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Pre-crusher stockpile modelling to minimise grade variability

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The use of pre-crusher stockpiles to store ore and buffer short-term fluctuations in production processes is generally well recognised and accepted. However, the potential to reduce short-term grade variation of ore entering the crusher is rarely recognised and generally poorly understood. Pre-crusher stockpiles are commonly built and reclaimed in an *ad-hoc* manner whereas well-designed and disciplined build and reclaim procedures can reduce variability into the crusher at low cost. Design options for pre-crusher stockpiling should consider the four competing roles of storage, buffering, blending and grade control, to produce predictable and uniform crusher feed grades. The selection of alternative grade allocation methods requires careful consideration, as decisions at this early stage of the production process have been shown to flow on to shipping and to the customer. This paper reports conclusions from studies simulating the reduction of grade variability for a range of alternative pre-crusher stockpiling configurations and grade allocation methods. The benefits achievable in reducing grade variance by systematically building stockpiles of appropriate dimension are quantified.

Introduction

Iron ore is used to feed blast furnaces to make steel. Steelmakers purchase and blend ore from multiple suppliers to create a consistent feed to the furnaces. A reliable long-term supplier of ore must satisfy three criteria to be an acceptable contributor of quality ore to the furnace feed blend. First the ore must be of an acceptable quality with suitably low level of contaminants, such as silica, alumina and phosphorus: this depends on the *in situ* resource and any subsequent upgrading process. Secondly, the supplier must maintain consistent average grades over time. Thirdly, there must be minimum grade variability from shipment to shipment. If these criteria can be satisfied, an iron ore supplier may remain a long-term preferred supplier, subject of course to satisfactory pricing.

Miners must therefore understand the grade variability of their delivered ore and have in place measures to control this variability.

Normally ore is hauled by haul trucks from the blasted mine face to an ore pad in front of a crusher, where it is dumped into some form of pre-crusher stockpile. When required for crushing, the stockpiled ore is picked up by a front-end loader and dumped into the crusher. Following crushing the ore is stacked onto post-crusher stockpiles, storing it ready for transportation to the port, where it is again stockpiled by automatic stacking. Finally the ore is reclaimed and shipped to customers. On some occasions the ore is dumped from the train and goes direct to the ship. Figure 1 shows a schematic of key steps in the mining process for reducing short-term grade variability[4]. The precrusher stockpiling step is highlighted.

In large operations the reduction of short-term grade variability can be achieved through capital intense methods, such as large stockpiles built by automatic stackers and reclaimers at the mines and ports. These stockpiles are essential for logistic purposes in large operations and so advantage is taken of their presence to reduce grade variability, for example by chevron ply stacking and pilgrim step reclaiming with bucket wheel reclaimers. Most of the effort put into understanding the control of short-term variability has been on these systems downstream of the crusher.[1,2,3] To date there has been little detailed study on the effect of pre-crusher stockpiling on short-term grade variability. These pre-crusher stockpiles are commonly built in an undisciplined manner and to a design that best suits the operations buffering requirements with scant regard for grade variation reduction and reconciliation.

A study has therefore been carried out into all aspects of the pre-crusher stockpile operations and the effect on short-term grade variability control. Simulation has been used to study the most effective ways to maximise the reduction of variability during crushing, through separating ore into various grade stockpiles and the design and manner of build and reclaim of these stockpiles.

