

Development, reconciliation and visualisation of hang-up frequency and fines entry forecasts at PT Freeport Indonesia

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Abstract

Fragmentation production and associated hang-up frequency and fines entry forecasts have been incorporated into the existing PCBC-based production forecasting workflow at PT Freeport Indonesia. These forecasts inform numerous operational aspects including draw scheduling, production planning, cave shape targeting and wet muck hazard management. This paper first describes two key aspects of the workflow that have enabled forecasting of these quantities at the drawpoint-month level for the life-of-mine: 1) block models of expected primary and secondary fragmentation, derived from block models of point load index, cave back stress potential and volumetric vein/fracture intensity measures of vein point load index and 2) an empirical relation between hang-up frequency, draw rate and rock block size and strength, derived from reconciliation of forecast versus measured hang-up frequency at GBC and DMLZ. This is followed by an overview of the forecast outputs and the reconciliation process, which is central to calibration of the methodology and the production of a reliable forecast. This process relies on rapid, accessible and up-to-date visualisation of the forecast and actual data in the form of time-based heat maps and charts, which are also used to communicate the forecast outputs to all stakeholders.

Keywords: *fragmentation production, forecasting, oversize, fines, hang-up frequency, productivity*

1 Introduction

PT Freeport Indonesia's (PTFI) Grasberg mining complex located in West Papua, Indonesia hosts some of the largest and deepest block cave mines in the world. The Grasberg Block Cave (GBC) mine is currently ramping up to full production, located directly below the Grasberg open pit (GRS), which closed at the start of 2021. The GBC is a typical copper-gold porphyry style deposit with complex geology, alteration styles and structure. The Deep Mill Level Zone (DMLZ) is the third lift in a series of panel cave mines within the copper-gold East Ertzberg Skarn System. It is located approximately 1,600 m below surface and currently is ramping up to full production. The DMLZ deposit is characterised as a massive, veined, strong and brittle rock mass. Both mines have broken through into overlying mines with GBC into the GRS and DMLZ into the Deep Ore Zone (DOZ) panel cave mine. Although the GBC and DMLZ both face their own challenges due to nature of mass mining, style of deposits, interactions with overlying mines and location in mountainous terrain with high rainfall, both mines share a common challenge related to oversize and fines management (Campbell et al. 2018; Nugraha et al. 2020; Priatna et al. 2020).

Fragmentation production forecasting has now been incorporated into the existing well-established PCBC-based metal production forecasting workflow at PTFI, which is aimed at providing metal forecasts on a quarterly basis that reflect actual tons drawn and future planned production. Incorporation of fragmentation into this workflow enables forecasting of the fragment size distribution reporting to the individual drawpoints

over time, from which hang-up frequency can also be estimated. These forecasts inform numerous operational aspects of cave mining at PTFI, including draw scheduling, production planning, cave shape targeting and wet muck hazard management. In recent years, a renewed focus has been placed on improving the understanding of the spatial and temporal fragmentation profile at a higher resolution. This stronger focus on fragmentation forecasting, linked to PTFI's production simulator (PCBC), was driven by the following points:

- **Oversize:** Forecasting of oversize and the resulting frequency of hangups is a key output from the PCBC-linked productivity forecast. The forecast can be used to better anticipate spatial and temporal secondary breakage requirements (e.g. equipment fleet) rather than traditional, lower resolution outputs.
- **Wet muck:** Forecasting of high fines content can aid in identifying mud-rush susceptible drawpoints and estimate wet muck entry timing. Outputs from the current forecast include heat maps of the fines entry on the footprint over time. Among other uses, this tool can be used by planners to prepare remote loaders ahead of production drive closure for manual mucking.
- **Mill throughput:** Improved forecasting of the full fragmentation profile reporting to the drawpoints can help oreflow and mill teams better understand material type and size profiles reporting to underground crushers and ultimately the surface mill facilities through the life of panel. Material sorting can also benefit from advanced production forecasts. Wet muck risk on inclined conveyors and potential wet/dry muck blending opportunities can be explored.

The fragmentation forecasting workflow developed for forecasting at PTFI is called FragPro (short for fragmentation production) and comprises a fragmentation block model workflow and a production forecasting workflow (Figure 1). The FragPro approach is similar to other forecasting methods that rely on production simulation to provide a higher degree of resolution on drawn fragmentation but is unique in its upfront development of a secondary fragmentation block model. It differs substantially from the block cave fragmentation (BCF) method previously applied at PTFI (Table 1).

This paper begins with a summary of the fragmentation block model development, focusing on refinements/additions since Pierce et al. (2020). This is followed by a description of the production forecasting workflow and the process for visualising and reconciling forecast outcomes against actual fragmentation (from drawpoint mapping) and hang-up frequencies.

