Optimum Dig Lines for Open Pit Grade Control

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ABSTRACT

Critical reviews of grade control generally focus on blast hole sampling and the estimation of ore control block model (OCM) grades with little or no attention given to dig line design. The estimation of block grades is deemed important as estimation errors lead to the misclassification of ore types and subsequent dollar loss. However, underestimation of block grades may be more or less costly than overestimation. Recognition of this problem led others to the application of loss functions for the assignment of ore type to individual OCM blocks. The method is known as MPS or maximum profit selection. However, each OCM block may be misclassified a second time by dig line design. Although each block may initially be assigned an optimum ore type, OCM blocks are seldom minable by ore type as individual blocks. A very common solution is the design of minable dig lines loosely constrained by a minimum mining width. These dig lines are often designed manually or by variations of computer generated contour lines and typically incur excessive dollar loss. This paper provides a method for constrained optimum dig line design where dig line misclassifications are also evaluated through loss functions or MPS. Constrained optimum dig line designs minimize the dollars lost by dig line misclassifications and are constrained by a minimum mining width. A case study is provided illustrating constrained optimum dig line design and subsequent benefits.

INTRODUCTION

Open pit grade control generally entails the sampling and assaying of blast hole cuttings followed by the estimation of ore control block model (OCM) grades. The estimated OCM block grades are then used in turn to design surface polygons or dig lines that outline and separate various ore types and waste material for the purposes of mining. Unfortunately, the estimation of block grades and the design of dig lines often results in the misclassification of ore types. For example:

- True block grades are not known and must therefore, be estimated. If the classification of ore type based on the true but unknown block grade is different from the ore type based on the estimated block grade, then the ore type of the block is misclassified.
- The locations of the true ore type contacts are not known and therefore their locations must also be estimated. Dig lines must be designed so that the contained ore type can actually be mined as designed by project mining equipment. If the dig line classification of ore type is different from the ore type classification based on block grade, then the block is misclassified. For example, a dig line containing a majority of blocks classified by grade as mill ore may include a small proportion of blocks classified by grade as waste. The waste blocks are misclassified by the dig line and as a result, will be sent to the mill.

Misclassification errors reduce revenue. They do not cancel one another. They simply accumulate. Interestingly, the misclassification of OCM blocks resulting from the estimation of block grades has received considerable attention. For example, several authors have shown that the classification of ore types based on the best[1] estimates are sub-optimal (Schofield, 1997; Srivastava, 1987; Deutsch, Magri, and Norrena, 2000). The following example illustrates this apparent paradox:

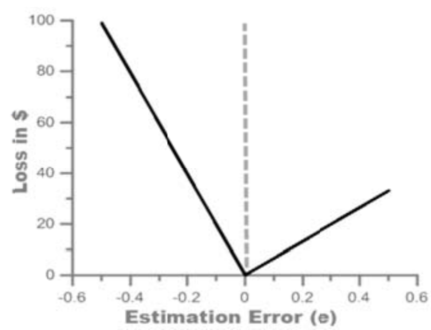
- Consider a truck that has just been loaded with muck pile material and the mill and waste dump are the only two possible destinations.
- If the truck is sent to the mill, and the true grade of the truckload is below the waste/mill cutoff grade, a relatively small dollar loss will occur because although the truckload is waste, it does contain some metal that will be recovered which will offset processing costs.
- If the truck is sent to the dump, but the true grade of the truckload is greater than the waste/mill cutoff grade, the full potential dollar value of the truck load of ore is lost – nothing is recovered.

In other words, the loss resulting from an underestimation of grade and misclassification of ore type may be greater than the loss resulting from an overestimation of grade and the ensuing misclassification of ore type. Srivastava (1987) points out that minimum error variance estimates[1] such as kriged estimates may not be the best for grade control because minimum error variance estimates are calculated by assuming the loss resulting from over and underestimation is symmetrical. But, as the example above illustrates, the losses due to underestimation may be far greater than those due to overestimation.