The purpose of this paper is to highlight the importance of pre-crusher stockpile design and operation and to demonstrate their potential effectiveness in reducing short-term grade variability if designed and operated correctly.[4]

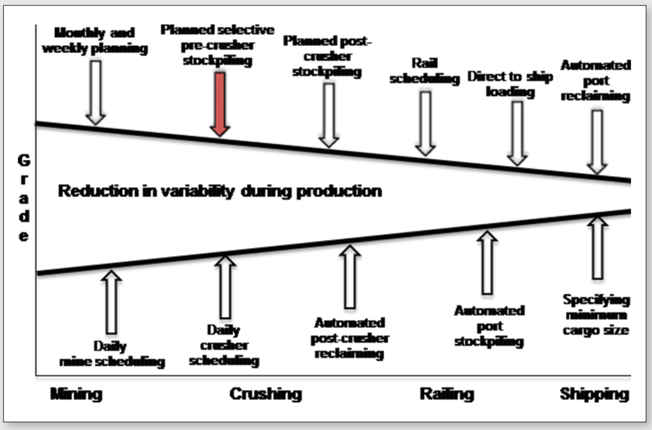

Figure 1. A schematic of key steps in the mining process in reducing short-term grade variability[8]. The precrusher stockpiling step is highlighted.

Roles of pre-crusher stockpiles

Pre-crusher stockpiles carry out the usual roles attributed to stockpiles, of buffering, storage and blending but they also have a role in grade control. Each role is summarised below:

Buffering

- Maintain sufficient tonnages to adequately decouple the mining extraction and crushing operations to maximise production, *i.e.* no bottlenecking of production.
- Allow ore to be stacked from the mine and recovered to the crusher simultaneously in a safe manner.

Storage

- When necessary, hold ore with grade that does not fit into the monthly plan but is too valuable to dispose of as waste. These stockpiles are usually referred to as long-term stockpiles. This function is outside the scope of this paper except to say that if stockpiles are used for this purpose they should not be seen as part of the normal production process.

Blending

- Break up as much of the grade serial correlation coming from the mine as practical (discussed in more detail below). It should be noted that, because of the nature of the building process, there is limited blending opportunity within the stockpile. Significant blending depends on the relationship between the stacking and reclaiming methods.
- Provide a highly predictable and uniform grade when ore is recovered from the stockpile in relatively small quantities for crusher feed.

Grade Control

- Contain adequate tonnage to allow compensation for natural grade fluctuations during a monthly plan.
- Allow ore to be traced back to floorstocks for tonnes and grade reconciliation, to examine grade bias, enable truck factor calculations and allow algorithm generation in the case of lump and fines product.
- Maximise grade separation of critical analytes to enhance the effectiveness of the daily scheduling system by providing diverse grade ore sources for the daily crusher plan (discussed in more detail below).

To satisfy all of these requirements a compromise in design is necessary. We suggest that the ideal pre-crusher stockpiling system requires:

- blended-in blended-out stockpiles (BIBO) which are paddock dumped from haul trucks in rows in one direction and then reclaimed across the build direction by front end loader for feed into the crusher;
- building to a width that facilitates full face reclaim over a period of 24 hours;[4]
- always pairing stockpiles of comparable grade, with one being built while the other is reclaimed;
- building sets of stockpiles (usually up to three pairs; high, medium and low grade) with maximum grade differential (described in detail below);
- adopting a grade separation method suited to the nature of the ore and the customer quality requirements to give maximum effectiveness when they are being blended back together to form the daily crusher product;
- allocating uniform tonnages to each set of stockpiles over a month to maximise the tonnage capacity of the pre-crusher pad;
- building to a maximum tonnage that can cover grade fluctuations within the month, so as to decouple delays in mining or crushing: *i.e.* maintain continuous sites for building and reclaiming;
- building to a minimum tonnage that satisfies the above requirements so that ore can be reliably traced back to original floorstocks for reconciliation purposes;
- building and reclaiming to completion: *i.e.* once a BIBO stockpile build commences it continues uninterrupted until it reaches the specified tonnage. It then changes to reclaim mode and is reclaimed until it is empty. This is essential to maintain grade knowledge of the stockpile as well as for reconciliation purposes.

Typical well-designed pre-crusher stockpiles are shown in Figure 2 while the building and reclaiming method is shown in Figure 3 and 4.

Figure 3. Building of pre-crusher stockpiles.

Figure 4. Reclaiming of pre-crusher stockpile for transport to the crusher.