Table 1 Features of FragPro forecasting methodology relative to BCF, which was used previously for fragmentation forecasting at PTFI

Component		BCF	FragPro
Spatial resolution	Inputs via block model	No	Yes
	Output by production block	Yes	Yes
	Output by drawpoint – panel	No	Yes (lower confidence)
Temporal resolution	Height of draw	Yes	Yes
	Month – tonnes	No	Yes
Mechanics	Vein-controlled	No	Yes
	Mixing considered	No	Yes

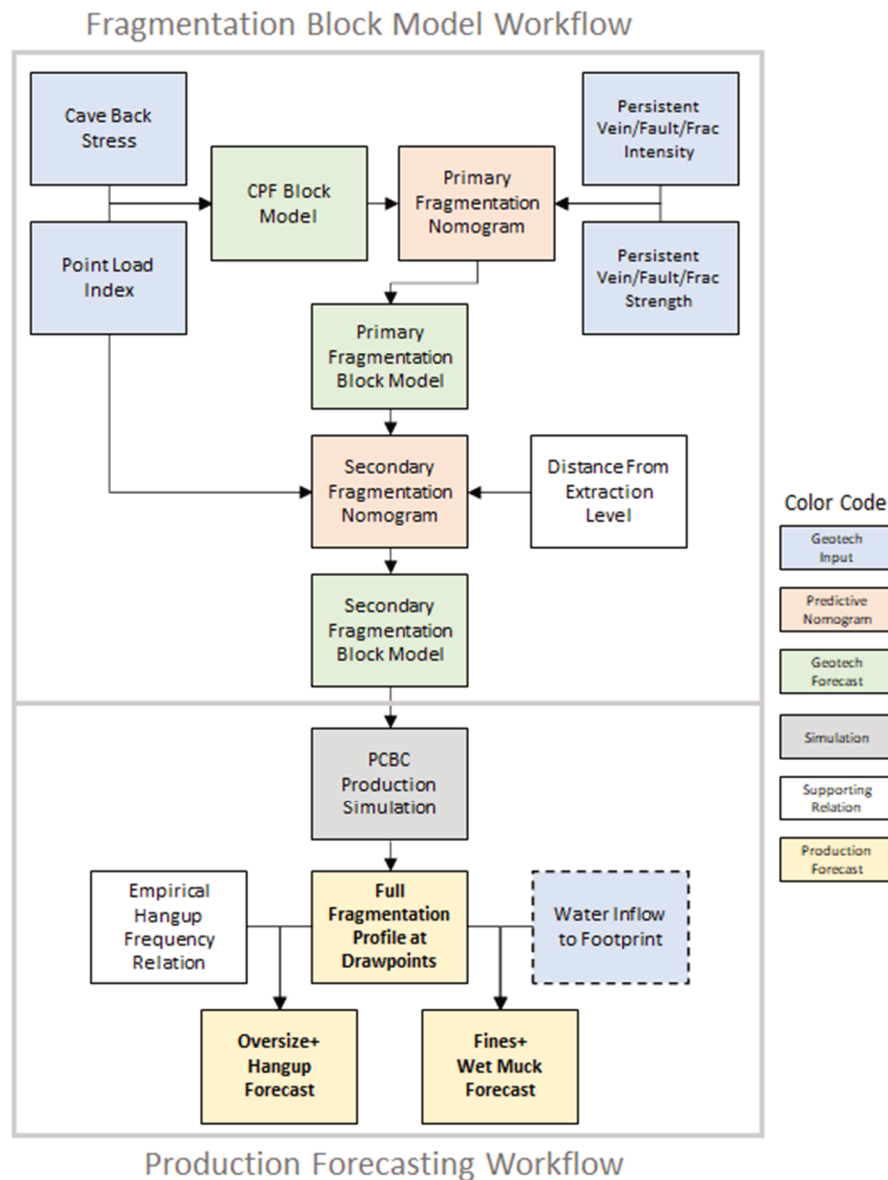


Figure 1 Two-part workflow employed in FragPro for fragmentation and productivity forecasting at PTFI

2 Fragmentation block model workflow

The main output of the fragmentation block model workflow is a block model of secondary fragmentation that can be input (alongside the grade block model) to PCBC as part of the production forecasting workflow. Primary fragmentation is estimated first, followed by secondary fragmentation.

2.1 Primary fragmentation block model

Primary fragmentation is estimated for each block in the orebody block model based on the cave back stress potential, point load index, persistent vein/fracture intensity and persistent vein strength:

- **Cave back stress potential (CBSP):** This is a spatially variable quantity representing the expected maximum elastic deviatoric stress at a fixed distance from the cave back (nominally 20 m). It is estimating from the results of a series of elastic numerical models in which the cave is expanded upward and outward manually and incrementally according to the production schedule and a caving rate informed by monitoring of historical production blocks.

- Point load index of host rock mass ($Is50_h$): This is a spatially variable material property estimated from standard point load testing at PTFI and represents the expected mean point load index when all possible break types are included (intact, multiple, structure, combined).
- Persistent vein/fracture intensity (P32): This is a spatially variable material property estimated from core logging and stereo photogrammetry and describes the estimated fracture area per unit volume (P32) of persistent veins, small-scale faults and hydrofractures.
- Point load index of veins ($Is50_v$): A distribution of point load index is derived for each main vein type (e.g. sulphide, gypsum, quartz) based on the results of targeted vein-specific point load testing at PTFI, where discrete failure along the vein surface is sought. The focus tends to be on weak veins, which have the greatest potential to impact fragmentation.

Numerous contemporary publications have stressed the importance of characterising and including defects within rock mass strength assessments, particularly in massive rock masses (e.g. Bewick 2021; Jakubec 2013). Since its conception in 2019 (Pierce et al. 2020), application of the FragPro methodology has indicated a need to factor vein intensities based on the ratio of vein to host point load index, $Is50_v:Is50_h$. This recognises that a weak vein will have a stronger impact on fragmentation when embedded in a rock mass of greater (rather than equivalent) strength. The relation in Figure 2 is used to factor each of the individual intensities based on $Is50_v:Is50_h$. These are then summed to generate a single 'effective' vein intensity for each block ($P32_{eff}$).

