A novel innovation for reconciliation

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ABSTRACT

Mine value chain reconciliation (MVC) is a necessary procedure to evaluate a mine's performance against the assumptions and models used to plan mining and processing operations. Using nomenclature from Parker (2012), F2 reconciliation is the ratio between material received at the mill, compared with material sent to the mill, commonly reported in terms of tonnes, grade and metal. Measurements of material sent to the mill can be estimated in many ways, including: fleet management system (FMS) records, truck counts, or volume reduction. Most time-based reconciliations (for example, month-end reconciliation) use short-term model depletions of *in situ* rock measured by periodic topographic scans or surveys.

There are three main problems with existing reconciliation practice:

1. Delineated *in situ* material is used to estimate the tonnes and grade of material sent to the mill, despite blasting causing the material to change (dip/strike/location/density). The disconnect between achievable value pre-blast and achievable value post-blast is not respected, nor is the swell for each individual blast used to determine the mass inside any grade control polygon.
2. An *in situ* model cannot accurately represent a partially mined blast.
3. Material can occupy different locations at different times.

In attempting to solve these problems, two solutions were investigated:

1. Creating an *In situ* Diluted Polygon Block model (IDPB)
   - Post-blast polygon block model moved back to the *in situ* locations.
   - Solves problem 1 but does not solve problems 2 or 3.
2. Creating a Model in Time (MIT)
   - Assembling long-term, short-term and moved block models into a single time-dependent model.
   - Swelled densities are measured and applied to blasted rock.

As no existing software could create an MIT, OrePro® Recon was purpose-built to perform these functions, and to provide more accurate reconciliation. Building on Parker's (2012) methods, an F2' (F2 prime) reconciliation (ratio of post-blast delineation to what the mill receives) is proposed. A blasting factor F_b is proposed as the ratio of F2 and F2', to evaluate the change caused by blasting.

INTRODUCTION

Reconciliation is a core mining process that has progressed significantly over the last 20 years. Coincidentally the knowledge of blast movement dynamics has also greatly increased. Blasting dislocates ore from its modelled location, inherently changing its structure and in turn the value that can be mined from the blast. Methods exist for evaluating blast movement and applying that data by either sliding polygons or a creating a moved model. These methods are not equal, and it is critical that quality grade control processes exist and can be audited as part of the reconciliation process (Isaaks, 2019; Poupeau, Hunt, and La Rosa, 2019). A common accounting method for blast movement as part of reconciliation calculations is assigning the attributes of the post-blast dig polygons to the short-term model, referred to as an *In situ* Diluted Polygon Block model (IDPB). There are limitations to this method, such as:

- blasts are handled as discrete events that do not interact
- the *in situ* model cannot accurately represent a partially mined blast
- different blasted material can occupy the same space over time.

Starting with a review of reconciliation in the context of blast movement, this paper assesses existing grade control and reconciliation practice and proposes a new concept to enable rapid and accurate reconciliations. Two new factors are proposed to assess the impact of blast movement and grade control practice as part of the reconciliation process. For consistency and clarity:

- a *long-term model* refers to any block model that is used as a resource model
- a *short-term model* refers to a grade control block model that is *in situ* and used for determining grade control for mining operations
- a *moved model* is used to refer to a short-term model moved to reflect blast movement.

RECONCILIATION

Mine reconciliation is a key statistic used to monitor the operational performance of a mine (Schofield, 1998). The most common reconciliation measures are in terms of mass and grade, over discrete time periods, such as months or years. Morley (2003) summarises the goals of reconciliation. They are to:

- measure performance of the operation against targets
- ensure valuation of mineral assets is accurate
- confirm grade and tonnage estimation efficiency
- provide key performance indicators – in particular, for grade control predictions.

Further to these, Hargreaves, Pattenden and Pettit (2016) demonstrate through a case study that reconciliation can be used to evaluate the efficacy of business improvement initiatives. These points are not necessarily limited to internal organisation reporting, as accurate reconciliation is also important in compliance with reporting standards. These include the Australasian Code for reporting of Mineral Resources and Ore Reserves (JORC Code, 2012), the South African Code for Reporting of Mineral Resources and Mineral Reserves (SAMREC, 2016), the Canadian National Instrument 43–101 (2011) and legislative requirements such as the Sarbanes-Oxley Act (SOX) (Morley and Thompson, 2006). In some cases reconciliation can even result in police intervention (Schofield, Moore and Carswell, 2012).

