A Cost Benefit Analysis to Explore the Optimal Number of Blast Movement Monitoring Locations

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ABSTRACT

Blast movement measurement is a key component of grade control, enabling mines to carry all of the precision involved in locating ore blocks, through a chaotic blast, to production. A monitoring system was developed about ten years ago so that mine operation personnel can measure three dimensional movement in every production blast. Research has shown that blast movement is always highly variable with a significant non-deterministic component. The consequence is that modelling will be inaccurate and therefore optimal ore recovery can only be achieved by direct measurement of blast movement.

Three dimensional movement vectors are measured at discrete locations in the blast. If blast movement is only measured at one location in a blast pattern, data is severely limited and has all of the inherent inaccuracies of modelling a variable population. It is intuitive that the accuracy of defining the post-blast ore block mark-ups are proportional to the number of movement measurement locations, however increasing the number of monitoring locations causes increases to the direct operating costs of the mine.

A cost-benefit analysis is used to explore the optimal number of monitoring locations. Using the method described in this paper, an automated selection of the number and location of blast movement monitors are analysed against the value of recovered ore compared to the control, for each trial.

INTRODUCTION

Significant time and resources in the mining geology department are dedicated to accurate determination of the parameters and geographic extents of ore blocks. The delineation of these blocks are defined with consideration for the most economic downstream destination of that material, using the site specific mining process. In order to carry the precision involved in locating ore blocks through a chaotic blast to production, blast movement must be accounted for.

Innovative technology has been developed and commercialised so that open pit mine operation personnel can measure three dimensional movement in every production blast. However, three dimensional movement vectors are measured at discrete locations in the blast. If blast movement is only measured at one location in a blast pattern, data is severely limited and the process of translating ore blocks takes the form of a model, with all of its inherent inaccuracies (Thornton, 2009a). The post-blast ore block mark-ups are proportionally accurate to the number of movement measurement locations, however increasing the number of monitoring locations increases the direct operating costs of the mine.

Real production blasts from three different mines, varying in commodities and geological deposits, are used to explore the optimal number of monitoring locations. Using the method described in this paper, relationships are explored between the number of blast movement monitoring locations and the economic impact as a result of misclassification.

BACKGROUND

Research at the University of Queensland resulted in the development of an active blast movement marker (Thornton, Sprott and Brunton, 2005 and Thornton, 2009b) and subsequent commercialisation by Blast Movement Technologies (BMT). The blast movement monitor (BMM) System comprises directional transmitters that are installed in the blast prior to blasting, that are remotely located after the blast by specialised hardware. The three dimensional movement vectors are then used in a software program to translate ore blocks using proprietary logarithms derived from over ten years of blast movement research.

Variation of blast movement

If there was no variation in the movement at discrete monitoring locations, then only one BMM would be needed to determine the vector of all ore translation, and could be placed anywhere in the blast. However, production blasting is a violent event in a heterogeneous environment and results from BMT and other researchers demonstrate that variation in

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horizontal movement in any given blast is at least 50 per cent either side of the mean (without edge effects). Figure 1 shows the distribution of horizontal movement for all blasts that were measured in 2013 at two different gold mines. Mine A is located in Western Australia where data was gathered from 368 blast movement monitors placed in 117 blasts, and Mine B is located in Africa where 354 blast movement monitors were placed in 71 blasts. The average horizontal movement at Mine A and B is 12 m and 6.5 m respectively, and the standard deviation is 4.2 and 4.8 respectively. Regardless of the magnitude of movement, the spread of data is similar, and is expected to be typical for all blasts measured at a mine.

There are a number of factors that contribute to the magnitude and direction of movement during blasting, including but not limited to:

- blast design parameters (ie powder factor, burden, spacing, detonation timing etc)
- rock mass characteristics
- boundary conditions (ie choked or free-faced).

In most mines, only a few of these characteristics are consistent between blasts, while others unavoidably vary. However, even in an individual blast, the magnitude of horizontal movement measured at discrete monitoring locations can vary significantly. Table 1 summarises the characteristics of three blasts used as case studies and Figure 2 shows the variation in horizontal movement graphically.

As shown in Figure 2, horizontal movement measured at a number of points throughout an individual blast, at similar depths, also varies significantly. Due to the variability between blasts at a given mine, and similar spread in data between points in individual blasts, modelling movement is inaccurate compared to direct measurement (La Rosa and Thornton, 2011 and Hunt, 2014). Further, using only few blast movement monitors inherently takes the form of a model.

Definitions

Stakeholders in different companies and regions throughout the global mining industry have different definitions for various terms that are used throughout this paper. For consistency please refer to the following definitions:

- *Waste* – material having less than the economic cut-off grade, and is not defined with an ore block. For this analysis, it is assumed that areas of waste have grades of 0 g/t.
- *Ore* – material that is delineated as an ore block
- *Ore loss* – ore that is mined as waste due to the incorrect translation of the post-blast ore block
- *Dilution* – waste that is mined as ore due to the incorrect translation of the post-blast ore block
- *Ore misclassification* – ore with a grade or characteristic (ie contaminant) that is mined as ore with a different grade or characteristic, due to the incorrect translation of the post-blast ore block.
- *Flitch* – in order to improve the accuracy of grade control, a bench can be blasted at full-depth but grade control and mining is conducted as multiple subbenches (typically up to four). These individual benches are referred to as flitches. For example, Blast B has different ore blocks in two flitches, the top from 0 m to 5 m below the surface and the bottom from 5 m to 10 m below the surface. Depending on the regions, flitch mining is also referred to as multipass mining or split-benching.