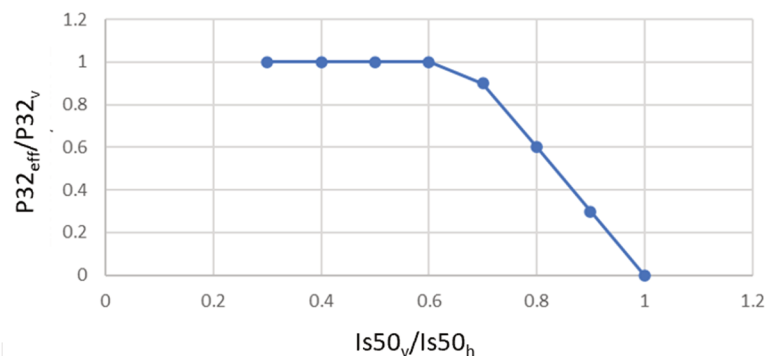


Figure 2 Relation used to account for the impact of vein strength relative to local host strength on the effective local intensity of a vein set

The nomogram in Figure 3 is used to estimate the primary fragmentation in each block from the local estimates of CBSP, $Is50_h$ and $P32_{eff}$. Both the nomogram and supporting $P32_{eff}$ relation (Figure 2) were derived from Synthetic Rock Mass (SRM) testing of large-scale [20 m (span) \times 10 m (height) \times 12 m (width)] rock mass samples containing persistent weak veins, small-scale faults and fracs (from hydrofracturing) represented via discrete fracture networks (DFNs). The SRM sample that hosts the DFN is comprised of an assembly of tetrahedral-shaped blocks with contact strengths defined by $Is50_h$. Fragmentation potential is estimated by subjecting SRM samples to a range of CBSP and deconfining from below to mimic advance of the cave back. The ratio of CBSP to $Is50_h \times 12$, forming the x-axis of the nomogram, is also termed the cave propagation factor (CPF) and is a metric for fragmentation potential in the absence of weak, persistent structure. The empirical factor of 12 in the denominator sets the onset of fragmentation at CPF = 1 when $P32_{eff} = 0$. The Weibull distribution is used to describe fragment volume distributions within the methodology due to its versatility and flexibility (see Appendix A). The output from the nomogram is the Weibull scale parameter of the primary fragmentation distribution, η_{pf} , which can be input with the Weibull shape parameter, β_{pf} , (estimated at 2.5 for GBC and DMLZ primary fragmentation) to the cumulative density function. This defines the percentage of fragments (by volume) passing a given volume, V , as:

$$F(V) = 1 - \exp[-((V/\eta_{pf})^{\beta_{pf}})] \quad (1)$$

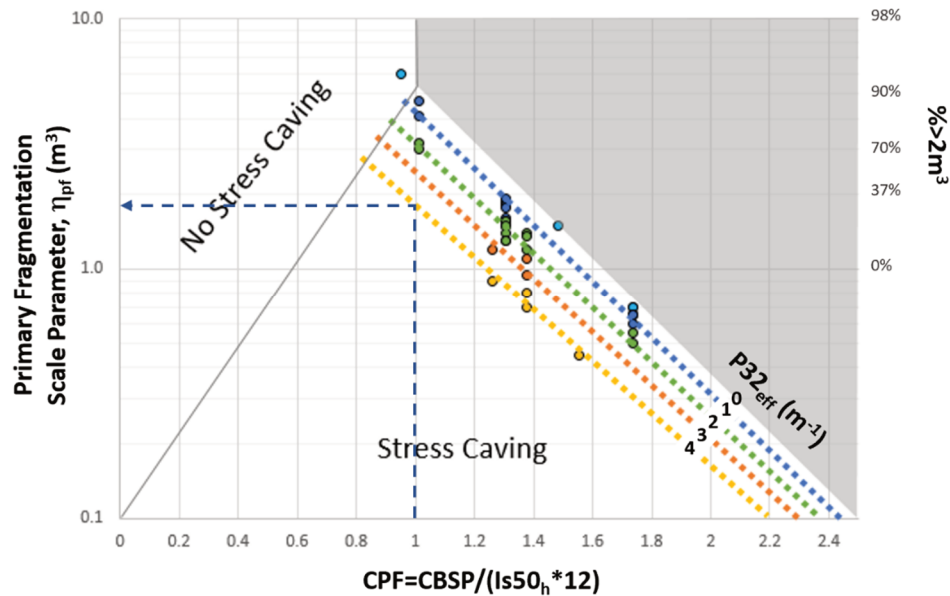


Figure 3 Nomogram used to estimate the Weibull scale parameter of the primary fragment volume distribution based on the ratio of cave back stress potential (CBSP) to host point load index ($Is50_h$) (termed the CPF) and the combined effective intensity of weak, persistent veins, faults and fracs ($P32_{eff}$). The arrowed dashed line illustrates the estimation of $\eta_{pf} = 1.8 \text{ m}^3$ from a combination of $CPF = 1$ and $P32_{eff} = 4 \text{ m}^{-1}$. Estimates of η_{pf} are input to the cumulative density function (Equation 1) to define the full fragment volume distribution. The secondary y-axis provides the output of this function for a 2 m^3 fragment volume, for convenience

2.2 Secondary fragmentation block model

The secondary fragmentation distribution within each block is estimated using the relations in Figure 4, which forecast the change in Weibull scale and shape parameters from primary to secondary fragmentation as a function of the distance travelled and $Is50_h$. These relations were developed for FragPro from a set of generic REBOP gravity flow simulations employing the shear-based attrition model of Bridgwater et al. (2003) (as implemented by Pierce 2010) and different combinations of primary fragmentation and rock block strength. With respect to external fines, blocks within the exhausted GRS and historic caves (e.g. DOZ) are conservatively assumed to contain 100% <50 mm diameter material by volume (30.4% <10 mm; 56.7% 10–20 mm, 12.8% 20–50 mm). This is a highly conservative assumption, especially as it relates to the significant volume of fines assumed to be present in the GRS.