Over the last 20 years, reconciliation methods have improved and become standardised, as mine operators sought to improve their processes and yield the benefits from the points listed above. Organisations with multiple commodities have unified reporting standards to create comparable metrics between mines. Fouet *et al* (2009) and Parker (2012) proposed three universal reconciliation factors, F1, F2 and F3:

$$F1 = \frac{short\ range\ model\ depletions}{long\ range\ model\ depletions}$$

$$F2 = \frac{received\ at\ mill}{delivered\ to\ mill}$$

$$F3 = F1 \times F2$$

The F2 factor described by Parker (2012) represents a logical ratio between two nodes in the mining value chain. An F2 value less than one indicates the mining operations had greater expectations than occurred. Conversely, an F2 value greater than one indicates that mining operations exceeded expectations. While a high F2 value may represent a financial boon for a mining operation, any deviation of the F2 factor from one indicates unexpected variation. Multiple F2 values may be calculated to account for tonnes and each grade variable (eg F2 Au g/t, F2 Ag g/t). Variations of these metrics exist, such as those used by Anglo American (Morley and Arvidson, 2017; Macfarlane, 2013; Hargreaves and Morley, 2014).

Parker (2012) calculates 'delivered to the mill' from short-term model depletions and describes 'received at mill' as either direct feed into the mill or from truck or stockpile reclaim. Stockpile sampling and modelling is covered elsewhere (Morley and Arvidson, 2017) and is not expanded on here. The nodes in the mining value chain between the short-term model and mill feed include the core processes of drill and blast.

Coincident with the popularisation of standardised reconciliation factors preceding Parker's 2012 paper, technological advancements were made in the field of blast movement. Thornton (2009) provides a thorough overview of blast dynamics and lists examples of vertical and horizontal displacement data. Thornton rightly notes the challenge for grade control is not tracking movement, but measuring the differential movement of ore. Ore concentration and dissemination induced by blast movement is a significant challenge for reconciliation that must be addressed to ensure the goals of reconciliation can be met with increasing precision. Additionally, for a mine to understand the accuracy of its modelling practices, there must be a way to reconcile back to the short-term model, even though the material mined has changed location and shape. Isaaks, Barr and Handayani (2014) identified a 5.2 per cent reduction in achievable value between the pre and post blast states and suggested that blast movement is a likely source of error in Mine to Mill (F2) reconciliation. Despite the increasing body of knowledge on blast induced movement, it appears to get limited consideration in contemporary reconciliation practices.

There are a few possible causes for this. One is that blasting is an intermediary, in-line process in the mining value chain. In this context, it has the misleading appearance of not influencing ore loss, dilution or misclassification. Another possible cause for the lack of change in reconciliation methods is the assumption that the reconciliation equation accounts for all sources of error made in ore selection (Schofield, 1998) and without sampling waste, it is possible to have perfect reconciliation and high ore loss. Adofo (2017) suggests that reconciliation, and any variations that arise, are the responsibility of the geologist to explain. This unnecessarily excludes blasting and blast practice from the reconciliation locus.

Ignoring blast movement may not be as significant an issue in homogenous ores, or in deposits where ore is visually disctinct and ore destinations can be accurately delineated in the muck pile. Where blast induced movement does occur it is probable that it will have a significant impact on reconciliation. Macfarlane (2013) identifies poor blasting as a source of error, and Shaw (2014) notes that sophisticated reconciliation practice is futile if the grade cannot be accurately located post-blast. It is likely that blast movement was a cause of the strong negative reconciliation reported in Berryman's (2003) second case study of an open pit mine with very narrow structures, 0.2–1.2 metres wide, transitioning from oxide to fresh rock. A similar narrative is described by Hargreaves and Morley (2014) in Case Study 1; reconciliation in fresh rock was improved with a focus on blasting practices, among other issues. In almost all cases, fresh rock is more competent than its oxide equivalent, and requires blasting with greater energy. As Thornton (2009) describes, powder factor (blast energy) is positively correlated with blast movement magnitude.