Figure 2. A well designed system of paired BIBO precrusher stockpiles.

Grade correlations in iron ores

Iron ore being extracted from a pit exhibits two types of grade correlations.

Table 1. Typical correlations (r) values between key analytes in iron ore.

Correlations between the key analytes typical in iron ore					
	Fe	Al_2O_3	SiO_2	P	LOI
Fe	1.000	-0.572	-0.868	-0.328	-0.699
Al_2O_3		1.000	0.429	-0.008	0.122
SiO_2			1.000	0.219	0.357
P				1.000	1.000
LOI					

Firstly, there is strong cross correlations between iron and the contaminants. Typical correlations of the analytes are shown in Table1.

As can be seen there are very strong correlations between iron, silica and LOI (loss of ignition) and to a slightly lesser extent alumina. The square of the correlation coefficient is the proportion of variance shared between two variables. The -0.868 correlation between silica and iron means that they share more than 75% of variance, so that low silica is a very strong predictor of high iron content, and *vice versa*. (Since each measurement includes random error variance, the true correlations are probably even larger). There are also weaker but statistically significant correlations between alumina and silica, and between phosphorus and LOI. These types of correlations exist in most iron ores and must be considered when establishing a grade control system. Blending does not alter these correlations.

The second type of correlation is the serial correlation evident in ore sequentially extracted direct from a pit. For example if a haul truck of ore from the pit is high in silica then there is a high probability that the next truckload from the same source will be similarly high in silica. This reflects the trends evident in floorstocks and again is dependent on the process used for mining. For example the serial correlation observed when one large digging unit is working on one floorstock will be much higher than the serial correlation observed when multiple small digging units are extracting ore from various parts of the same pit. Figure 5 shows the serial correlation in the major analytes in the data used for the simulations described later in the paper.

The grades for the analytes of interest (iron, silica, alumina and phosphorus) show strongly positive serial correlation, giving short-term grade variations. This type of correlation can be reduced through the processing stream.

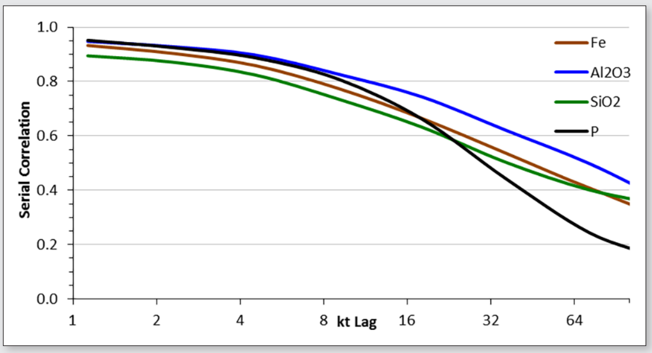

Figure 5. Serial correlation of each analyte for extracted blast blocks up to a lag of 100 kt.

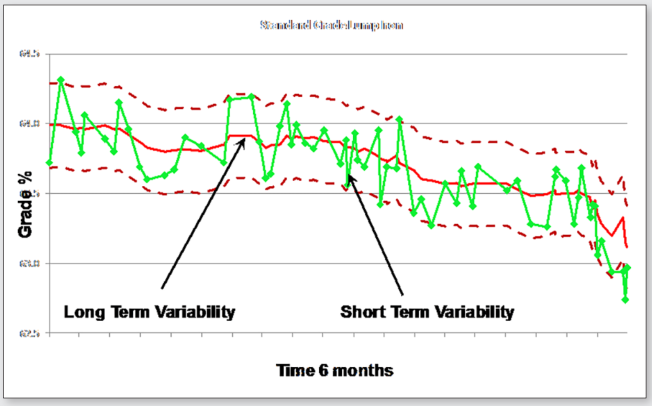

Figure 6. Typical variability coming from a mine.

Mined ore variability

An example of typical grade variability of mined ore is shown in Figure 6.