In order to enable tracking of fragmentation in PCBC, the secondary fragment size distribution is subdivided into 10 size ranges and the volume fraction associated to each size range quantified. By including each of these volume fractions as separate block properties, each size range can be mixed and tracked like any other quantitative block model feature such as grade or density and then recombined at the drawpoint into a complete fragment size distribution.

The main inputs to the fragmentation forecast (CBSP, $Is50_h$, $P32_{eff}$ and elevation) are added to each block as well as calculated quantities (e.g. CPF) and flags for defining undercut and hydrofracked ground. By adding these to the PCBC simulation as tracked quantities, they can be used to help understand the fragmentation emerging from drawpoints within the forecast. For example, a forecast of fine fragmentation is likely to correlate with a low $Is50_h$ and/or high CBSP reporting to the drawpoint during the same period. The $Is50_h$ and CBSP values will be representative of the strength of in situ blocks from which the mixture of caved rock in the drawpoint originated and the cave back stress potential these were subject to during primary fragmentation.

The fragmentation block models are updated any time there are significant changes to the planned production schedule (which can impact CBSP) or if the geotechnical block models are updated (Is50h, P32v).

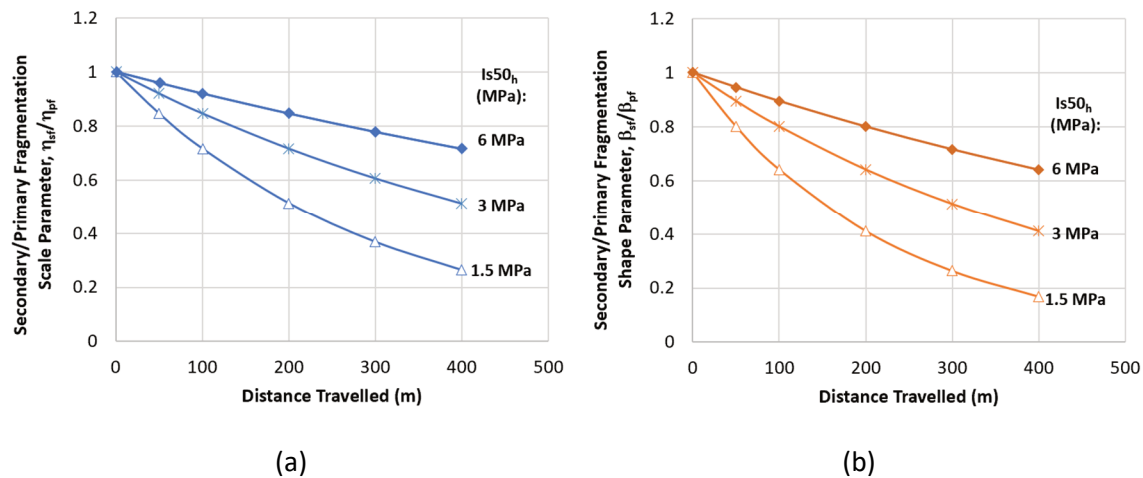


Figure 4 Relations used to estimate the (a) Weibull scale parameter (η_{sf}) and (b) shape parameter (β_{sf}) of the secondary fragment volume distribution based on the original primary fragmentation parameters (η_{pf} and β_{pf}), the host point load index (Is50h) and vertical distance travelled to the drawpoint

3 Production forecasting

Once a new or updated secondary fragmentation block model becomes available, it is imported into PCBC so that the volume fractions associated to the 10 size range bins and other properties outlined in Section 3.2 can be added to the PCBC block model for tracking during production simulation.

3.1 Mixing model assumptions

The mixing model and associated parameters used within PCBC for both GBC and DMLZ were based on pre-vertical mixing. This assumes vertical mixing only, with no impact from draw order or sporadic/stalled cave boundaries present to drive lateral flow. A fixed cone of 15 m radius is used to assign material available to each drawpoint, independent of primary and secondary fragmentation.

Recently, the mixing model was switched to Marker Mixing (MMIX) for GBC and DMLZ. At present, the model is still largely assuming vertical mixing only with no cave boundary inputs. The DMLZ MMIX parameters were adjusted to use the secondary fragmentation block model as a fines input to drive variable mixing across the footprint depending on fragmentation size. Work to further incorporate the secondary fragmentation block model into the new mixing model is currently underway.

3.2 Post-processing

3.2.1 Fragmentation distribution

Once the production simulation is complete, the fragmentation distribution reporting to a given set of drawpoints within a given time period can be determined by calculating and summing the tonnes of each size range that has reported and expressing as a percentage of total tonnes drawn across those drawpoints. The changeover time, plotted as a cumulative distribution of fragment size or volume, can be used gain insight into the evolving mix of primary and secondary fragmented material that is expected to be sent to the mill from a given production area (e.g. see Figure 5).