BLAST MOVEMENT

Research into rock movement induced by blasting was limited until the early-1990s. Yang and Kavetsky (1990) modelled post blast surface movement, Favreau (1993) proposed a solution to predict post-blast swell. Preece and Scovira (1994) used discrete element methods to model blast movement induced in stratified overburden in two dimensions, and Zhang *et al* (1994) measured blast movement with markers located pre and post blast, confirming blast movement to be perpendicular to the timing contours. The concepts in these early papers describe the elemental concepts of blast movement:

- post-blast topography profile
- augmentation of *in situ* density
- movement in the body of the blast
- inference of blast movement without measurement.

The evaluation of blast movement took a step change with the invention and commercialisation of the transmitting blast vector indicator (BVI). Thornton, Sprott and Brunton (2005) first reported using transmitting BVIs to determine blast movement in the body of the blast in 2005. The transmitter enables the location of the post-blast BVI to be determined without excavation which can then be compared to its initial location to determine the blast movement vector. Data from transmitting BVIs determined the fundamentals of blast dynamics, shown in Figure 1. Specific zones of the blast have been identified to feature local and unique characteristics, such as a choked face, free face, back of the blast and centrelines (Thornton, 2009).

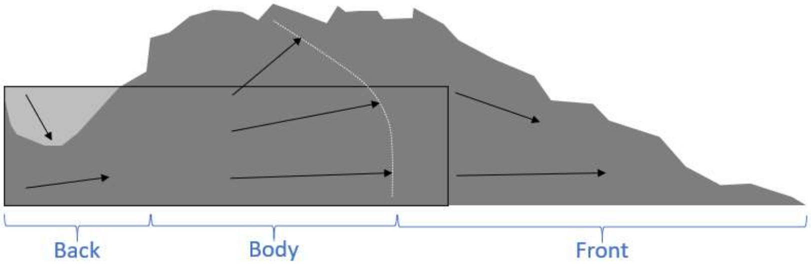

FIG 1 – Simplistic overview of blast dynamics (after Thornton, 2009).

The error of transmitting BVIs described by Thornton, Sprott, and Brunton (2005) was reported to be between ± 0.1 m and ± 0.5 m, increasing with depth. The relationship of that error to depth and the degree of error at greater depths was not listed. Further, the initial vertical location of the transmitting BVI is critical to the resultant vector in both vertical and horizontal axes. There are limited examples of action taken to ameliorate these constraints. Fitzgerald *et al* (2011) mentions placing the transmitting BVIs in locations representative of the blast pattern, but does not provide detail. Loeb and Thornton (2014) recommend using a large number of transmitting BVIs; from a sampling viewpoint this merits consideration. Their argument is predicated on applying an increasing number of vectors to slide polygons horizontally and then taking the difference with the solution that used the largest number of transmitting BVIs, which is presumed to be most accurate. This is a demonstration of standard error, a statistical metric, and does not provide any evidence of increased efficacy of increased transmitting BVI use from site reconciliation results to validate their argument, as recommended by Isaaks (2019).

An alternative to using transmitting BVIs uses a reactive model to generate movement vectors (Poupeau, Hunt, and La Rosa, 2019; Hall and Hunt, 2019). The blast design is used to evaluate the intended blast movement, and the post-blast topography is used as the limit of all movement. A fluid dynamic model then links the two together with movement vectors, using multiple characteristics from the blast design and post blast topography to determine vector length, bearing and azimuth. This approach has the benefit of more accurately applying the correct blast dynamics in each zone and adapting to heave and cast variations.

Utility of movement vectors

There are two key methods of using blast vector data in contemporary practice: move polygons or move the short-term model.

Sliding polygons involves creating polygons using the short-term model. The vector data is used to map the polygon nodes to a post-blast location. This is a fast and computationally simple method. The key issues with sliding polygons are:

- vertical movement is disregarded
- mass, grade and geochemistry are not conserved
- the post blast polygon shape depends on the number of polygon vertices and interpolation method
- the curved horizontal movement profile is aggregated to a single magnitude at each node.

These are critical flaws that can result in substantial error. For example, there is a report showing polygon tonnage changes between pre- and post-blast from minus 90 per cent, to over positive 100 per cent. Such variability is undesirable in any reconciliation process.

