Considered individually* – each single realisation will reflect the realistic, unsmoothed variability of grades, which is again consistent with the known statistical and geostatistical characteristics of the deposit (or domain).

In our case study, a method called direct block simulation (Marcotte, 1993) was used for the Ag variable only, which was the dominant economic driver for the deposit.

A full conditional simulation model comprising 50 realisations, as well as the kriged model (ie a total of 51 models), were loaded into a bespoke SQL database and evaluation platform. The same project assumptions, constraints and transfer functions (describing metallurgical recovery and ultimately NSR, for example) were applied to each of the 51 resulting models. Because block-by-block Ag head grade differs in each realisation of the simulation, the NSR calculation needed to be re-run for each block in each realisation. The value chain modelling, including all transfer functions and the financial model, were therefore re-run for each realisation (and the kriged model).

Figure 6 shows the average Ag grade (ppm) per annual mining period with a cut-off applied (block NSR value >0). Figure 6 shows the impact of the non-linear NSR functions on the selection of blocks from the values derived from the realisations. The variation range is significant in most periods. The most important point is that the kriged result is not the central estimate for many time periods. This is as a result of the non-linearity of the transfer functions combined with the impact of variability.

Figure 7 shows Ag doré produced per year. There are significant variations in some periods, especially in the first ten years. Again, the kriged prediction is not a central estimate over many subperiods of the schedule, highlighting the advantages of using the SBPE approach.

Another outcome of using the simulation realisations as opposed to (ordinary) kriged grades is that material selection

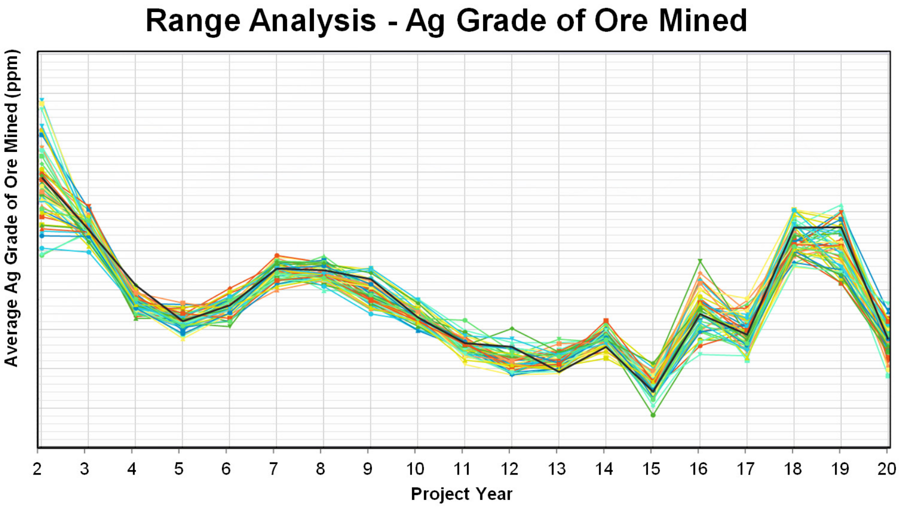


FIG 6 – Plot of average Ag grade per annual mining period from each of the 50 realisations and from the kriged model (dark) with net smelter return>0.