METHODOLOGY

A module has been developed for the BMM System software that automatically calculates areas of ore loss, dilution and misclassification, completing all of the basic tools required for automatic ore loss and dilution quantification. To facilitate this optimisation analysis, another module was developed to perform these grade control calculations for every combination of measured movement vectors in selected blasts.

Error is reduced as the density of known points increases. Subsequently, the more movement monitoring locations used in a blast pattern, the less error there is when interpolating between measured vectors, resulting in a more accurate post-blast ore block translation. Since the data set is limited by the total number of blast movement locations used in a particular blast, three actual production blasts from three different mines were chosen that used between seven and sixteen movement monitoring locations.

The post blast location of the ore blocks translated by all vectors in each blast are used as the control case in each of the optimisation analyses. For each case, the ore blocks are then moved by a combination of vectors contained within the blast, referred to as a trial, and the post blast ore block locations for

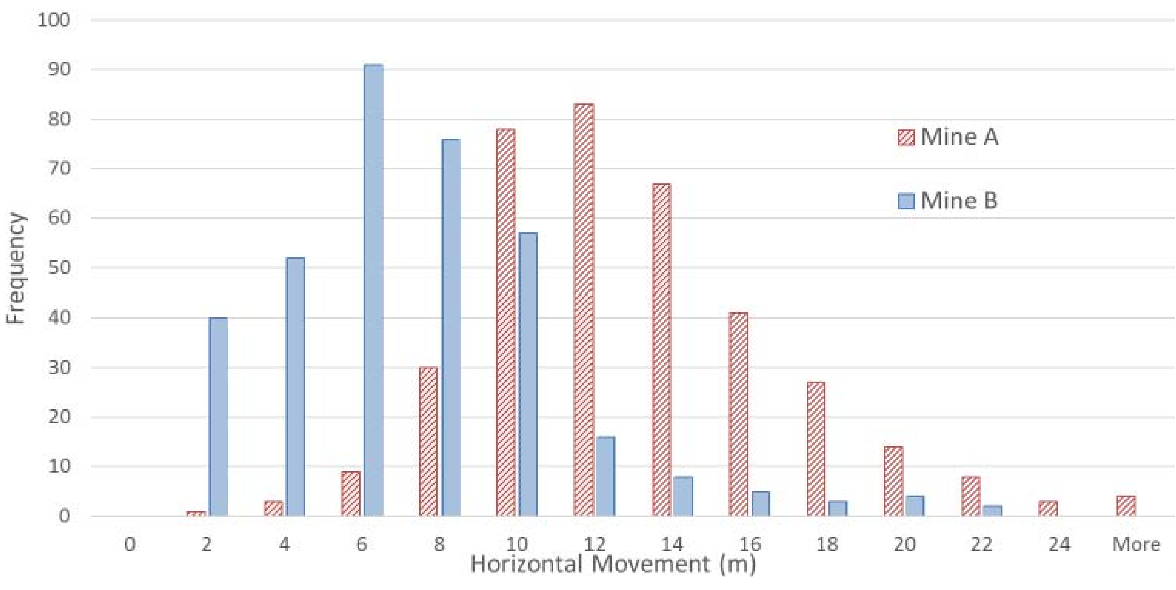

FIG 1 – Variation in horizontal movement for all blast movement monitors used in 2013.

TABLE 1
Individual blast characteristics at three separate mines.

	Mine A/Blast A	Mine B/Blast B	Mine C/Blast C
Location	Australia	Africa	Africa
Commodity	Gold	Gold	Platinum
Initiation	Echelon	Offset V	Offset V
Bench Height (m)	12.0	10.0	15.0
Powder Factor (kg/m3)	1.15	0.96	1.3
Assumed Density (t/m3)	2.7	2.9	2.7
Number of Monitors	16	7	14
Range of Horizontal Movement (m)	9.4 to 18.1	5.0 to 14.4	2.4 to 19.7
Average Movement (m)	14.1	8.7	10.3

each trial are compare to the control. A set of trials are carried out for every incremental number of BMMs from one to the total number of BMMs in a given blast. The number of trials in each set is the lesser of every combination of vectors, or 50. For example, given a blast that has 16 BMM vectors:

- there are 16 trials selecting one BMM, as there are only 16 vectors to choose from
- there are 50 random trials selecting eight BMMs, as there are 12 870 combinations to choose from
- there are 50 random trials selecting 14 BMMs, as there are 120 combinations to choose from
- there is one trial selecting 16 BMMs, as there is only one combination of choosing 16 vectors.

CASE STUDIES

For each of the three mine examples used in this analysis, the following assumptions are made:

- The control case is the post-blast location of the ore blocks, translated from their preblast locations by all vectors measured in the blast. If there were more vectors to choose from, the post-blast ore would be defined more accurately, however this study is limited by the data available in the blasts.
- In addition to the conditions of the blasts previously provided in Table 1, it is assumed that the price of gold and platinum are $1300/oz and $1450/oz respectively.