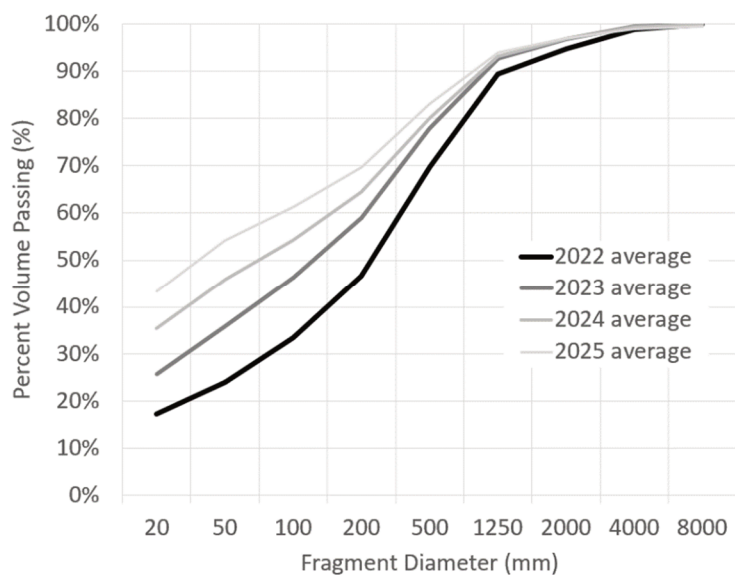


Figure 5 Example forecast output showing the evolution in expected fragmentation size distribution over time from a specific production area

3.2.2 Hang-up frequency

The hang-up frequency is estimated for every drawpoint in every month based on the percentage of fragments greater than 2 m³ in volume reporting to the drawpoint (from the PCBC forecast) and the average draw rate (from the draw schedule input to PCBC). The sensitivity to draw rate has been anecdotally noted in PTFI operations, with experience at DMLZ Mine in particular suggesting that maintaining or sustaining flow usually assists in minimising the hang-up frequency, specifically where low draw orders are received. By comparing actual hang-up frequencies and draw rates from GBC and DMLZ to the forecast oversize, it was possible to develop an empirical relation between hang-up frequency, monthly draw rate, DR_m, and percentage oversize, OS:

$$\text{Hang-up Frequency (hangups/1,000t)} = A1 * \exp(OS * (B1 * \exp(-DR_m/B2) + B3)) - A1 \quad (2)$$

where the coefficient A1 controls the threshold percentage oversize at which hangups start to occur, B1 and B2 control the sensitivity of hang-up frequency to draw rate and the non-linearity of this relation and B3 controls the sensitivity of hang-up frequency to percentage oversize. The relations are shown graphically in Figure 6 along with the best fit coefficients. More work is required to understand why the DMLZ relation predicts higher hang-up frequencies but there is evidence that it is related to the stronger rock blocks there, which are able to hang up more easily in the drawpoint (less susceptible to splitting) (Simanjuntak et al. 2020).

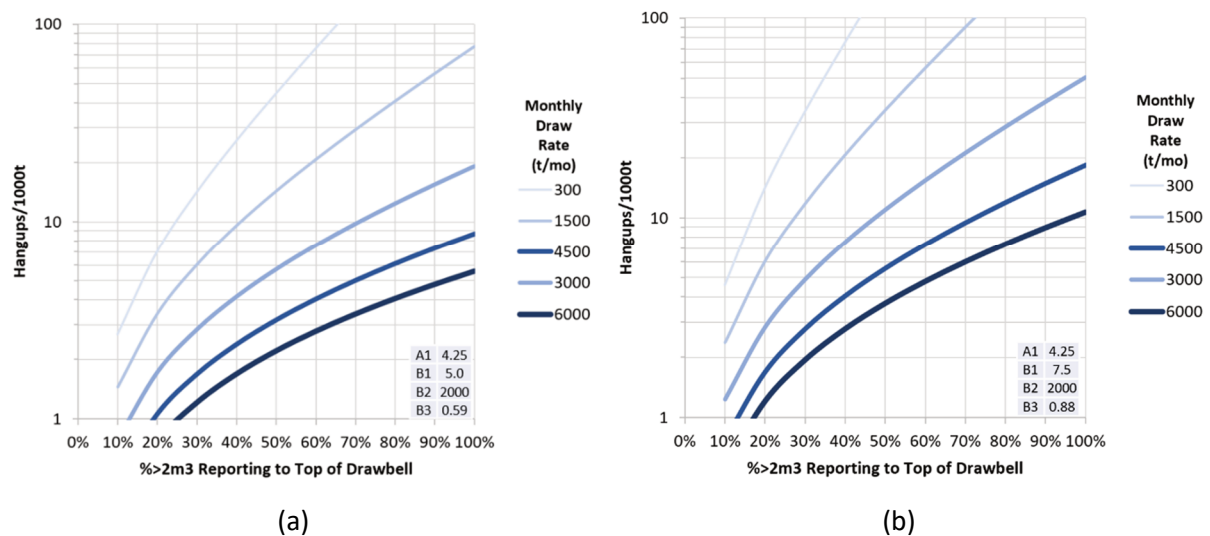


Figure 6 Empirical hang-up frequency relations derived from comparison of forecast oversize with actual hang-up frequency and draw rates at (a) GBC and (b) DMLZ

4 Reconciliation via monitoring and visualisation

Reconciliation is central to calibration of the methodology and the provision of a reliable forecast. This process relies on two key elements:

- Monitoring of actual drawpoint fragmentation and hangups.
- Rapid, accessible and up-to-date visualisation of the forecast against actual data (historical draw) and in isolation (future draw).