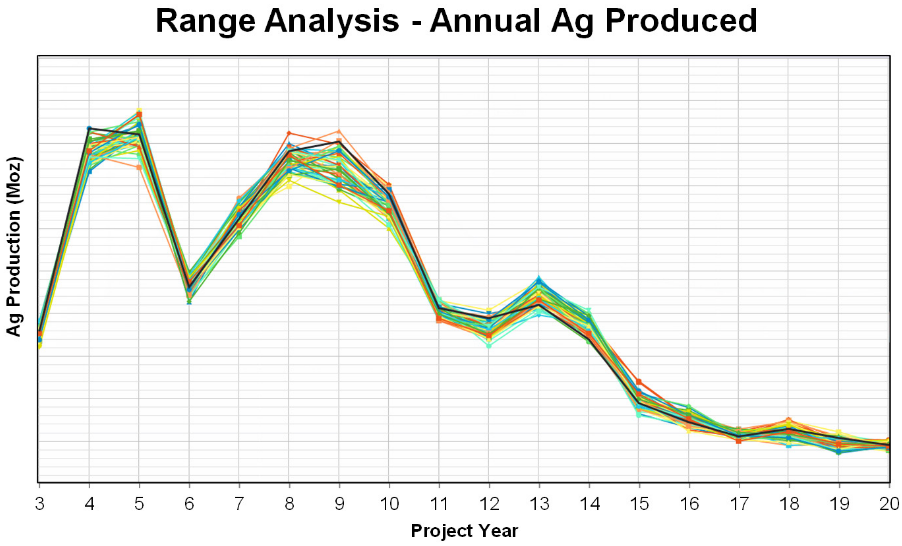


FIG 7 – Plot of the tonnes of Ag doré produced per annum from each of 50 realisations and from the kriged model (dark).

is based on a different grade tonnage curve. Ordinary kriging (OK) is a linear estimate, whereas a collective set of simulation realisations constitutes a non-linear ('recoverable resource') estimate akin to a multiple indicator kriged estimate or uniform conditioning estimate. This means that the grade tonnage curves resulting from the simulations are more realistic than those from the OK. For example, this is especially marked in positively-skewed distributions such as silver, where greater grade variability (in simulations) is likely to result in the selection of less tonnes at a higher grade compared to the same volume selected using the kriged results. This has the effect of bringing planned metal production forward in this instance.

UNCERTAINTY THROUGH THE VALUE CHAIN

'Essentially, all models are wrong, but some are useful' (Box and Draper, 1987). In this sense, the 'wrongness' of the model that Box and Draper alluded to can be thought of as 'model uncertainty'. Therefore, it is critical that in any model we are able to characterise this, preferably in a quantitative manner (ie the uncertainty that is associated with model outputs (predictions)). The detection of potential biasing effects of the interaction between sources of uncertainty and the constraints in the system is especially important.

The specific forms of uncertainty considered in this section include:

1. uncertainties that arise from an inability to acquire exhaustive data (on grades and other geochemistry, mineralogy and other primary geological attributes) from the mineralisation itself
2. those arising from an inability to obtain complete information regarding the subsequent performance of the mining and metallurgical processes.

Of these, point 1 is related to a fundamental and irreducible problem: we cannot 'mine the deposit with a drill rig'. We can collect more data in staged campaigns through to ultimately grade control levels of drilling, but there is irreducible residual uncertainty even in the closest economically-viable drilling pattern. Uncertainty on the mining and processing performance (point 2) can also, ultimately, not be reduced to zero. However, as the industrial internet becomes fully operational in coming years, the uncertainty on many (but not all) processes will start to fall dramatically.

It is clear that to realise the full benefit of the systems approach that we are championing (SBPE), the uncertainty present in all critical inputs must be taken into account. This in turn requires stochastic models of the orebody and of mining processes and mineral processing.

In mining, the critical step of blasting constitutes the first step in the processing system, and there are various approaches proposed to the simulation of blasting fragmentation, movement dynamics etc. Modern approaches now include sophisticated use of physics engines to give realistic outcomes for movement and settling of blasted materials (Onderra *et al*, 2013). In concept, this can be incorporated into the stochastic modelling of these critical steps. However, we have not yet progressed SBPE to this point.

There are several options available to incorporate uncertainty in metallurgical processes. The objective in SBPE is to link this uncertainty to the variability of the mineralisation characteristics. The evolution of the field of geometallurgy (Bye, 2001; Dunham and Vann, 2012) points towards deposit models containing a higher number of attributes that can be used to predict process response to orebody characteristics. These variables should be primary attributes of the rocks rather than processing responses of the metallurgical engineering system (see Coward *et al*, 2009). The authors argue that prediction of granular metallurgical responses to fundamental rock properties (which is the ultimate objective of geometallurgy) is best achieved by modelling the responses via transfer functions rather than, for example, 'kriging the recovery' or 'kriging the NSR' directly. This is because most transfer functions are, as alluded to previously, non-linear and frequently have embedded uncertainty. As a consequence, simple linear averaging of response variables risks material biases of the type shown in our case previously.

In an ideal world, sufficient samples for all material types would be tested at full operational scale to obtain a full characterisation of the relevant primary-response relationships. In reality, process responses are usually modelled on a relatively small number of laboratory tests, where grades of the head feed are the input variables and a limited number of output process responses are modelled.