One solution to the problem of asymmetric losses consists of assigning loss functions to estimation errors. Equation 1 and Figure 1 provide an example of an asymmetric loss function where the loss due to underestimation is greater than the loss due to overestimation.

$$L(\hat{Z}, Z) = \begin{cases} c_1 * \left|\hat{Z} - Z\right| & \hat{Z} \le Z \\ c_2 * \left|\hat{Z} - Z\right| & \hat{Z} > Z \end{cases} \tag{1}$$

where Z are $\hat{Z}$ are the true and estimated grades, $L(.)$ is the loss function, c_1 and c_2 are constants. The estimation error e is calculated as $e = \hat{Z} - Z$.



[1] Geostatistical estimators that minimize the variance of the distribution of estimation errors are often referred to as B.L.U.E estimators or *best linear unbiased estimators.*

Figure 1: An example of an asymmetric linear loss function where $c_1 = 198$ and $c_2 = 66$.

The estimate minimizing the expected loss for linear loss functions is the quantile of $\hat{Z}$ that corresponds to the ratio $c_1/(c_1 + c_2)$. For the example in Figure 1 the estimate that minimizes the expected loss is the 0.75 quantile of the probability distribution of $\hat{Z}$. The probability distribution of $\hat{Z}$ can be obtained by conditional simulation methods (Davis, 1987; Deutsch, Magri, and Norrena, 2000; Isaaks, 1990). In all likelihood, the 0.75 quantile of the distribution of $\hat{Z}$ is greater than the mean. This would tend to increase the number of blocks classified above cutoff grade which would in turn increase the profit given that underestimation is costlier than overestimation. If this seems counter intuitive, consider a block whose kriged estimate is slightly less than the waste/ore cutoff grade. The kriged estimate would classify the block as waste, however, the 0.75 quantile of the probability distribution of $\hat{Z}$ may be above the cutoff grade, which would render the block as ore and reduce the dollar loss.

The ore type classification of OCM block grades by using loss functions of the block grades rather than by the block grades themselves is sometimes called MPS or maximum profit selection. Misclassification errors made by assigning an ore type to a block based on either the block grade or loss functions of the block grade are referred to as *grade misclassifications*.

The efficacy of MPS is frequently demonstrated by calculations based on "free selection" (Schofield, 1997; Deutsch, Magri, and Norrena, 2000; Dagdelen and Coskun, 1999). Free selection presupposes that each OCM block is equivalent to a selective mining unit (SMU) and each SMU can be mined and sent to the correct destination according to its classified ore type. In other words, none of the SMU will be misclassified or sent to the wrong destination at the time of mining. This presumption is not true in practice. The spatial configurations of SMU blocks with the same ore type are often very complex, rendering the mining of an individual SMU impractical. Moreover, many OCM models consist of blocks much smaller than an individual SMU.

A practical method for the layout of minable ore types is the design of dig lines constrained by a minimum mining width (MMW). In fact, most open pit mining operations have a designated ore control engineer or geologist who is tasked with the design of dig lines for each blast.

However, the design of dig lines is typically charged with additional misclassification errors. Figure 2 shows an example of an ore control block model overlain with dig lines. The various ore types are symbolized by different shades of grey. The two arrows illustrate the MMW. Admittedly, the blocks are smaller than the MMW or SMU, however, the misclassification of many OCM blocks by dig line design is obvious. These misclassification errors are referred to as *dig line misclassification errors* as opposed *to grade misclassification errors*.

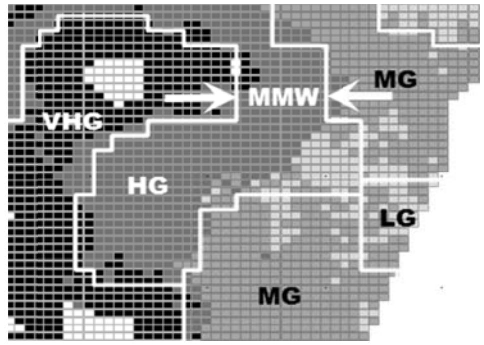


Figure 2: An example of an ore control block model. The white lines represent dig lines constrained by a minimum mining width (MMW). The various shades of grey indicate very high grade (VHG), high grade (HG), medium grade (MG, and low grade (LG) ore types.