To appreciate the role of pre-crusher stockpiles in controlling variability in mining it is necessary to understand the various types and associated concepts of variability.

Wills, Jupp and Howard[5] explain the two types of variability (long-term and short-term), which are shown in Figure 6. We take their definition given to short-term variability and apply it to the variability in the run of mine ore that is delivered to the crusher for processing.

Long-term variability

Long-term variability (Figure 6) represents the trends that occur in average grade over extended time periods longer than a month and up to the life of mine. This is due to geological trends in the ore bodies as the mining progresses, or changes to the blend ratio between pits as resources are depleted and new pits come on line. The acceptable level of long-term variability is determined through the trade-offs between customer goals and the economics of the mine and resource. This type of variability is only controlled through the long-term planning process and, if unacceptable, necessitates potential changes to the mining sequence. It has no impact on the design and utilisation of pre-crusher stockpiles and as such is outside the scope of this paper.

Short-term variability

Short-term variability in the mining extraction process relates to the grade variation of the mined ore over time periods of up to a month. It is a reflection of the process capability that is embedded in the mining operations which includes the system of mining over the month and the natural variability of the ore deposit. For example, short-term variability coming from a single large digging unit that works its way through a floorstock and is then moved to another is very different from the short-term variability experienced from having multiple small mobile digging units moving around the pit. Short-term variability necessitates the design of the downstream process to reduce it to an acceptable level by the time the cargoes are produced.

Pre-crusher stockpiles play a critical role in the control of this short-term variability by one of two mechanisms. Firstly, some control is achieved by the allocation criteria on which extracted ore is directed to one of several grade separated pre-crusher stockpiles and then later blending back into the crusher blend. Secondly, blending also occurs through the systematic building and reclaiming of pre-crusher stockpiles[4]. Both mechanisms play an important role in minimising the ship-to-ship grade variability seen by customers.

Short-term grade variability minimisation

Several simulation models were constructed in Excel using Visual Basic to examine different aspects of the short-term variability and its effect on variability of shipments.

The total data input for simulations was twelve months of data taken from the mining plan, based on the kriged block models of a planned iron ore mine located in Western Australia's Pilbara region[4]. The data were from five individual ore sources (pits) over three separate mining hub areas where pre-crusher stockpiles were used to collect ore ready for transport to the crusher. The distance between the various pits necessitated this design. Long-term variability was removed from the data to avoid clouding the short-term variability.

Ore allocation methods for pre-crusher stockpiles using floorstock grades

As previously stated, the ideal pre-crusher stockpiling system sends similar tonnages through each set of paired stockpiles, maintaining a maximum spread of grade to allow flexibility in the grade control system so as to smooth mined grades over a monthly period. This was modelled using a simulation that took an annual mine plan and simulated the flow of ore from the pit into pre-crusher stockpiles and then through the process to shipping. The simulation collected data on the effects of the different allocation methods on daily crushing grades, and on mine, port stockpiling and shipping grades which were later analysed.

A crusher decision support system based on the Continuous Stockpile Management System was incorporated to create the daily crusher feed plan, taking ore from the three hubs to maintain the daily target grade.

Nine alternative grade allocation criteria were simulated and their effectiveness determined by comparing the standard deviation of grade into the crusher, into post-crusher stockpiles, and at shipping, both with and without direct ship-to-train unloading. The best ore allocation criteria would achieve ore allocations generating pre-crusher stockpiles having maximum practical differences of all grades to give flexibility to smooth out the grades at crushing. The daily grade control system concentrated on smoothing silica and alumina: because of the high cross-correlations it also controlled iron.

A data set was developed for a twelve-month mining period that contained all of the typical ore characteristics evident in mining operations. The long-term trend was removed from these data so the results would be directly comparable to a normal monthly production run, but with the statistical power provided by the extra data across the twelve-month duration. As is normal practice for iron ore, the daily grade control simulation software emphasised silica and alumina and to a lesser extent phosphorus, with only a slight emphasis on iron.