Blast A

The blast chosen from Mine A is shown in Figure 3. The entire pattern is delineated with ore blocks with no waste, except for the small area in the southeast corner. Recall that 16 BMMs ranging in horizontal movement from 9.4 m to 19.7 m were used to translate the ore blocks to their post-blast location. If the ore blocks were mined in their preblast location, then 40 per cent, or 247 000 t of the ore would have been misclassified.

The post blast location of the ore blocks translated using all 16 BMMs is used as the control case in the optimisation analysis. The translated ore blocks for each trial are then compared to the control. For example, Figure 3 compares using zero BMMs to the control, which results in 40 per cent misclassification. Each subsequent trial is represented by a data point in Figure 4.

The spread in the values for each set of trials is due to the variability of the movement throughout the blast. If the blast was only monitored with one BMM, ore misclassification would have ranged between 5 per cent and 15 per cent (31 000 t and 92 000 t) depending on how well the randomly selected vector represented the typical movement of the blast – defined by the movement of 16 vectors. Since ore blocks are delineated throughout the entire blast area, and given the large spatial variability of horizontal movement throughout the blast, no combination of any number of vectors results in a misclassification of 0 per cent. As previously stated, the use of 16 BMMs in this blast will not perfectly define the post blast location of the ore blocks – but we are limited only to the data available in the blast. If there were more vectors to choose from, there would be a similar spread of values for 16 BMMs with the average of all trials expected to be near the line. This is described further in the Appendix.

Nevertheless, the intention of this paper is to evaluate the break-even point, or the point at which adding another

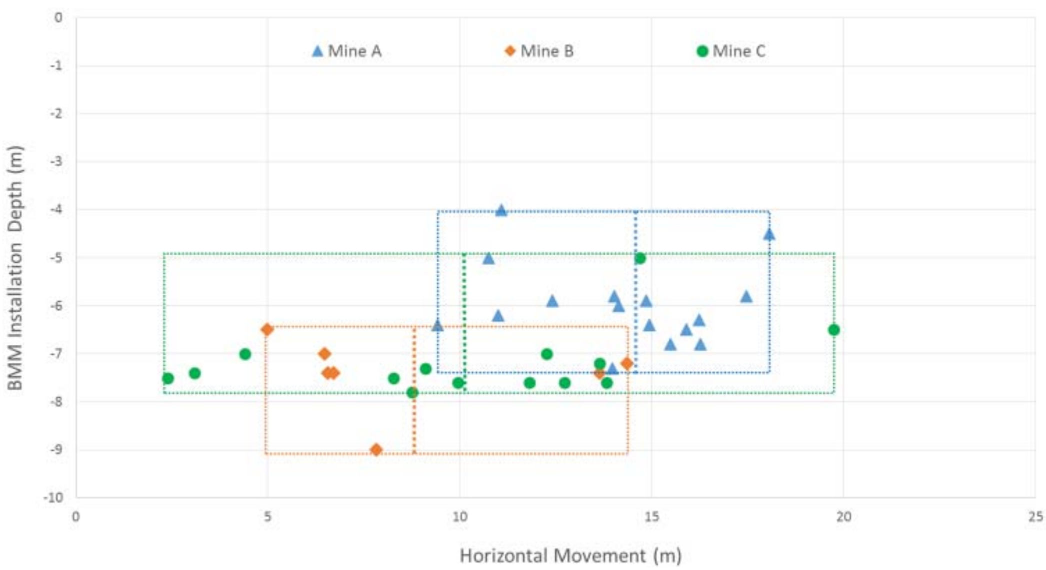

FIG 2 – Variation in horizontal movement for individual blasts.

FIG 3 – Mine A Blast ore blocks translated using 16 Blast Movement Monitors placed throughout the pattern.