Experience suggests that the revenue lost by dig line misclassification errors is far greater than that lost through grade estimation errors. First, there is considerable uncertainty associated with the actual location of the ore/waste contacts. Second, this uncertainty is compounded by the imposition of a MMW constraint on the dig line design. Thus, a significant number of OCM blocks may be misclassified by dig line design.

A recent literature search on dig line design fails to identify references that describe methods for open pit dig line design constrained by a MMW. References are found for dig line design, but without a MMW constraint (Norrena and Deutsch, 2002; Srivastava, Hartzell and Davis, 1992). Rendu, (1982) discusses the application of MMWs to the mining of veins, but the discussion pertains to underground mining methods and does not describe an algorithm for open pit constrained dig line design.

OPTIMUM DIG LINE DESIGN

Isaaks & Co. developed an algorithm and computer program (Digger) for the design of dig lines constrained by a MMW. The algorithm is revenue based and minimizes dollars lost due to dig line misclassifications through loss functions. The general problem is illustrated by Figure 3.

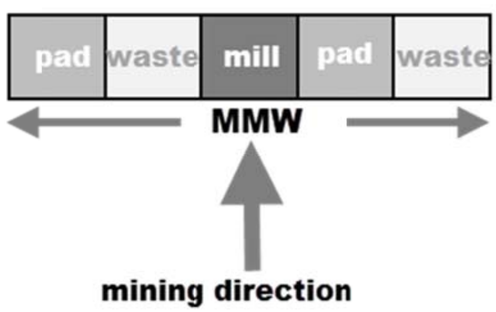


Figure 3: This figure illustrates the minimum mining width problem. All five blocks will be mined together and sent to either the waste dump, the leach pad, or the mill. The correct destination is the one that minimizes the dollars lost due to the misclassification of ore types, thereby maximizing net revenue.

The Digger algorithm resolves the “correct destination” problem by application of loss functions to the blocks within the MMW. For example, the potential revenue of each OCM block is calculated for each ore type using equation (2). Loss functions can then be evaluated for each block and for each possible destination. The correct destination is the one where the combined dollar loss of all 5 blocks is minimum.

$$P_i = \$ * Z * R_i - B_i, \quad i = 1, \text{n ore types} \tag{2}$$

where

- P = net revenue in dollars
- \$ = metal price
- Z = block grade
- R = metallurgical recovery rate
- B = break even cost in dollars
- Zc = cutoff grade

Cutoff grades are almost always pre-defined by mining personnel, so the calculation of corresponding break even costs can be calculated using Equations (3). Note that each ore type is featured by a unique recovery function, R_i, i = 1, n ore types.

$$\begin{aligned} B_1 &= \$ * Zc_1 * R_1 \\ B_{i+1} &= \$ * (Zc_{i+1} * R_{i+1} - Zc_{i+1} * R_i + B_i) \quad i = 1, n \textit{ ore types} \end{aligned} \tag{3}$$

An example of the loss functions employed by Digger is shown in Figure 4. The hat on the symbols M, S, and W indicate mill, stockpile, and waste ore types that are assigned to a block by the encompassing dig line while M, S, and W without hats symbolize the ore types assigned to the block by the OCM block grade. The symbols within the table cells are the calculated dollars lost (using equation 2) as a result of dig line misclassifications. For example, the table cell containing $|P_M|$ conveys an OCM block that is waste (W) by its block grade, but the block is within a mill dig line $(\widehat{M})$ where it will be mined as mill ore and sent to the mill. The symbol $|P_M|$ is the dollar loss which is calculated using mill recoveries and break even costs. Because the block is waste grade, it contains insufficient metal to pay for the mill processing costs and will be processed at a dollar loss.

M	P_M	$P_M - P_S$	0
S	P_S	0	$P_S - P_M$
W	0	$\lvert P_S \rvert$	$\lvert P_M \rvert$
	$\widehat{W}$	$\hat{S}$	$\widehat{M}$

Figure 4: This figure tabulates the loss functions for 3 ore types, waste (W), stockpile material (S), and mill material (M). The symbols in the table cells are the calculated dollars lost (using equation 2) as a result of dig line misclassifications. See text for additional definitions.