The computational simplicity of sliding polygons also applies to their reconciliation. As the polygons were generated on the *in situ* short-term model, when the slid polygon has been mined the *in situ* voxels can be assigned as mined also. This process is straightforward with a completely mined polygon, however a partially mined polygon presents a challenge. Further to this is the handling of the polygon mass and grade errors. Fitzgerald *et al* (2011) presented an improvement in reconciliation variance after implementing transmitting BVIs and sliding polygons. However the improvement is difficult to quantify as an exact figure is not stated. From the data presented in Fitzgerald's case study it is estimated that the F2 variance at KCGM of total metal and ore tonnes was reduced to 8 per cent, and grade average was limited to fluctuating between ±5 percentage points. In the case studies identified that assessed the efficacy of sliding polygons, only hypothetical results were calculated using average polygon grades and assuming no vertical movement (Silveira and Loeb, 2017; Watson, 2017; Eshun and Dzigbordi, 2016; Loeb and Thornton, 2014; Hunt and Thornton, 2014; Mwijage, 2012; Rogers *et al*, 2012; Thornton and La Rosa, 2011).

The alternative to sliding polygons horizontally is to move the short-term model and generate mining polygons on the moved model. Isaaks, Barr and Handayani (2014) describe moved model created from a stochastic movement model using a database of transmitting BVIs and the post-blast topography. The moved model was used to create grade control polygons. It is not clear how accurately the stochastic model replicated blast movement dynamics or if the generated polygons were subsequently employed for mining.

The OREPro® 3D software can determine blast movement vectors, move the short-term model and generate optimised grade control polygons. The short-term model is moved using the reactive vector field previously described and bound by the post blast topography. The designed blast floor and pre-blast topography can also be used as the lower bounding limit to increase the accuracy of the movement and moved model. The density of the moved model and the attributes of each moved voxel are augmented to conserve mass and geochemistry. Using the mining parameters: mining height, width, length and angle; polygons are generated and optimised to create the greatest value. It is critical that the mining parameters are used, as material mined from a polygon from different directions will vary due to the mining angle. The efficacy of OREPro® 3D at Kinross's Tasiast mine resulted in the F2 reconciliation for grade, tonnes and volume reducing to less than 1 per cent error from 18 per cent over a three month period (Poupeau, Hunt, and La Rosa, 2019).

Using the moved model that is analogous in shape, grade and tonnes to the muck pile enables reconciliation depletions to be calculated using topographic scans, or if the fleet management system is suitably equipped, the mining locations. The challenge is to deplete the mined blocks from the short-term model. This is presently handled in OrePro® 3D by creating polygon block models. A polygon block model is a block model with the attributes of the mining polygon applied to each voxel bounded by that polygon. Several polygon block models can be created, including a pre-blast polygon block model (pre-blast polygons coded to the short-term model), post-blast polygon block models (post-blast polygons coded to the moved model), or the IDPB (*in situ* diluted polygon block model). The IDPB is created by coding the voxels of the short-term model with the polygon block model data from the moved model by *in situising* the moved voxels.

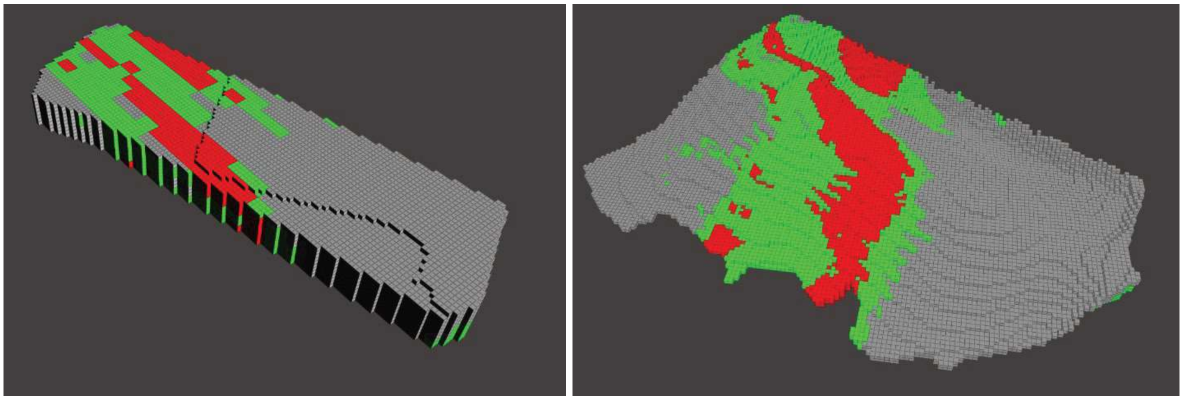

FIG 2 – The block model is imported and classified (LHS). A moved model is created using the blast design, the post-blast topography and a fluid dynamics engine (RHS).