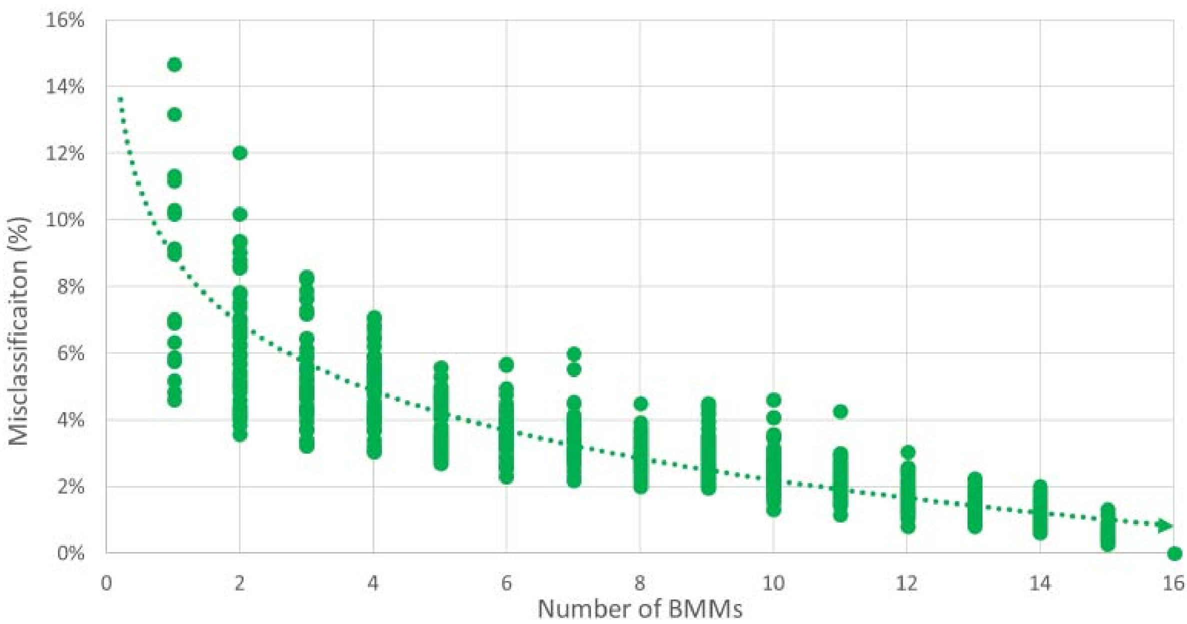

FIG 4 – Mine A – Comparative analysis showing the reduction of ore misclassification per added BMM.

monitoring location to the blast becomes redundant, or uneconomical. This sort of analysis for the selected blast at Mine A is difficult to evaluate due the complexity of the economics of misclassification, and is outside of the scope of this paper. These analyses are reserved for comparisons of ore loss shown in the blasts selected at Mines B and C.

Blast B

At this mine, blasts are conducted on 10 m benches but grade control and mining are performed on separate 5 m flitches. The higher grade, selective mining operation has ore blocks as small as 4 m by 20 m and Figure 5 shows the lower 5 m flitch of a blast, ie it is half of a full bench blast. Blast movement was measured at seven locations, and the horizontal movement ranged from 5.0 m to 14.4 m. If the ore blocks were mined in their preblast location, then there would have been up to 565 oz of gold lost, valued at $745 000, compared with using the seven measured vectors.

The cost-benefit analysis is done by assessing the value of the mineral that will be mined from the blast for each combination of monitoring locations. There is approximately $4.08 M of gold in the bottom 5 m flitch of this blast. The same vector selection method used in Case A is applied to this blast to determine the incremental revenue gain for each additional blast movement monitoring location. Figure 6 displays the results of this analysis. The total benefit of monitoring is limited to $4.08 M, and on the graph, seven BMMs achieve this because that is the total amount of data that was collected. However, this is not reality and it is important to recall from blast A, that if there were more vectors to choose from, there would be a similar spread of values for seven BMMs with the 'average' expected to be near the trend line. The total ore that would be mined if the blocks were mined in their preblast location is dependent on the actual location of the post-blast ore blocks. Figure 5 is just the best estimate based on only seven vectors. Subtracting this base-case ore loss ($745 000)

FIG 5 – Mine B Blast: Gold polygons translated using seven Blast Movement Monitors placed throughout the pattern.

from the total value of ore results in the value of ore sent to the mill being approximately $3.35 M. These extreme points can be seen on Figure 6 with the ranges of values in between and a fitted curve. As described in the Blast A case study, the variability in horizontal movement is responsible for the spread of data for each set of trials. This is explained further in Appendix.

In order to evaluate the optimal number of monitoring locations, the derivative of the fitted curve from Figure 6 is plotted with the incremental cost of monitoring in Figure 7. This shows the added revenue that each incremental monitoring location provides compared to the cost of adding that monitoring location. A conservative estimate of $500 is used as the total cost per monitoring location which includes; total ownership of the BMM system, drilling, installation and detection time and materials etc. The breakeven cost-benefit point is found when adding another monitoring location costs more than the additional revenue gained, which is the point where the benefit and cost curves intersect in Figure 7. In other words:

- On average, if only one BMM were used to monitor this blast, approximately $140 000 additional gold would be processed at the additional monitoring location cost of $500 (ROI = 28 000 per cent).
- Add a second monitoring location at the cost of $500, and on average, approximately $70 000 additional gold would be processed (ROI = 14 000 per cent).
- Using seven monitoring locations compared with six, will increase revenue by $20 000.
- The point at which the incremental ROI = 100 per cent, exceeds 100 monitoring locations.

Due to the variability of the blast data, and extremely high discrepancy between the value of ore in the blast and the cost of monitoring, a practical limit is reached before a financial limit.