The application of loss functions to groups of OCM blocks defined by a MMW is the key to Digger. Digger initially defines a mosaic of SMU type dig lines. Based on simulated annealing, Digger repeatedly iterates through the OCM testing the existing dig line locations. If a new dig line location can be found that reduces loss and does not violate the MMW, then the dig line is re-located to the new location. Digger continues iterating through the OCM until either no new dig line locations can be found or until a pre-defined number of iterations is reached.

CASE STUDY

The efficacy of constrained optimum dig line design is easily evaluated by comparing potential Digger revenues to those generated by other methods given an identical OCM. A simple summation of the ore type tonnes and grade generated by each set of dig lines is all that is needed. Differences between tonnes, grade, and revenue can only be due to differences between dig line designs.

In addition to providing an example comparing manually designed dig lines to optimum computer dig line designs, the case study also provides examples that focus on the impact of varying the MMW. Generally, once the MMW is defined it is seldom altered by grade control operations. Thus, the benefit of evaluating potential recoverable tonnes and grade by ore type as a function of MMW is typically not known. The MMW examples clearly illustrate the benefits of being able to rapidly evaluate potential dig line recoveries for various MMWs.

Although this study does not account for the uncertainty associated with the estimation of block grades, any accounting such as MPS would likely have very little impact on dig line misclassifications. Increases in net revenue as a consequence of assigning initial ore types to the OCM blocks by MPS would simply be in addition to revenue increases as a consequence of optimum dig line design.

The examples provided are based on actual mine data. However all grades, costs, and recoveries have been altered to preserve confidentiality. The case study considers data from a small open pit gold mine where oxide, transition and sulfide ore types exist. Ore type destinations are waste, leach pad, and mill.

Case study data

The OCM under study consists of 4,183 blocks, each measuring 2 m x 2 m x bench height. The OCM blocks are classified into 4 ore types plus some minor waste based on the oxide, transition, and sulfide classification rules described below.

Ore types

- Sulfide mill (SuM)
- Transition mill (TrM)
- Oxide mill (OxM)
- Oxide leach (OxL)
- Waste (W)

Processing costs

- Sulfide mill $ 30.00/tonne
- Transition mill $ 15.10/tonne

- Oxide mill $ 14.95/tonne
- Oxide leach $ 3.15/tonne

Metal prices

- Au $1500.00/oz
- Ag $30.00/oz
- Cu $3.00/lb

Metal recovery

The metal recovery functions are complex non-linear functions of ore type and metal grades.

Oxide, transition, sulfide classification rules

```
If soluble copper > 1500 ppm or sulfide sulfur > 10% then
      ore type = sulfide
else if soluble copper > 250 ppm then
     ore type = transition
else if sulfide sulfur  < 1.5% then
   ore type = oxide
else if ratio of soluble gold to total gold < 0.6
   ore type = transition
else
   ore type = oxide
```

Computer program input (OCM block grades)

- Total Au grade
- Soluble Au grade
- Ag grade
- Soluble copper grade
- Sulfide sulfur grade

Computer program output

- Dig line tonnes and grade by ore type.
- Dig line revenue by ore type as a function of recoverable Au, Cu, and Ag.
- Dig line polygons

Manually designed dig lines versus Digger

This section compares dig line recoveries from a set of manually designed dig lines to those from a set of optimum dig lines designed by Digger. The manually designed dig lines by the company geologists were not available for this study, so we challenged an outside Ph.D. geologist with the task of constructing dig lines that minimize the misclassification of the OCM blocks while maintaining a MMW of 12 m or 6 blocks. The manual dig lines are shown in Figure 5 on the left. The Digger dig lines are shown by the map on the right side of Figure 5. Although the minimum mining width is 12 m or 6 blocks for both sets of dig lines, the white X’s drawn on the manual set of dig lines indicate MMW violations. The tiny squares in each map represent the original ore control block model. Ore types are identified by the grey scale. The labels in the maps indicate the dig line ore type.