Process simulation of an operating plant requires the use of calibrated unit process models. A common approach is the use of 'population balance models', where the mass of material in the circuit is maintained (Napier-Munn *et al*, 1999; King, 2001). These approaches are computationally intensive and are currently unrealistic to run for every block, when block models typically contain hundreds of thousands to millions of blocks.

Case study example of the impact of process uncertainty

The approach suggested for use in SBPE by the authors is to model the relationship between input primary attributes and the process responses of interest (Coward *et al*, 2009). Pragmatically, these can often be reasonably modelled by linear ($y = mx + c$) or second-order quadratic functions. Fitting these parameters is more generically known as parameterisation of inverse problems (Tarantola, 2005).

In the following case study, the lead flotation circuit process was modelled from results of a number of test samples treated at laboratory scale. Figure 8 shows the recovery of Pb in Pb rougher concentrate measured in test samples (shown as diamonds in Figure 8), the base case recovery model (a quadratic transfer function of the form $y = a \times 2 + bx + c$ fitted using least squares regression and capped with an upper bound shown as the black line) and a number of plausible alternative recovery functions (grey lines). From the base case function, a heuristic set of plausible curves was generated by independently simulating the errors of each parameter from a normal distribution. In this manner, we are expressing uncertainty, albeit via a simple model, around an underlying deterministic function. The resulting family of curves comprises a stochastic model of a transfer function and are depicted as grey lines in Figure 8. A similar procedure was followed for the values used for each grade for each unit process throughout the circuit (in the end, 30 different base function equations were modelled this way).

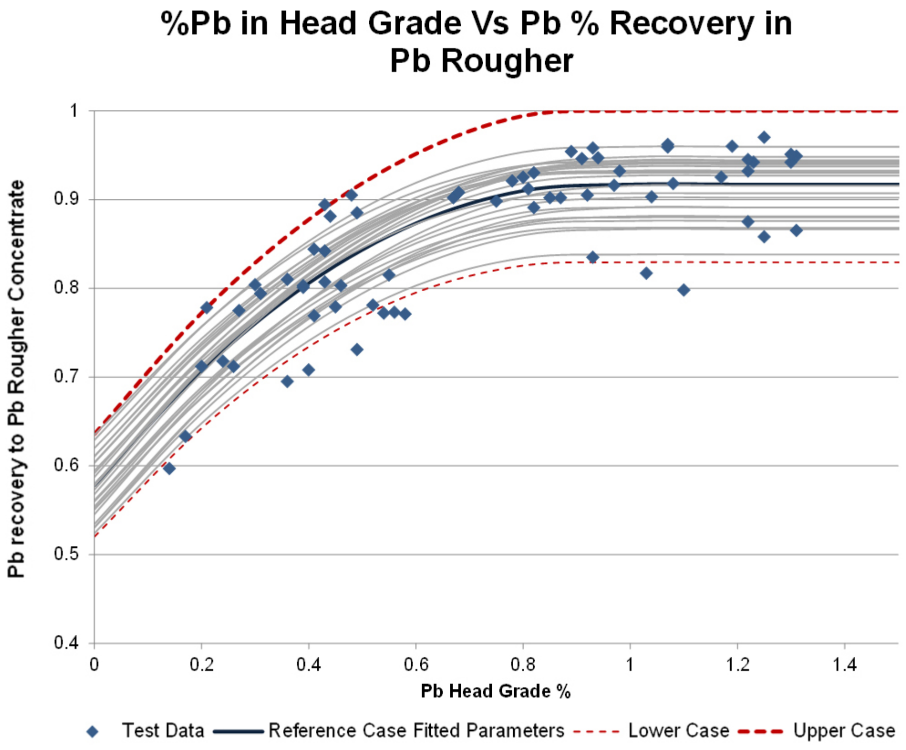


FIG 8 – Example of a stochastic transfer function for metallurgical recovery derived in the manner discussed in the text of the paper: relationship between input head grade and Pb recovery in Pb rougher circuit.

The impact of process uncertainty was then modelled by pushing each SMU block in the resource model through the process functions, one block at a time. Figure 9 depicts the range of Pb in lead concentrate for the years of the project. From this plot, it is evident that over the first six years of the project's operation, the uncertainty of Pb in Pb concentrate is substantial (as depicted by the range of values in Figure 9), and mine operators should be very aware that the quantity of Pb produced may vary significantly from the expected base case.