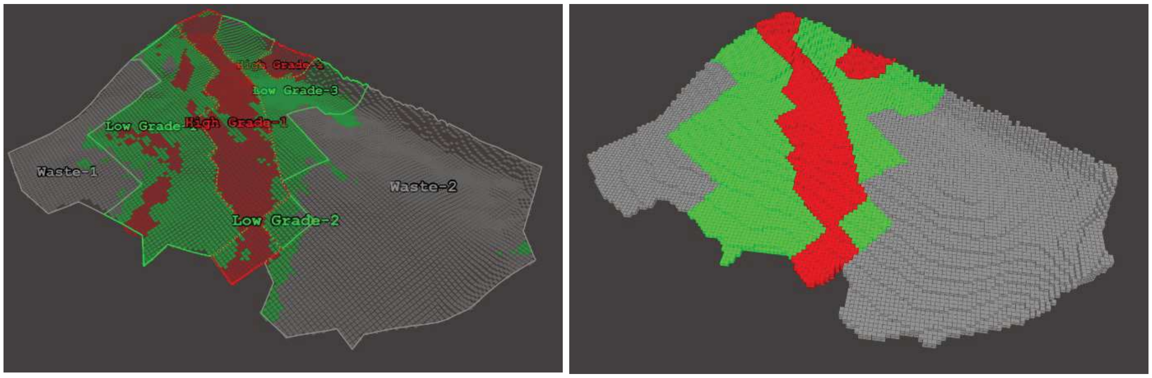

FIG 3 – Optimised dig blocks are generated using the mining constraints and entered mining direction (LHS). The attributes of the generated polygons are used to generate a post blast diluted polygon block model (RHS).

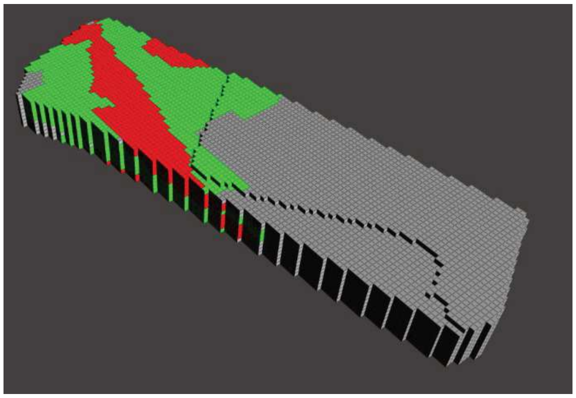

FIG 4 – An *in situ* diluted polygon block model (IDPB) can also be generated.

1. partially mined polygons and blasts cannot be easily reconciled to the short-term model
2. for moved models, the same space can be occupied by different material as mining progresses
3. blasts are treated as discrete events that do not allow for any mixing of material between blasts. For example, one blast is fired onto another blast, mined together.

A solution that addresses these three points needs control over both the spatial and temporal change that each voxel experiences.

DIGITAL TWIN AND MODEL IN TIME (MIT)

A digital twin is a virtual representation of a physical object or system across its life cycle, using real-time data to enable understanding, learning and reasoning (IBM, 2021). This definition is expanded by Nazari and Cristonffanini (2019), and modified here to define a digital twin as having:

- replication as the core functionality of the process
- the entire life cycle mapped
- direct linkage to the operation.

Digital twins are a nascent technology in the mining industry. Two examples of digitals twins used in mineral processing are Newcrest's Telfer mine (Oliver and Tooher, 2018) and Oceania Gold's Haile Gold project (Schug *et al*, 2018). In both examples a digital twin operated in parallel with the plant, with models to replace processes that could not be monitored. Deviations between the digital twin and plant performance were used to create alerts. Mineral processing lends itself to digital twinning as processing plants have a dedicated control room, a large array of sensors and electronic infrastructure, and the plant is static.