Blast C

The blast chosen from Mine C is shown in Figure 8. The blast was initiated in an offset-V configuration, in a direction

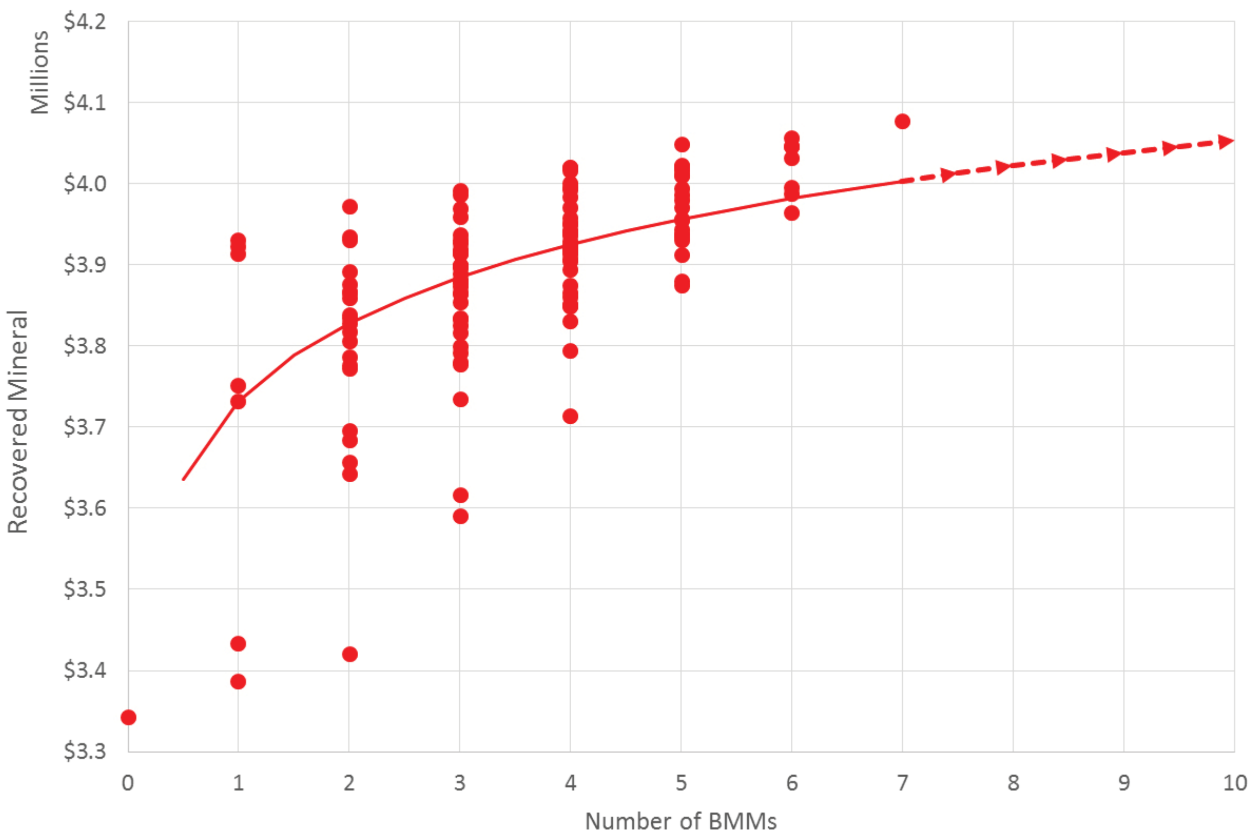

FIG 6 – Total recovered mineral, represented by added revenue, per added monitoring location.

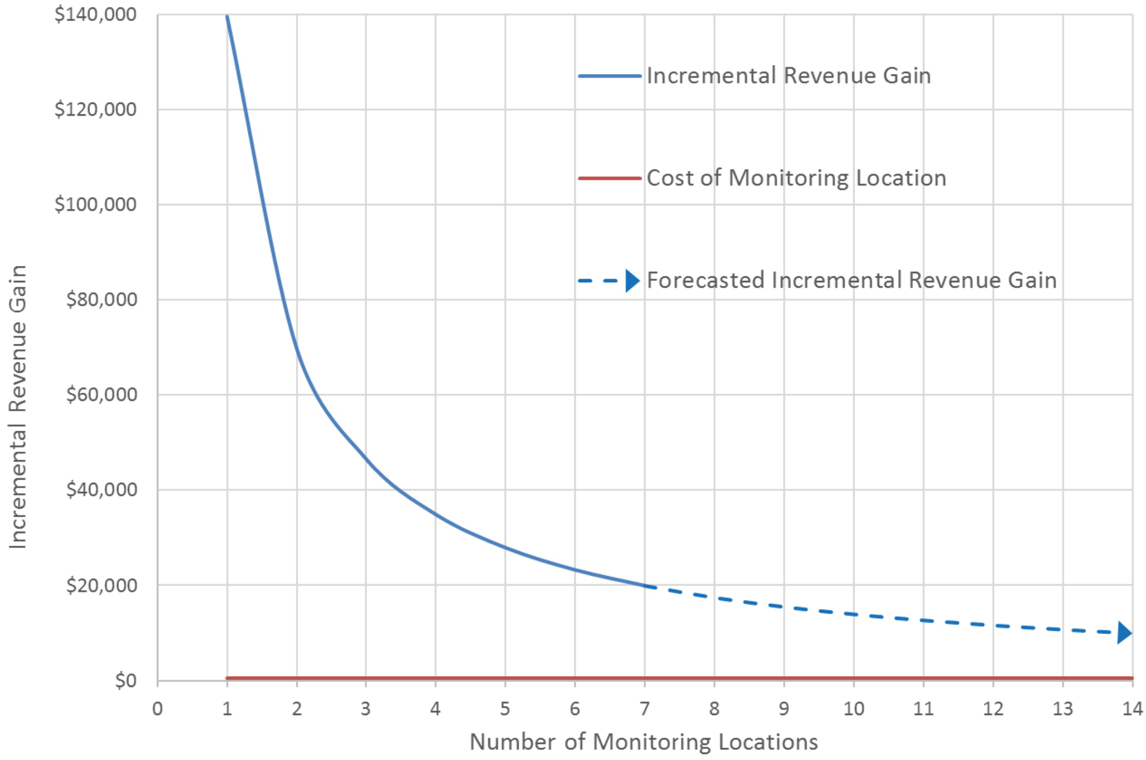

FIG 7 – Incremental revenue gained as a resulted of the addition of each monitoring location.