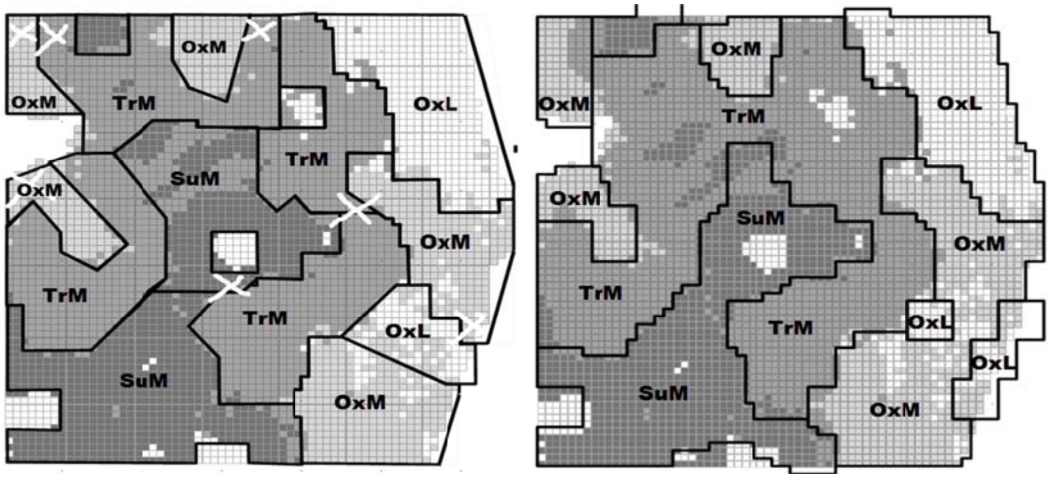


Figure 5: This figure compares a set of manually designed dig lines (on the left) to a set of computer generated optimal dig lines (on the right). The grey scale indicates the initial ore type by block grade; black is SuM ; dark grey is TrM; medium grey is OxM; light grey is OxL; and white is waste. The labels on the maps indicate the dig line ore type.

The relative dig line tonnages, Au and Ag ounces, and dollar revenues by ore type are given in Table 1. All of the entries in Table 1 are percentages of the manual dig line quantities. For example, the total *in situ* dollar value of the material within the optimum dig lines is 102.8% of the *in situ* value of material within the manual dig lines. In other words, the optimum dig lines potentially provide a 2.8% increase in net revenue over the manual set of dig lines. Although the recoverable ounces of Au and Ag compare very closely, the manual dig lines contain approximately 116% more SuM ore tonnage than the optimum dig lines. Note that the processing costs of SuM ore are approximately double the cost of milling either TrM or OxM. Thus, the misclassification of material within the SuM dig lines is very costly and is likely the major contributor to the manual dig line dollar loss. This example clearly illustrates the value of loss functions or MPS.

Table 1: Comparative Dig Line Statistics.
Table entries are % of manual dig line quantities.

Ore Type	Tonnes (% of manual)	Au (wt % of manual)	Ag (wt % of manual)	Revenue (% of manual)
OxL	85.4	83.3	78.8	88.9
OxM	111.3	114.9	108.6	100.0
TrM	110.5	103.0	109.1	108.5
SuM	87.2	84.5	84.5	98.1
Total	99.2	100.5	100.8	102.8

The 2.8% increase in net revenue provided by the optimum computer dig lines over manual designs is typical of what has generally been observed at other mines. Increases in net revenue generally range between 2% to 5%.

Minimum mining width examples

This section compares dig line recoveries for 4 different MMWs, namely 10 m, 12 m, 15 m, and 18 m. All dig lines were generated by Digger and the employment of loss functions. In other words, the dig lines are physically located by minimizing the dollar loss due to the misclassification by dig lines constrained by a minimum mining width.

The 4 sets of dig lines are shown in Figure 6. Dig line misclassifications are clearly visible in each map. For example, near the center of the MMW-12 map, a number of waste blocks (white) are located within a SuM dig line, e.g., these are waste blocks that will be sent to the SuM process.