For the purposes of this paper, the life cycle is considered from the long-term model to delivery of ore to the mill. A digital twin enables a voxel to be tracked from the long-term model, through iterative modelling changes to the short-term model, the moved model and mining. Unlike mineral processing, the voxel life cycle is much more complex spatially and temporally. There are two key challenges with creating a digital twin in the mining environment: the data linkage (real time supply of spatial data) and data volume.

Mining environments can be extremely large. In the case of iron ore mines, the mining footprint can exceed the area of small cities. Complicating this is the presence of multiple mining faces. To meet the definition of a digital twin, real time spatial data must be collected and processed to create a direct link to all working faces in real time. This represents a significant challenge. Gaps in sensor data could be met using simulations, as per the mineral processing examples. To simplify data requirements and reduce complexity, lower frequency supply of topography from the survey department with a frequency ranging from daily to intra-weekly may be used. An alternative to topographic data is the use of high precision GPS data to determine where the bucket teeth have and have not mined. A low frequency link is a departure from the definition of a digital twin and it is proposed such a model is described as a Model in Time (MIT). The reduction in data processing and volume achieved by using an MIT over a digital twin is considerable, however the data processing and storage requirements remain significant as every block model and topography must be saved and remain accessible for the entire mining environment for substantial periods of time. To navigate this cloud hosting or co-located server hardware can be used. The latter minimises latency and connectivity risk.

OREPRO® RECON

A platform to demonstrate the MIT concept called OREPro® Hub was developed by OreControl Blasting Consultants with support from Anglo American. The user interface features both a spatial viewing window and a timeline, giving the graphic user interface the appearance of a video editor. It is designed to support various data formats, including block models, moved models, spatial data, orthographic imagery, drill holes and fleet management system integration. All must be spatially and temporally located. Each data type is imported into a layer and timestamped. Where coincident data exists, the newest data replaces the old data. An example of this is shown in Figures 5 and 6, which shows the progress of mining. A playhead is shown in the time bar, which can be scrolled through time. Doing so changes the active layers and how they intergrate to replicate the state of the mine at that time. The spatial window can be moved with the standard mouse zoom and pan controls. The model in this example has been generated with 0.5 m × 0.5 m × 0.5 m voxels and has a maximum of 800 billion available voxel positions.

Real-time depletion is also possible in this environment. For example, if a muck pile is only partially mined before an adjacent blast is fired, the resultant moved models can be evaluated together to determine the appropriate material destination.

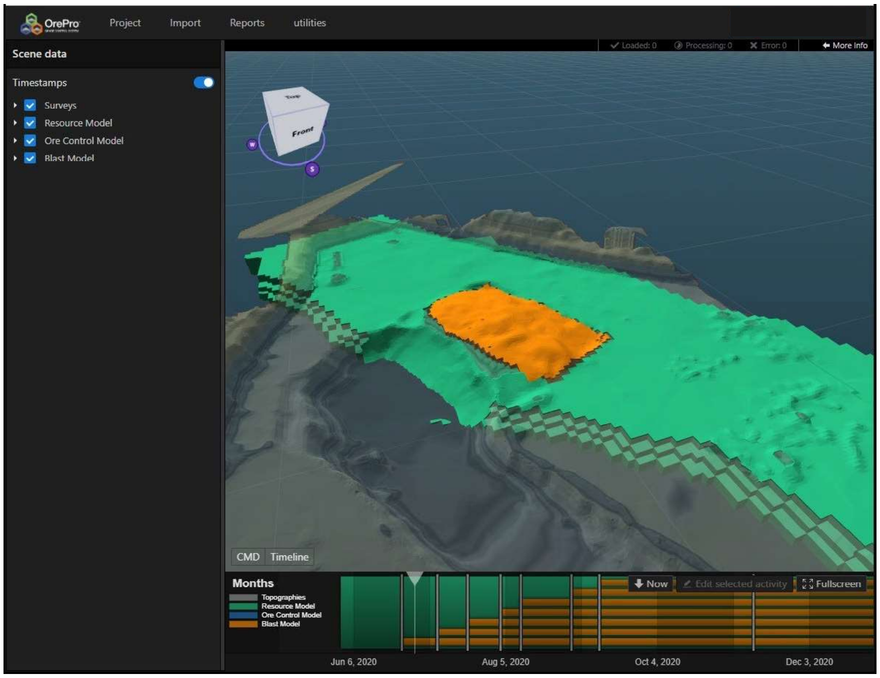

FIG 5 – A preliminary view of the graphic interface. A moved model is shown in orange. Note the location of the playhead in the timeline.