4.1 Monitoring (actuals tracking)

As with sampled metal grades, records of actual drawn fragmentation from drawpoint mapping using visual observations, supplemented with digital techniques, and actual hang-up frequencies from secondary breakage records provide a means to test the forecast on a regular basis and provide a target for ongoing calibration and reconciliation.

4.1.1 Hangups

Hang-up events are recorded by the loader drivers when muck cannot be removed from the drawpoints. The type of hang-up is classified as 'Types A, B, C or D' based on where the hang-up occurs in the drawbell. This classification is used by the planning engineers to assign the correct secondary breakage equipment and crews to handle the hang-up. The secondary breakage crew then carries out the task of bringing down the hang-up or breaking up the large boulders into sizes that fit into the loader also recording if the task was successful or not. This data source is used to calibrate against the forecast by only using the successful attempted hang-up removal events. Efforts were also made to ensure that any hangups that were recorded and not treated during the same shift were excluded from the calibration data source. As an example the Type D classified hangups are those high up in the drawpoint throat and required induced treatment with a solo drill so would not be treated at the end of every shift, resulting in the same Type D hangups occurring many times. These were counted as a single Type D hang-up for calibration. Forecasts currently do not distinguish based on hang-up type but work is underway to add this capability to FragPro.

4.1.2 Fragmentation

PTFI maps each drawpoint for fragmentation on a bi-weekly schedule during normal operations. The mapping is carried out visually and supported by digital mapping. A photograph is taken of all drawpoints and those

with a high percentage of fine material are analysed using fragmentation estimation software. The software estimates the fragmentation profile of a drawpoint and the user carries out a systematic checks of the results to ensure that it is representative of the fragmentation seen in the drawpoint. PTFI have carried out studies to validate the results against laboratory particle size distribution (PSD) testing and corrections are applied to this to ensure that the calibration of the model takes account for this.

The drawpoint fragmentation measures have a known bias resulting from the presence of blasted material in the drawpoint (from secondary blasting activities) during mapping and the absence of the largest fragments (which hang up and are not visible in the drawpoint). As a result, it is difficult to make direct comparisons between the volume percentage and size range of oversize ($>2 \text{ m}^3$) between the forecast and mapped data. This is one of the main reasons that oversize forecasts are directly correlated to monitored hang-up frequency rather than mapped fragmentation. It is also difficult to obtain accurate estimates of the percentage of finer material reporting to the drawpoints since this material tends to migrate to the base of the muckpile.

As a result of above challenges, drawpoints at PTFI are normally classified into relatively broad categories on the basis of mapped fragmentation (Priatna et al. 2020), with a letter designation defining the percentage of fragments $>5 \text{ cm}$ in diameter:

- Class A: $>70\%$ larger than 5 cm diameter (dominated by coarse material).
- Class B: $30\text{--}70\%$ larger than 5 cm diameter (mix between coarse and fine to medium material).
- Class C: $\leq 30\%$ larger than 5 cm diameter (dominated by fine material).

A water content score is also applied to drawpoints during mapping:

- Class 1: Water content $<8.5\%$ (dry).
- Class 2: Water content $8.5\text{--}11\%$ (moist).
- Class 3: Water content $\geq 11\%$ (wet).

These classes are used for wet muck handling with classes B2, B3, C2 and C3 having been correlated to a higher potential for wet inrushes and therefore only mucked using remote loaders. Since the fragmentation forecast does not yet incorporate water inflow estimates, direct comparisons can only be made to the fragmentation class (A, B or C).

4.2 Visualisation

Visualisation currently takes the form of time-based heat maps and charts in an interactive data visualisation software available in desktop and online formats. This same tool is used to communicate the forecast outputs to all stakeholders in the form of a dashboard containing pre-defined key graphs and heat maps. These examine changes over time and also spatially across the footprint.

4.2.1 *Variability between production blocks*

The largest scale for reconciliation is the mine or production block scale and this generally takes the form of charts illustrating monthly hang-up counts, cumulative hang-up counts and monthly average hang-up frequency, as shown in Figure 7. Good reconciliation has been achieved at the mine and production block scale for draw to date, with the characteristic rise and decay in average hang-up frequency well-captured. This includes differences between DMLZ and GBC, with DMLZ experiencing coarser fragmentation and correspondingly higher hang-up frequencies. Refinement of the relations between oversize, draw rate and hang-up potential (Section 3.2.2) was critical to the achievement of production block scale reconciliation of hang-up frequency.