The following alternative allocation criteria were included in the investigation:

1) **Principal components**: the calculation of principal components of each floorstock grade[6] takes into account all analytes in maximizing the separation of grades. Theoretically this method would provide the best compromise of maximum spread of all analytes over all stockpiles.
2) **Each key analyte alone**: individual analytes iron, alumina, silica, phosphorus and LOI were used as allocation methods.
3) **Silica plus alumina**: similar to above but representing the majority of gangue in the ore.
4) **Random**: blocks were allocated in a totally random manner, independent of grade, to each of the pre-crusher stockpile sets available. The allocation of incoming ore was based on which paired build stockpile had the lowest current tonnage, with no

Table 2. Distribution of grades achieved in the simulation for various separation criteria. Grey background indicates the analytes used to select in the particular allocation criteria. The absolute differences between the stockpiles (highlighted) are a proxy for the 'most effective' analyte grade separated in the stockpiles.

Allocation critria	Pile Distribution	Average BIBO Stockpile Grades						Absolute Difference in Average Stockpile Grades					
		Fe	Al_2O_3	SiO_2	P	LOI	SiO_2+Al_2O_3	Fe	Al_2O_3	SiO_2	P	LOI	SiO_2+Al_2O_3
Principal Component	Low	56.64	3.63	6.58	.113	8.06	10.22	1.65	0.49	1.54	0.007	0.30	2.03
	High	58.29	3.14	5.04	.120	7.76	8.18						
Fe	Low	56.55	3.56	6.48	.120	8.37	10.04	1.84	0.34	1.34	0.006	0.94	1.68
	High	58.39	3.22	5.14	.113	7.44	8.36						
Alumina	Low	56.94	3.68	6.31	.109	7.85	10.00	1.06	0.59	1.00	0.016	0.11	1.59
	High	58.00	3.09	5.31	.125	7.96	8.40						
Silica	Low	56.65	3.61	6.61	.113	8.04	10.22	1.62	0.44	1.58	0.008	0.27	2.03
	High	58.27	3.17	5.03	.120	7.77	8.19						
Phosphorus	Low	57.17	3.31	5.84	.142	8.30	9.15	0.60	0.15	0.05	0.091	0.78	0.10
	High	57.77	3.46	5.79	.091	7.52	9.25						
LOI	Low	56.86	3.36	6.00	.125	8.62	9.36	1.23	0.06	0.38	0.02	1.44	0.32
	High	58.09	3.42	5.62	.108	7.18	9.04						
$SiO_2 + Al_2O_3$	Low	56.69	3.65	6.59	0.11	7.96	10.24	1.54	0.51	1.54	0.012	0.11	2.05
	High	58.23	3.14	5.05	0.12	7.85	8.19						
Random	Low	57.45	3.39	5.83	.118	7.90	9.22	0.03	0.01	0.03	0.003	0.02	0.04
	High	57.49	3.38	5.80	.115	7.91	9.18						
Value	Low	56.59	3.62	6.57	.117	8.16	10.18	1.74	0.46	1.50	0.000	0.50	1.96
	High	58.34	3.16	5.06	.116	7.66	8.22						

reference to grade. This would represent a practice of stockpiling with no grade control objective or the ultimate situation for a poorly executed grade control regime.

5) **Value**: this criterion was developed to allocate the ore coming from the pits based on the "value" to customers; for example; high iron, low silica, alumina and phosphorus are of greater value than ore of low iron, high silica, alumina and phosphorus. The exact calculation is:

$$\text{Value} = \sum \text{Stress}[i] = P[i].\sum(\text{Grade}[i]-\text{Target}[i])/\text{Tolerance}[i],$$

where: X[i] = the relevant number for Fe, Al_2O_3, SiO_2 and P

P[i] = 1 for Fe and -1 for Al_2O_3, SiO_2 and P, categorising their value to the customer.