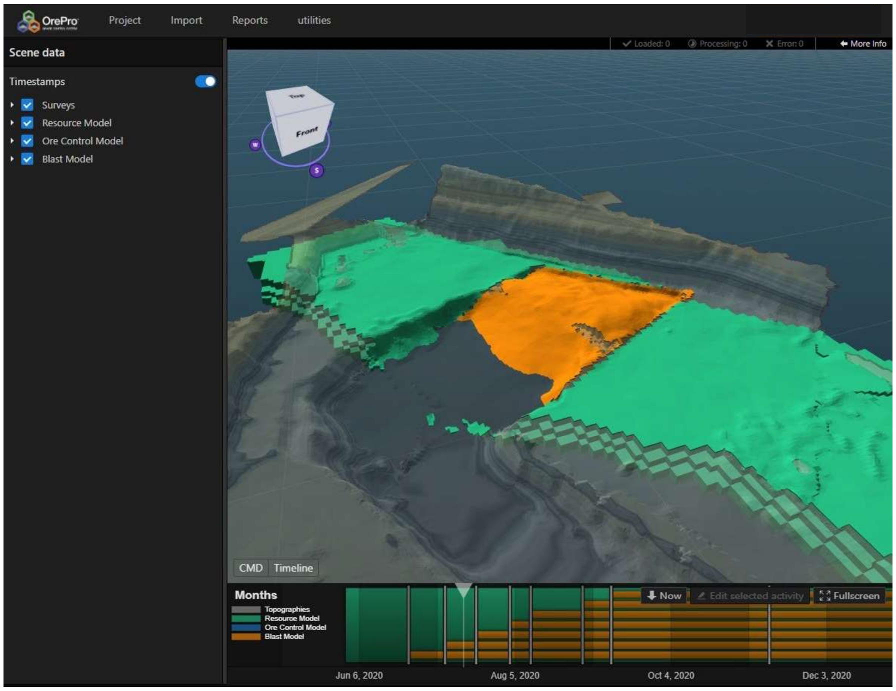

FIG 6 – Progression of mining. The playhead has progressed, depleting old layers, and revealing new ones.

Data relating to the relocation of material from the moved model to a destination is supplied via integration to the site's fleet management system. The material type can be assigned using the mining location against the moved model or the mining polygons, with the actual destination confirmed via the FMS.

CALCULATING RECONCILIATIONS

OREPro® Hub is a platform that amalgamates all data required to calculate reconciliation. The key reconciliation metrics, such as those specific to Anglo American (Morley and Arvidson, 2017), and those described by Parker (2012), can be readily calculated:

- F1 Report: Performance of the long-term model
- F2 Report: Performance of the short-term model
- F3 report: Efficiency of the entire system (F1×F2).

Further to these, additional metrics can be calculated:

- F2' Report (F2 Prime): Performance of the moved model
- Digging Accuracy: Compliance of mining plant to dig lines
- Dynamic Routing: Accurate classification of what is inside a haul truck when it is loaded
- Voxel life cycle tracking.

As part of this project, the requirement for a new metric, F2 Prime was identified, denoted as F2'. The F2 Prime is proposed to evaluate the performance of the moved model against what was received at the mill. A high F2' factor indicates conservatism by the moved model, and a low F2' factor indicates optimism. This was proposed as blasting inherently changes the distribution of mineralisation (Isaaks, Barr and Handayani, 2014), which can result in ore being disseminated or concentrated. This result confirms blasting to be an economic risk that must be evaluated as part of the reconciliation process. A blast factor F_b is also proposed, calculated as the ratio of F2 and F2' to provide insight into the change caused by blasting. A high F_b factor indicates the generation of value, while a low F_b factor indicates value loss.

$$F2\ Prime = F2' = \frac{received\ at\ mill}{delivered\ to\ mill\ (moved\ model)}$$

$$F_b = \frac{F2'}{F2} = \frac{delievered\ to\ mill\ (moved\ model)}{delivered\ to\ mill\ (short\ term\ model)}$$

A preliminary F_b can be calculated by evaluating the maximum value mining polygons on the short-term model (F2), then replicating the process on the moved model (F2'). This metric should be an important key performance indicator for all hard rock drill and blast engineers and bring blast design and implementation into the locus of reconciliation. The relationships of the reconciliation factors are summarised in Figure 7.