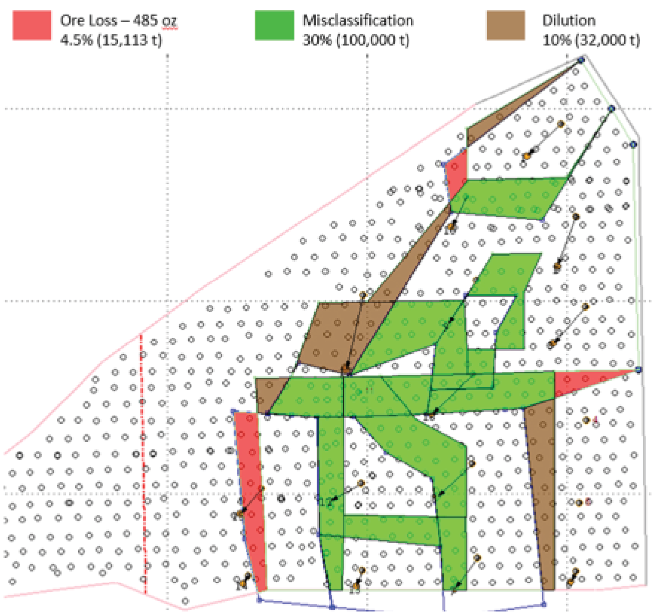

FIG 8 – Mine C Blast: Platinum polygons translated using 16 Blast Movement Monitors placed throughout the pattern.

slightly offset from the strike of the orebody. Sixteen BMMs ranging in horizontal movement from 2.4 m to 19.7 m were used to translate the ore blocks to their post-blast location in the 15 m bench. Assuming a conservative average grade of 1.0 g/t Pt, if the ore blocks were mined in their preblast location, then there would have been ore loss of up to 485 oz of platinum, or approximately $700 000 lost revenue.

The total value of platinum in this blast is approximately $15.5 M. The same analysis method used in Case A and B is applied to this blast to determine the incremental revenue gain per added blast movement monitoring location. Figure 8 displays the results of this analysis. The total benefit of monitoring is limited to $15.5 M. It is important to recall that if there were more vectors to choose from, there would be a similar spread of values for seven BMMs with the 'average' expected to be near the line. Similarly, the total ore that would be recovered if the blocks were mined in their preblast location is dependent on the actual location of the post-blast ore blocks – but it will be approximately $14.8 M (total platinum $15.5 M subtract ore loss $0.7 M). This is explained further in the Appendix.

As described in the two previous examples, the variability in horizontal movement is responsible for the spread of data for each set of trials. In this particular example, there are ten trials of translating ore blocks with only one, two and three BMM vectors that would actually result in worse ore recovery than not translating the ore blocks at all. This is caused by the selection of vectors that vary greatly from the actual movement in the areas of the blast where ore loss is seen. In all ten trials, the vector with the greatest horizontal movement measured in the blast (19.7 m) was randomly selected. Lacking a high density of known movement vectors, the blast inherently takes the form of an inaccurate model. Similarly there are many trials across all sets of data where very little ore is lost because the vectors chosen during that trial included those in close proximity to the areas of ore loss. Of course it would be prudent to place BMMs in areas of expected ore loss based on anticipated movements, however if only those few areas are targeted, there is still a significant amount of misclassification – which requires blast monitoring locations dispersed across the entire orebody. For example, when randomly selecting four BMMs, the trial with the highest recovered ore includes the four vectors closest to the areas of ore loss, yet there is still 7 per cent, or 24 000 t of misclassified ore in the bulk of the blast.

Similar to Mine B, the derivative of the fitted curve in Figure 9 is plotted against the incremental cost of monitoring. In other words, Figure 10 shows the added revenue that each incremental monitoring locations provides versus the cost of an additional monitoring location.