The average grades achieved using the alternative allocation criteria for two sets of pre-crusher stockpiles, *i.e.* low and high grade at one of the mine sites using the nine alternative criteria, are shown in Table 2. Note the cut-offs to each high and low stockpile set were determined so as to facilitate uniform tonnes into each stockpile set at each hub.

The results show the analyte specific allocation criterion gives the maximum separation of that analyte, as expected. The cross correlations complicate but also complement the allocation criteria based on a single analyte. While it appears that it is only one analyte that is being used to allocate ore, other analytes are also being separated, because of the cross correlations. For example when alumina is used as the separation criteria, a reasonable separation of iron and silica also occurs. This cross correlation is obviously not destroyed during the allocation criteria for single analytes and is the reason for success of these apparently simple allocation methods.

The principal components have an averaging effect on the grades in the stockpiles and are not as effective in utilising the natural cross correlations within the ore. Hence the principle component and value do not achieve as large a separation of any individual analyte overall when compared to the single analyte methods of separation.

Random allocation presented no significant grade separation, as expected.

These stockpiles from all pits were then run through the simulation, allocating a constant tonnage to be crushed each shift. The standard deviations of the daily crusher grades for each analyte produced over the year are shown in Figure 7. However, the standard deviations do not provide comparable measures of quality, since each analyte has a different dimension.

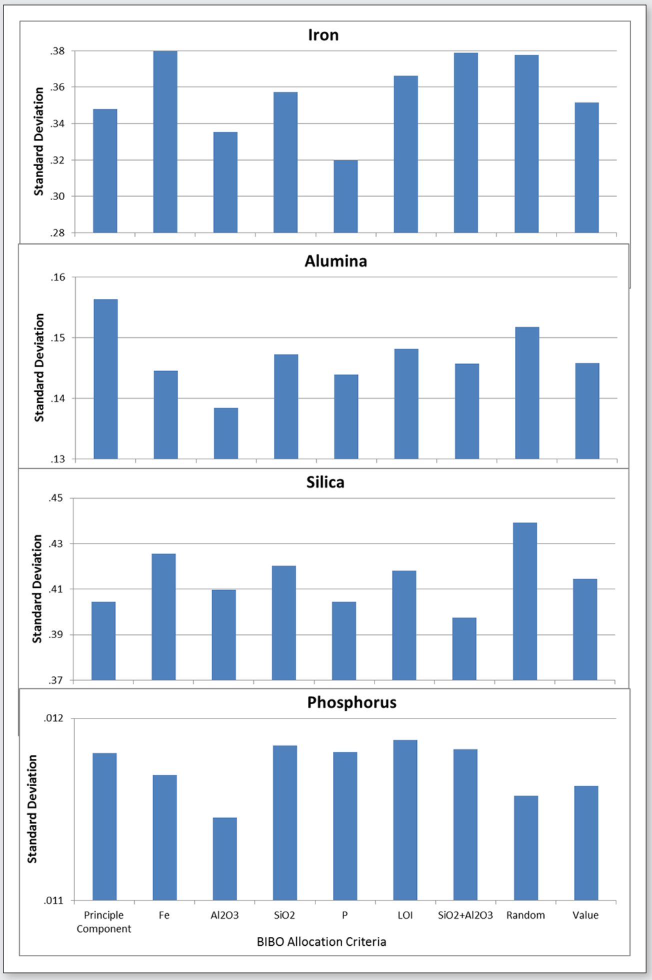

Figure 7. Shows standard deviations of the daily crusher grades for each allocation alternative.