Figure 10 shows the impact of processing uncertainty on project NPV. The cumulative discounted cash flow starts at zero, declines as we expend capital during construction and then increases until the end of the mine life. The actual values are not specified for reasons of confidentiality, but the reader can see that the impact of process uncertainty on NPV could be ±50 per cent. This level of risk is likely to be considered unacceptable by any board contemplating a project. However, on further analysis, it was discovered that most of the spread is due to a single component transfer function that relates metal recovery to oxidation state. This finding allowed management to understand where best to focus technical attention in sampling and operational optimisation work in order to reduce project risk.

CONCLUSIONS

Economic evaluation of mineral projects is based on models of mineralisation attributes, mining processes and mineral processing. Because the information on which these models are constructed is not exhaustive, it is inevitable that there must be uncertainty present in the models of these attributes. Whether that uncertainty is incorporated into deposit models is a choice made at the time of modelling.

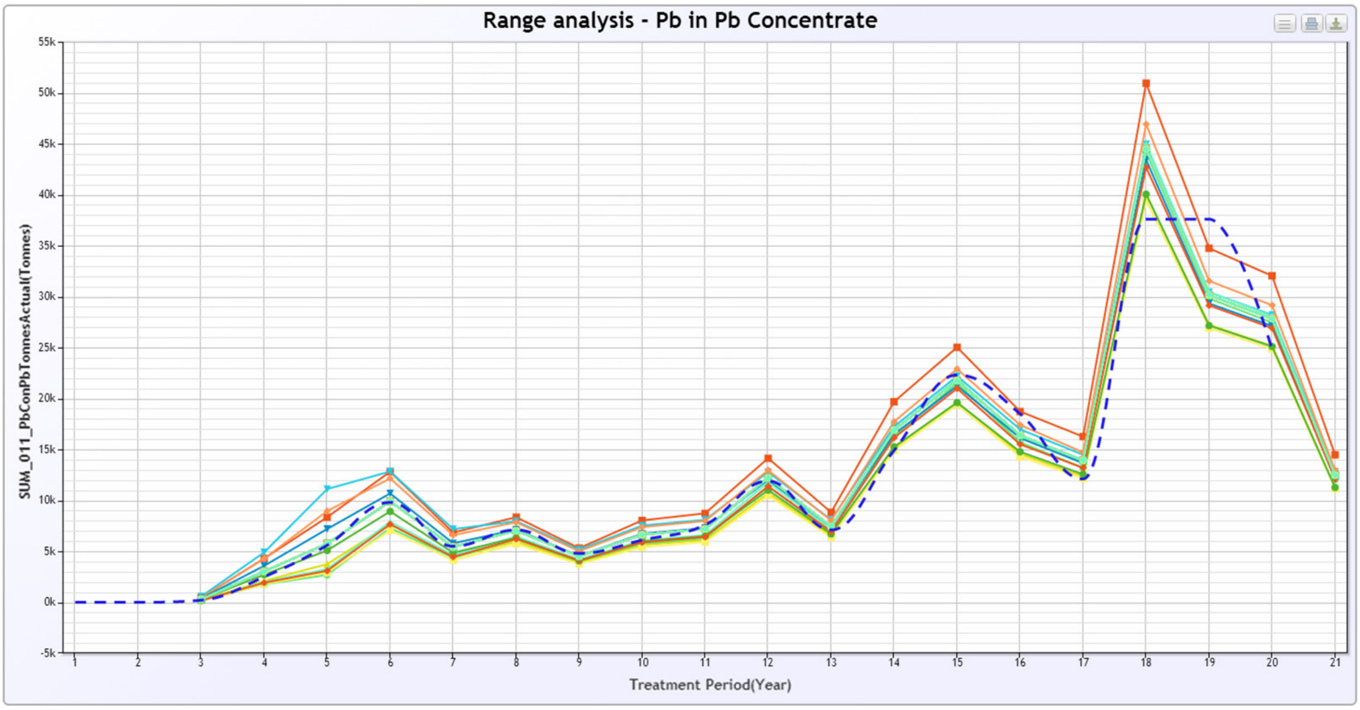


FIG 9 – Plot of the annual tonnes of Pb in Pb concentrate produced.