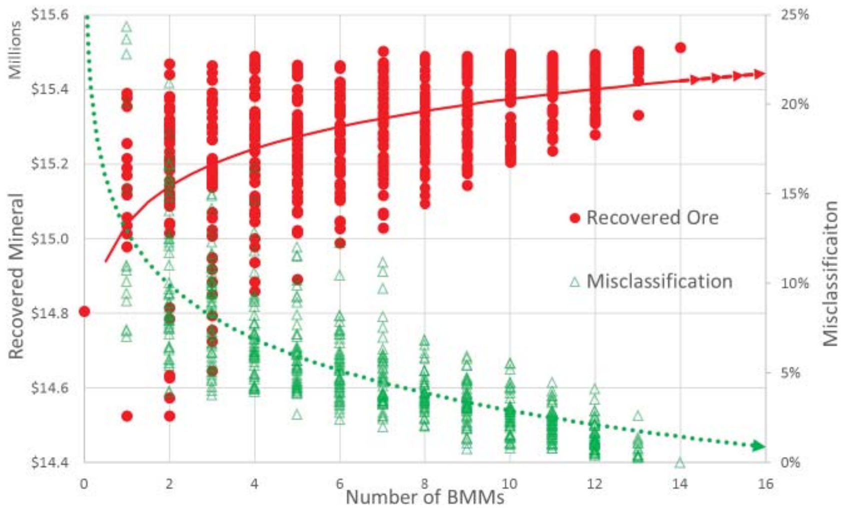

FIG 9 – Total recovered mineral, represented by added revenue, per added monitoring location.

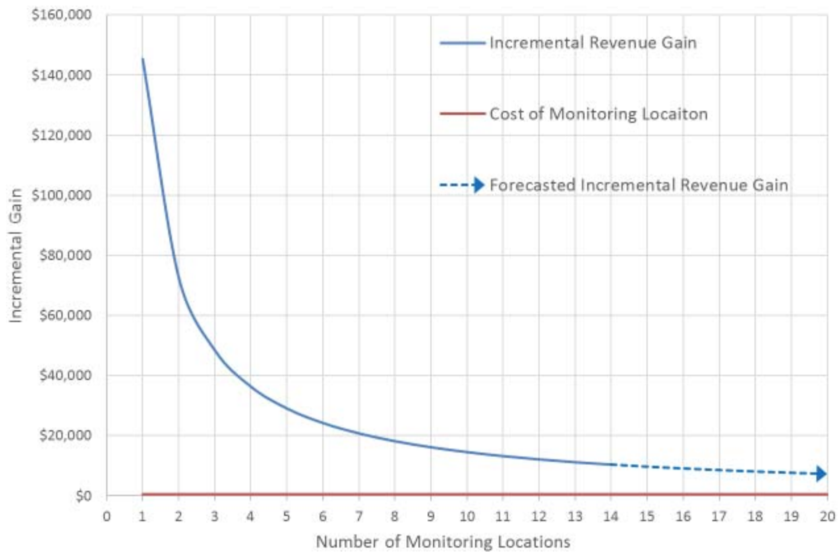

FIG 10 – Incremental revenue gained as a result of the addition of each monitoring location.

Evaluating ore loss alone, and ignoring the large costs of misclassification, the break-even point for randomly placing BMMs in this blast would be >250 monitoring locations. Recall that this analysis assumes that the average grade of all ore blocks is 1 g/t Pt. In order to force the break-even point to 14 BMMs (the point at which the two curves would cross in Figure 10), the average grade of all platinum ore blocks would have to be 0.05 g/t Pt. Similar to Mine B, due to the variability of blast movement at Mine C, a practical limit of blast movement monitoring locations is reached well before a financial limit.

DISCUSSION

The case study blasts were not monitored specifically for this study but rather just normal grade control practices at those sites, and are therefore limited to the number and location of the blast monitors used. In both Blast B and Blast C, where financial metrics were used to evaluate the optimal number of random blast movement monitoring locations, a practical limit was reached well before a financial limit.

However, for trained personnel, the general direction of movement is predictable and there will be varying degrees of information about the location of ore blocks prior to blasting. In these instances, areas of anticipated ore loss (or any other critical criteria) can be targeted with higher concentration of blast movement monitors. The significance of ore misclassification will vary from site to site so monitoring is required to define grade boundaries but there will be areas in some blasts where there is not a practical benefit of installing a BMM, provided there is adequate coverage in other zones. For example, in Figure 9 (Blast C), it can be seen that there is a particular combination of only four movement vectors that translated the ore blocks resulting in nearly 100 per cent ore recovery. This is because there are only three areas of ore loss so only a few vectors have a direct impact, however there is still 7 per cent (24 000 t) of misclassified ore when using those vectors.

Therefore, in practice, the financial and practical limit is related to the number of ore contacts and the complexity and length of these boundaries. The grade has lesser influence because the value of the ore, or the cost of processing waste or a contaminate, is so much greater than the cost of monitoring. When precise locations of ore blocks are not available prior to blasting, a reasonably high density grid of monitoring holes throughout the blast is recommended. When the ore blocks are available prior to blasting, a practical spread of BMMs along all ore and ore/waste contacts is recommended.