The last two points represent a powerful development in reconciliation. Locating all the information during the life cycle of a block model voxel enables tracking and reconciliation of a single voxel through space and in both directions of time. This could have significant consequences by ensuring blends are on specification, and, if the blend specification was not met, act as an auditing tool to determine why.

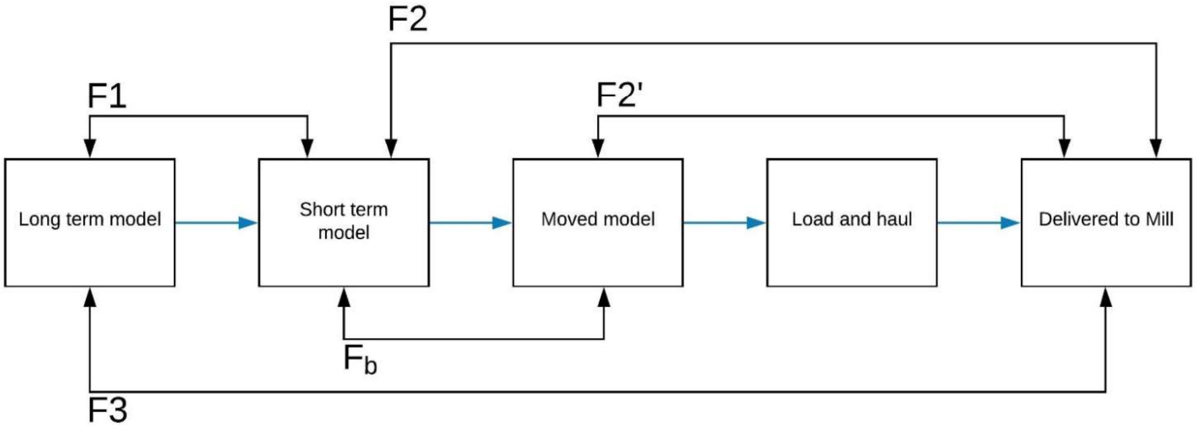

FIG 7 – Relationships of reconciliation factors (after Parker, 2012), with the addition of F2' and F_b.

ANGLO AMERICAN TRIAL

Anglo American trial data was successfully processed to demonstrate OrePro® Hub as a model in time, capable of handling large volumes of data and calculating the reconciliation metrics proposed by Parker (2012) and Morley and Arvidson (2017). At the time of writing, trials are underway at multiple large mining operations.

Reconciliation is a critical operational metric. It can be used to drive site improvement and comply with reporting requirements. Advances in reconciliation practice over the last 20 years have not accounted well for the concurrent advances in blast movement knowledge. Blasting dislocates the rock mass from its *in situ* modelled location. This change can change the ore distribution, due to variable, three-dimensional blast movement. The practice of horizontally sliding polygons generated on the short-term model disregards vertical movement and does not conserve mass or grade. A literature review undertaken to evaluate the effect of sliding polygons on reconciliation performance showed that in all but one case, hypothetical results were reported. Moving the short-term model has been investigated and shown by multiple authors to conserve mass and grade. Importantly, blasting was also identified to result in a change in the achievable value. Blasting is therefore presented as an economic risk to the operation and must be effectively accounted for with grade control processes, audited as part of the reconciliation process.

A digital twin is an ideal solution for processing reconciliation as it enables all key spatial data to be plotted in one repository, temporally. The sensor requirements and data demand for a digital twin are significant, so a prototype model in time (MIT) was developed by OreControl Blasting Consultants with support from Anglo American. OrePro® Hub handles large volumes of spatial data in time and was successfully used to calculate the reconciliation metrics proposed by Parker (2012) and Morley and Arvidson (2017). These metrics were expanded to address the effect of blasting on grade control by suggesting two new factors:

- F2 Prime (F2') to evaluate the performance of the moved model compared to what was received
- F_b (blasting factor), to evaluate the change due to blasting between the short-term and moved models by comparing F2 and F2'.

OrePro® Hub is now advancing to field trials.

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