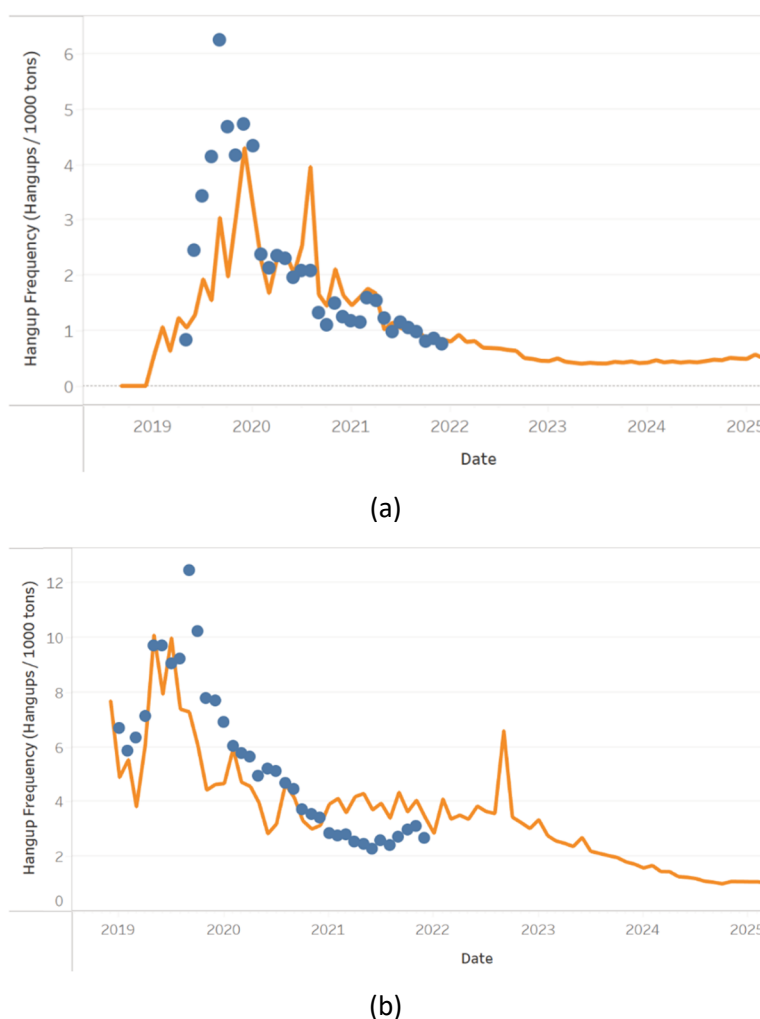


Figure 7 Reconciliation of forecast average hang-up frequency (lines) against actuals (dots) as of Q42021 for (a) GBC and (b) DMLZ

4.2.2 Variability within individual production blocks

As at many caving mines, a high degree of variability in the drawpoint fragmentation and associated hang-up frequency and fines entry can be observed across the DMLZ and GBC footprints at any point in time (Figure 8a). This is generally attributed to differences in lithology (material type), geotechnical properties (intact/vein strength and fracture/vein intensity), location in the cave back (reflecting different stress conditions at the time of primary fragmentation) as well as preconditioning and mixing. The FragPro forecasting methodology considers the impact of all of these variables and so exhibits similar patterns in the magnitude and length scales of variability in hang-up frequency (Figure 8b). Fragmentation production forecasts do not normally attempt to reconcile to the drawpoint scale due to the high combined uncertainty associated to the above quantities. Nevertheless, heat maps of forecast minus actuals (Figure 9) are useful for identifying sectors on the footprint with persistent local under- or over-prediction in both hangups and fines entry. These sectors have been the subject of targeted reconciliation efforts, primarily via auditing of the CBSP and $Is50_h$ associated to the material drawn in the sector. These efforts have yielded better reconciliation in some sectors and are carried out on an ongoing basis to improve forecast quality.

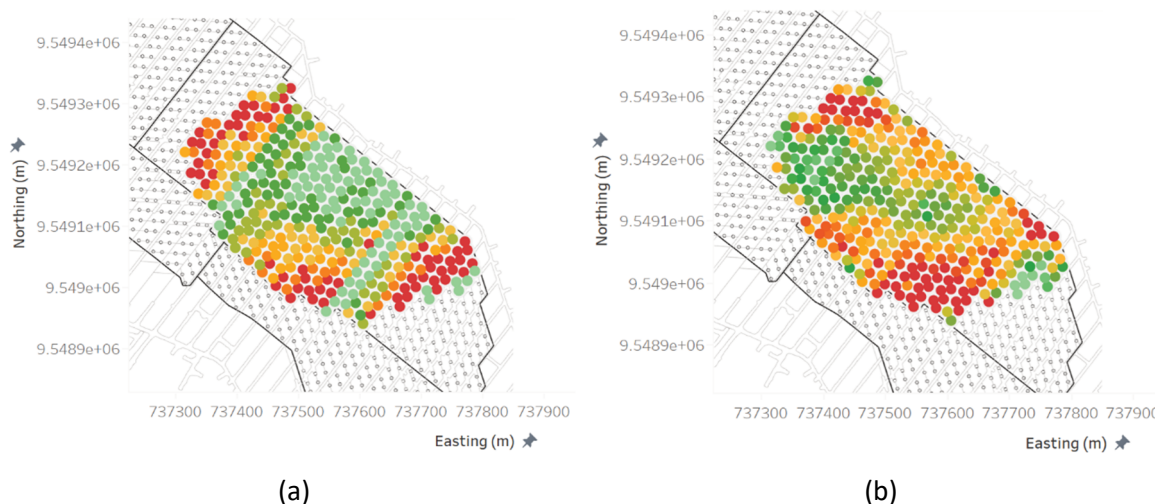


Figure 8 Heat maps of (a) actual and (b) forecast average hang-up frequency at DMLZ in December 2021. Colour scale in hangups/1,000 t ranging from 0 (light green) to 6 (dark red)