CONCLUSIONS

Blast movement measurement is a critical component of production grade control, enabling mines to carry all of the precision involved in defining ore blocks, through a chaotic blast, to production. This study explores the optimal number of blast movement monitoring locations in three different blasts by comparing ore loss, dilution and misclassification resulting from selecting numerous combinations of measured movement vectors. The conclusions from the study are:

- Blasting is highly variable, and horizontal movement measured at discrete monitoring locations in a single blast can have a range that exceeds 100 per cent of the mean.
- Due to this variability, in the event that only few measurement locations are used to quantify blast movement, there is a chance that the measured movement at the selected locations will be significantly different from the actual movement at ore block boundaries. The case studies demonstrate that under certain circumstances, using very few vectors (or modelling) to translate ore blocks, a mine may actually lose more ore than if the ore blocks were mined in their preblast location ie doing something inappropriately could be worse than doing nothing.
- Blast movement cannot be modelled with sufficient accuracy to optimise grade control. Direct measurement of blast movement is the only accurate method of translating ore blocks and due to the inherent variability of movement, more monitoring locations leads to more accurate delineation of the ore boundaries.
- For the two case studies with complete financial data, from a purely cost-benefit perspective (cost per additional monitoring location versus the incremental revenue gain), hundreds of monitoring locations would improve the accuracy of ore control to be cost-effective – approximately 100 and 250 respectively. This quantity is clearly not practical but it highlights the value of accurately accounting for blast movement and that a practical limit on the number of BMMs is reached well before a financial limit, ie in practice, every additional monitoring location will pay for itself many times over. A high concentration of monitoring locations in important areas and intelligent selection of these locations would be the best practical outcome.
- Short-sighted reductions in operating cost by reducing the number of blast movement monitoring locations in a blast can result in significant losses in revenue. For example, the average increase in revenue from using three BMMs instead of two BMMs in Blast B is $46 000 (ROI – 9200 per cent). In blast C, the average increase in revenue from using nine BMMs instead of eight BMMs is $16 155 (ROI – 3200 per cent).
- Given the large spatial variability of horizontal movement throughout Blasts A and C, and the distribution of ore blocks, no combination of any number of measured vectors resulted in reduction of misclassification to near 0 per cent. Even if the ore blocks are available prior to the blast, and the direction of movement is anticipated, a high density of monitoring locations is still required across all ore contacts.

There are too many variables in both the properties of production blasting and the orebody being fragmented to provide a blanket recommended number of blast movement monitoring locations. Given the disparity between the high value of the ore and the low cost of monitoring, it is anticipated that a practical limit will always be reached before a financial limit. However, mines should conduct their own analyses and evaluate the results based on their site-specific characteristics.

APPENDIX

This appendix serves as an explanation why the curves in Figure 4, Figure 6 and Figure 9 do not cross the y axis and do not cross the x axis at the control. When the analysis is run using the methodology described in this paper, it must be assumed that the ore blocks translated by all BMMs contained within the blast is the correct location of the post-blast ore blocks. This is because we are limited to the data available. For example, if you had a blast with only four BMMs in it, and you ran the analysis, comparing each trial to the ore blocks moved with four BMMs, we know that we are likely underestimating the true ore recovery of using four BMMs, but we have to assume that it is 100 per cent.

Figure 11 is a comparison of the outcomes of the analysis, based on the number of BMMs used as the control for the example described at Mine C. The grade is assumed to be 0.5 g/t Pt, and the total ore contained in the blast, as a result, is $2.7 M. Each number in the legend represents the total number of BMMs used for the control for each analysis. Each line is the averages for all trials in that analysis (similar to the fitted lines in Figure 6 and Figure 9).

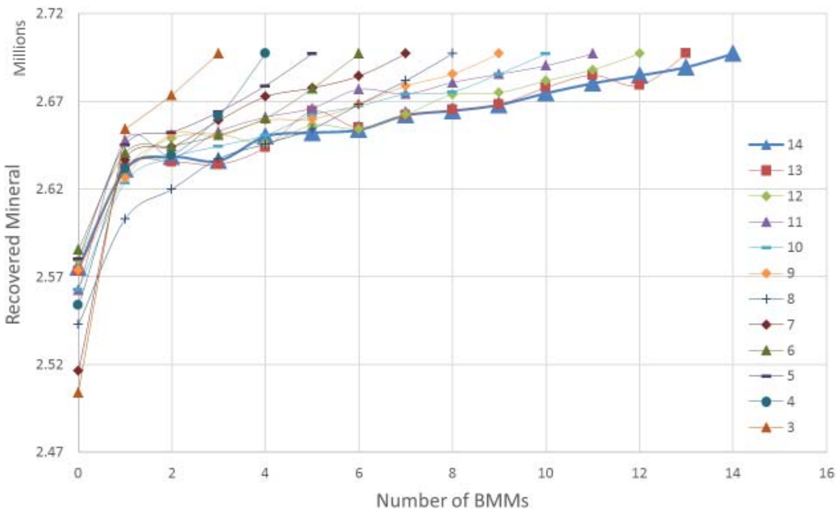

FIG 11 – Outcomes of the comparative analysis based on the number of BMMs used as the control.

There are two important conclusions drawn from this:

1. The starting point of the curve, which is the recovered ore if you were to mine the preblast ore blocks without translating them, is always going to vary, based on the accuracy of the assumed control (the assumed actual post-blast location of the ore).
2. As expected, the line of best fit through the data should not meet the maximum amount of ore contained within the blast at the maximum number of BMMs used in the analysis, but rather it will carry on to an unknown point. For example, if we placed 10 BMMs into this blast and conducted the analysis, the average values curve for all trials would appear as the light blue line in Figure 11. However, when doing the same analysis with 14 BMMs, on average, we overestimated our control by at least $50 000 (difference between the dark blue line at 14 BMMs and the light blue line at 10 BMMs).

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