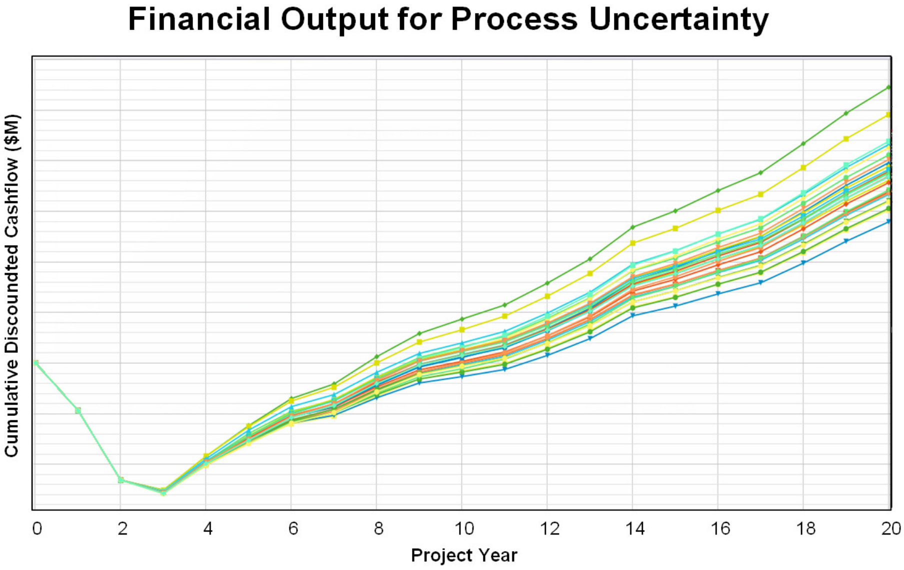


FIG 10 – Cumulative discounted cash flow curves showing the differences in cash flow arising due to process uncertainty.

The traditional approach taken to project evaluation has been to base analysis on a singular kriged orebody model that ignores uncertainty in the deposit model and in the mining and processing steps, and knowingly understates the variability that will be encountered when the deposit is actually mined.

Using the approach of SBPE on conditionally-simulated inputs allows the impacts of this uncertainty on the entire mine-to-market value chain to be explicitly modelled. Furthermore, the use of conditional simulations also allows realistic modelling of variability of key attributes that drive financial and engineering performance of the project. Using overly smoothed representations of key grades and other attributes can result in poor prediction of project outcomes that, in some cases, may be materially incorrect.

The power of SBPE is that it couples explicit models of uncertainty and variability in mineralisation attributes with a 'whole of system' approach to evaluation, including modelling of mining and processing performance (including key uncertainties). In this way, SBPE can provide unique insights into the incremental value of various contributing steps on a range of alternatives considered for project execution or mining operation, as well as give useful measures of confidence on outcomes to project managers and boards.

The end result is to improve the resilience and success of mining projects in several diverse ways, including (but not limited to):

- identification of areas in the deposit (translating to periods of production in the schedule) where variability and/or uncertainty are unacceptably high, allowing strategies or technologies to be adopted that mitigate the resulting risks (eg acquire additional information, reschedule in the mine plan, adapt the treatment strategies and technologies or deliberately engineer flexibility into systems in light of irreducible variability/uncertainty)
- identification of critical constraints in the system and how these impact on the performance of the entire value chain, thus allowing the opportunity to re-engineer the project to reduce or eliminate the impact of such constraints
- assessment of financial strategies that will be required to support the operation from construction through ramp up and into sustainable operations.

The mining value chain is in the beginnings of a fundamental revolution as we write this paper. The advent of the industrial internet, ever increasing computing power (via the cloud) and digital engineering of infrastructure design, construction and ultimately operation will utterly transform mining over the coming decades. We believe that SBPE is a critical component of this vision as it connects a fundamental characteristic of mineral deposits (spatial variability) to this rapidly evolving digital system world in a way that will provide mining companies with enormous value capture opportunities. These range from the obvious (reducing project failures and ramp up underperformance) to the less obvious (enabling far more sophisticated use of automation and robotics and ultimately far greater control over product variability).

This last example may allow mining companies to connect to their downstream customers in a more tightly-coupled system that benefits both the seller and the customer and can thus enable increased value capture for both parties. The authors predict that the combination of the industrial internet and SBPE, with full digital engineering of mining and processing infrastructure, promises to deliver an unprecedented transformation of our modelling, understanding and implementation of mining value chains in the coming years.

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