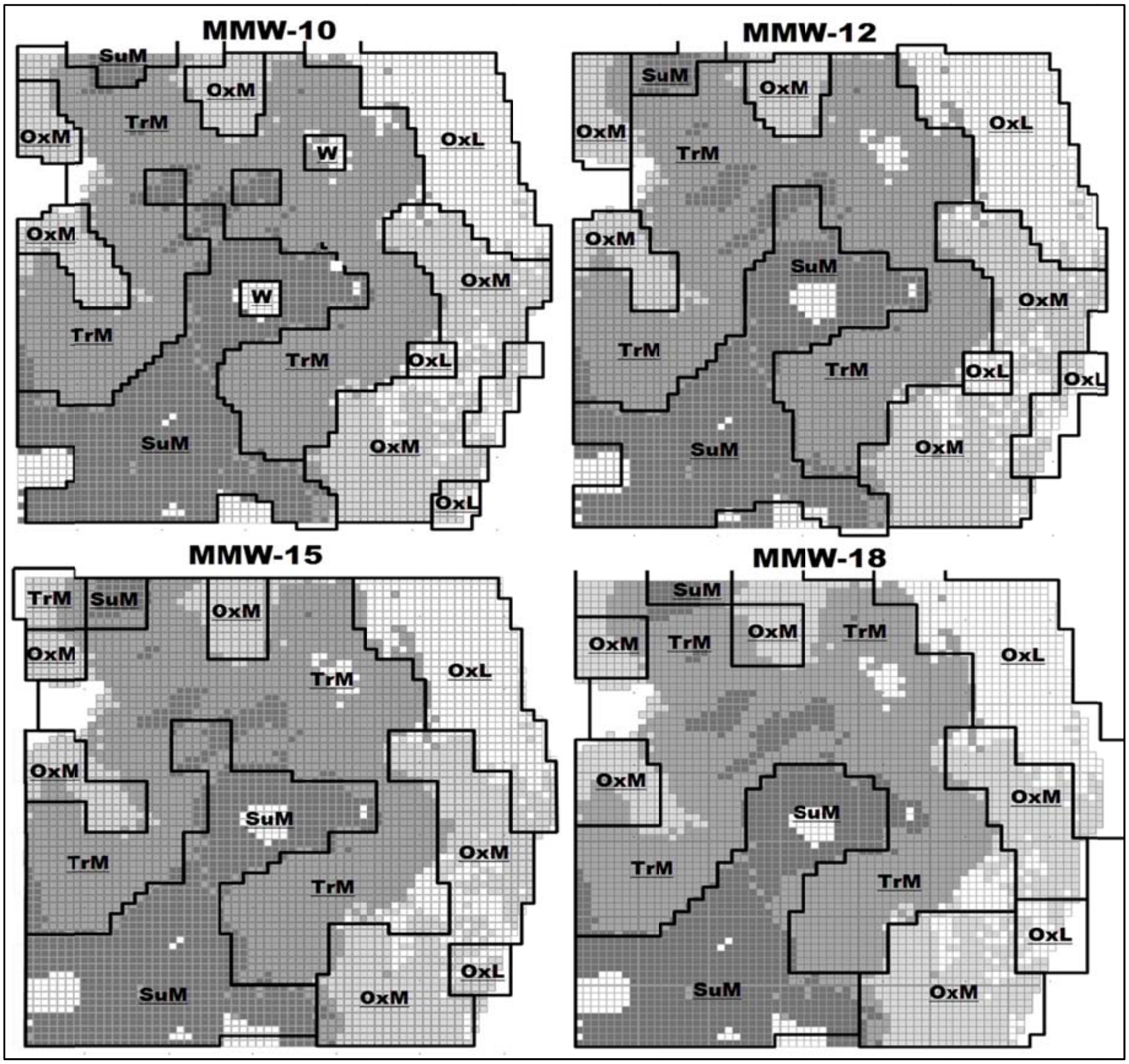


Figure 6: This figure shows 4 sets of dig lines constrained by 10 m, 12 m, 15 m, and 18 m MMWs. The grey scale and labels indicate the ore types as explained in Figure 5. Although the 10 m MMW appears to be more selective, with less dilution and ore loss, the relative simplicity of the 18 m MMW likely reduces dilution and ore loss as a result of digging error at the time of mining.

Summary statistics by MMW

The dig lines shown in Figure 6 are very efficient. For example, the dollars lost due to dig line misclassification are computed by comparing the total OCM revenue before dig line design to the total revenue after dig line design. For example:

- MW10 dig line loss = 1.36% of total OCM revenue;
- MW12 dig line loss = 1.99% of total OCM revenue;
- MW15 dig line loss = 2.56% of total OCM revenue; and
- MW18 dig line loss = 2.12% of total OCM revenue.