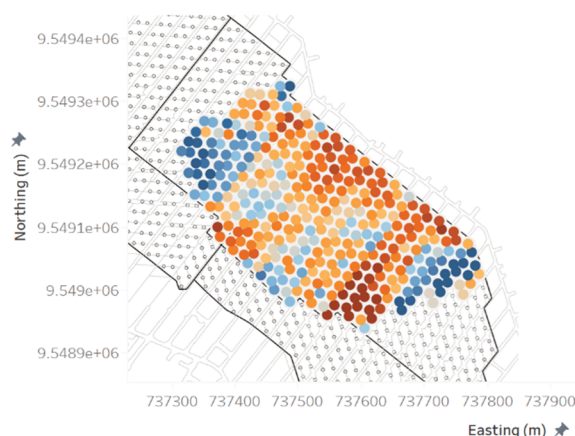


Figure 9 Heat map of forecast minus actual average hang-up frequency at DMLZ in December 2021. Colour scale in hangups/1,000 t ranging from -6 (light blue) to +6 (dark red)

5 Future work

A number of future work initiatives have been defined for FragPro-based forecasting. The following points summarise the leading objectives heading into the next stages of fragmentation forecasting at PTFI:

- **Wet muck forecasting.** There is the potential to extend the fines forecast into a wet muck forecast by overprinting understanding of water inflow trends onto the existing fines production forecast.
- **Caving rate forecasting.** There is evidence from examination of fragmentation and cave growth in DMLZ and GBC as well as the results of SRM testing that caving rate is also closely related to CPF and $P32_{eff}$. The potential for producing a caving rate block model from FragPro to aid in caveability and cave shape studies will be examined.
- **Gravity flow and mixing.** Any adjustments made to PCBC (e.g. to flow and mixing rules) to improve grade reconciliation will also benefit the fragmentation forecast. This could include inclusion of lateral mixing due rilling in air gaps and along static cave boundaries. This could be informed by the learnings on gravity flow and mixing derived from Elexon beacon data from GBC. Additionally, an investigation to incorporate aspects of the secondary fragmentation block model into the PCBC mixing model is currently underway.

- Visualisation improvements. Visualisation is currently focused on drawpoint class (fines content) and hang-up frequency. In order to aid in reconciliation there are plans to add material type heat maps (which can be compared against drawpoint mapping data) and heat maps of the key inputs to the fragmentation calculation that are already mixed by PCBC (CBSP, $Is50_h$, CPF, $P32_{eff}$).

6 Conclusion

As with other porphyry deposits, the relatively massive, veined rock at GBC and DMLZ results in significant spatial and temporal variability in the fragmentation reporting to the drawpoints. This is generally attributed to differences in intact/vein strength, fracture/vein intensity, location of origin in the cave back (reflecting different stress conditions at the time of primary fragmentation) as well as preconditioning and mixing. The FragPro fragmentation production forecasting methodology developed for PTFI considers the impact of all of these variables and has been demonstrated to reproduce measured trends in average hang-up frequency over time at GBC and DMLZ and to reproduce the magnitude and length scales of variability in hang-up frequency within individual production blocks. The FragPro workflow has been incorporated into the existing well-established PCBC-based metal production forecasting workflow at PTFI, enabling forecasting of the fragment size distribution reporting to the individual drawpoints over time, from which hang-up frequency and drawpoint class (fines content) can also be estimated. These forecasts inform numerous operational aspects of cave mining at PTFI, including draw scheduling, production planning, cave shape targeting and wet muck hazard management.

Visualisation within the FragPro workflow currently takes the form of time-based heat maps and charts in an interactive data visualisation software available in desktop and online formats. This same tool is used to communicate the forecast outputs to all stakeholders in the form of a dashboard containing pre-defined key graphs and heat maps. These display changes over time and also spatially across the footprint. Examination of differences between actuals and predicted within the dashboard offers the opportunity to identify sectors on the footprint with persistent local under- or over-prediction in both hangups and fines entry. While reconciliation to the drawpoint scale is not considered realistic, auditing of the material types being drawn in these sectors can be used to identify and reduce gaps or bias in the key inputs (e.g. rock mass strength, cave shape, cave back stress), ultimately leading to an improved forecast quality. In addition to improving input data quality, development of the FragPro workflow is also ongoing, with efforts focused on forecasting of wet muck, caving rate and hang-up type as well as improvements to mixing and visualisation.

Appendix

The Weibull distribution is used to describe fragmentation distributions within the methodology due to its versatility and flexibility. The probability density function (PDF) and cumulative density functions (CDF) are defined as follows:

$$\text{PDF: } F(x) = (\beta/(\eta^\beta)) (x^{\beta-1}) (\exp[-((x/\eta)^\beta]) \quad (3)$$

$$\text{CDF: } F(x) = 1 - \exp(-((x/\eta)^\beta)) \quad (4)$$

where β is the shape parameter, also known as the Weibull slope, and η is the scale parameter. The scale parameter corresponds to the 63.2 percentile of the data, while the shape parameter describes the shape of the distribution. A low shape parameter corresponds to a distribution that is skewed towards the left while a large-scale parameter results in a more symmetric distribution, similar to a normal distribution. More specifically, a Weibull shape parameter of 1.0 represents an exponential distribution, a shape parameter of 2.0 is a Raleigh distribution and a Weibull shape parameter of about 3.0 or above represents an approximately normal distribution.

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