Table 2 is interesting because it shows that the total revenues attributable to each MMW compare very closely in spite of the increasing quantities of metal lost with larger MMWs. Although more ounces of Au and Ag are lost with larger MMWs, the recoverable metal grades are almost equivalent across all four MMWs. This is evident because revenue and tonnes are nearly equivalent across the four MMWs.

Table 2: MMW Statistics
Table entries are % of OCM quantities (no dig lines).

MMW	∑Rev (% of OCM)	∑Tonnes (% of OCM)	Au Loss (wt%)	Ag Loss (wt%)
10 m	98.6	97.7	1.59	2.69
12 m	98.0	98.1	1.68	3.94
15 m	97.4	99.4	2.54	7.05
18 m	97.9	99.5	2.02	4.71

MMW summary statistics by ore type

A comparison of the dig line dollar revenues, tonnes, Au ounces, and Ag ounces by ore type is provided by Figure 7. A noteworthy observation in Figure 7 is that maximum recoverable quantities for each ore type[2] are delivered by different MMWs. For example, suppose a monthly mine plan calls for the maximum production of TrM tonnes. From Figure 7, it can be seen that the 18 m MMW is the best option. Alternatively, if the mine plan calls for the maximum production of OxL tonnes, then a 10 m MMW is the best option. The MMW corresponding to the maximum recoverable quantity of metal also varies with ore type. For example, if the monthly mine plan calls for the maximum production of OxM ounces of Au, then the 12 m MMW is the best option. Alternatively, if the mine plan calls for the maximum production of SuM ounces of Au, then a 10 m MMW is the best option, and finally, a 15 MMW is the best option for maximizing the production of TrM ounces of Au.

[2] In Figure 7, the total quantity of metal recovered across all ore types including waste is identical for each MMW. Thus, the comparisons of MMW percentages within an ore type are relative to one another.

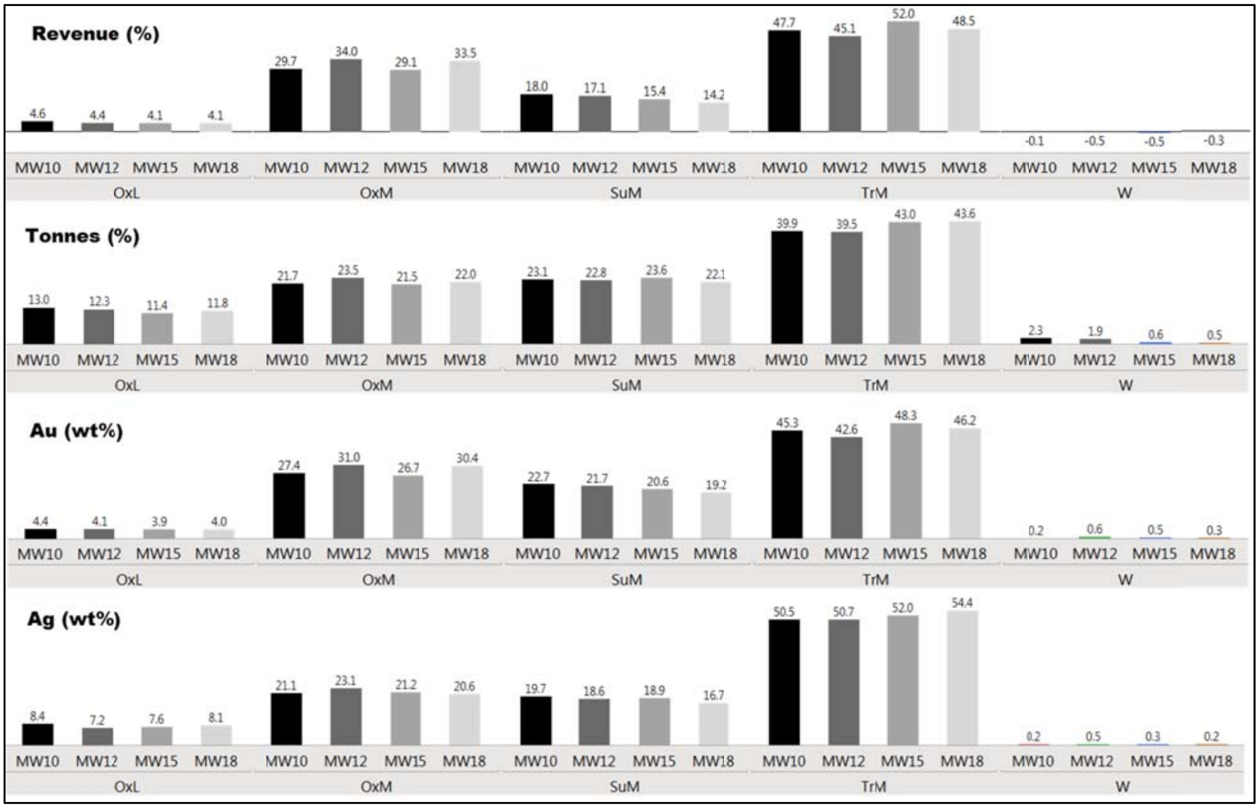


Figure 7: A comparison of recoverable quantities attributable to each MMW by ore type. All comparisons are given as the percent of total. For example, the total potentially recoverable ounces Au associated with the 10 m MMW is 4.4% + 27.4% + 22.7% +45.3% + 0.2% = 100%.

Evidently, the complexity of the *in situ* ore type contact boundaries influences the efficiency of dig line design. Extremely complex spatial configurations of ore type boundaries increase the number of dig line misclassifications. Consequently, the benefit of optimum dig line design will increase. On the other hand, in deposits where the *in situ* ore types are relatively continuous with reasonably well defined contacts, the problem of dig line misclassification should be minimal. At this point, an obvious question might be, "What about blast movement"? Good question, but that is a topic for another paper.

CONCLUSIONS

Computer design of optimum dig lines constrained by a MMW is a new and relatively unknown tool available to the mining industry. As a consequence, the benefits of constrained optimum dig line design are largely unrealized. Constrained optimum dig line design is a low risk – high return investment with huge potential gains:

- Optimum dig line design maximizes net revenue. Material sent to the wrong destination is costly. At $1500US/oz, the dollars lost by sending a single 600 tonne OCM block of gold averaging 0.5 g/t to the dump exceeds $14,000.00. Over the course of a year, sub-optimal dig line designs can cost hundreds of thousands of dollars. These losses can easily be avoided by using optimized computer designed dig lines. No additional equipment, personnel, or samples are required.
- Computer dig line design enables one to quickly evaluate different dig line designs. The benefits of different MMWs or cutoff grades can be evaluated in a few minutes enabling

the selection of a dig line set that best satisfies current short term mine plan targets or changes in the local patterns of mineral continuity as mining progresses through the deposit. This is not possible with manually designed dig lines. The numerous calculations required within a few seconds are too many for the human brain.

- Computer dig line design enables rectangular MMWs. For example, the MMW in the direction of shovel travel may be wider or narrower than the MMW in the perpendicular direction. Rectangular dig lines may reduce loss where the patterns of mineralization form narrow bands or veins with a reasonably consistent strike and dip. Dig lines are easily designed in directions parallel to the strike of a vein system or a contact trace by an internal rotation of the OCM before dig line design.
- Computer dig line design can be applied to resource/reserve risk assessment. For example, the uncertainty associated with the predictions of an annual production schedule is often studied by calculating the *in situ* recoverable tonnes and grade from multiple conditional simulations of drill hole data across the deposit. But these calculations are typically based on *free selection* which is unrealistic. Computer generated optimum dig lines permit realistic simulated recoveries of tonnes and grade for different MMWs which not only provide the means to explore various mining options, but also increase the accuracy of the study.

FUTURE WORK

Currently, Digger works with the OCM block grades as they are provided, no matter which block grade estimator is used. However, work is underway with the full implementation of MPS. Given this option, Digger will simulate a block probability distribution for each OCM block based on the LU decomposition of the covariance matrix (Davis, 1987). This will enable Digger to assign initial MPS ore types to each block which will subsequently be used for optimum dig line design. The combination of MPS applied to block grades and dig line design will further increase the value of recoverable ore at the time of mining.

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