Figure 8 shows the average daily total grade stress for the alternative allocation criteria. As we saw earlier, the stress for each analyte is its deviation from target grade, divided by the tolerance. Each analyte stress is dimensionless. Squaring each stress component and adding them together gives the total grade stress. The total grade stress is thus a dimensionless measure of overall departure

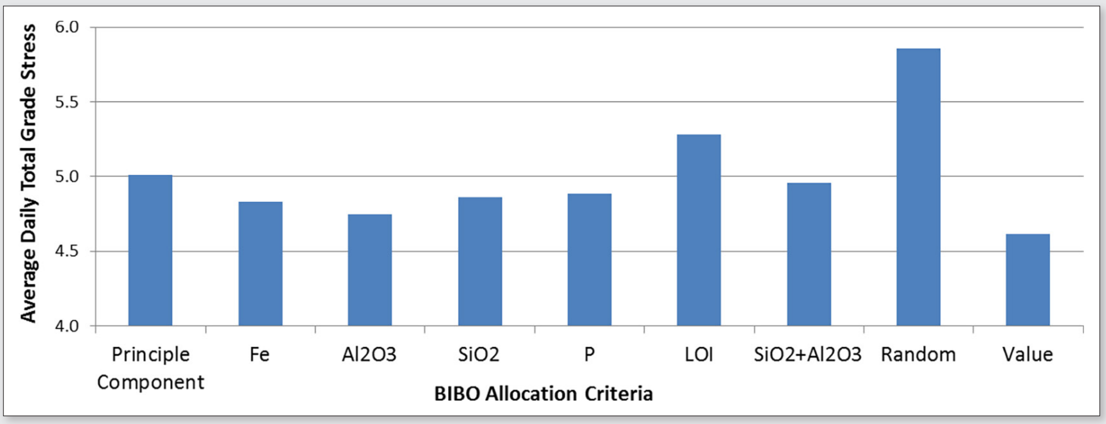

Figure 8. Average daily crusher total grade stress for alternative allocation criteria.

from target grade, appropriately weighted for each analyte. A total grade stress of zero would mean that the target grade has been exactly met for each analyte.

The average crusher total grade stress can thus be used as a measure of success in achieving target on all analytes during each daily grade scheduling process. From Figure 8, it appears that the alumina allocation criterion gave near to the best result, *i.e.* lowest standard deviation overall for all analytes. For total grade stress, the value criterion was slightly better, but its complicated nature makes it less attractive for the normal production process.

The effects of various ore grade allocation methods on shipping variability

The reclaimed BIBO stockpile data from each allocation method were finally used as input data for the overall process simulation that took the ore from pre-crusher BIBO stockpiles through crushing, onto 130 kt post-crusher stockpiles. The ore was then railed to the port and stacked onto 200 kt stockpiles, or as an alternative it was loaded direct to ship 33% of the time simulating the normal potential for such an activity (a method to reduce serial correlation). Finally the ore was loaded as 90 kt ship cargoes.

The standard deviations for each key analyte for a selected number of the allocation criteria are shown in Figure 9.

While there is a significant reduction in variability as a result of the post-crusher and port stockpiling, the influence of the allocation method for pre-crusher stockpiles is still evident with the alumina allocation criteria giving the lowest overall shipment standard deviations. Even when direct to ship is employed to reduce variability, the effect of pre-crusher allocation criteria can still be seen.

Mechanism of grade reduction in grade separated pre-crusher stockpiles

The relationship between the variation in grade over a month coming out of the pits and the ore movement tonnage in the pre-crusher stockpiles was studied in more detail at one of the mine hubs to better understand the mechanisms at play in the pre-crusher stockpiles which are reducing the serial correlation and hence the variability. Alumina was used as the allocation criteria.

Note that ore was coming out of the pit at the grade shown but was moved from the stockpiles to the crusher so as to maintain the average grade for all the analytes, taking into account the other hub contributors as well. The results are shown in Figure 10 with the grades on the left for iron, alumina and silica and the percentage of the total tonnes on the pre-crusher pad in each of the high, medium and low alumina stockpile sets on the right. The red lines represent the average grade and percentage tonnes. What can be seen is the build-up of tonnes in the high alumina stockpile set when the pit is running high in alumina and decreasing when the pit is running low in alumina. The effect of the cross correlations are also evident in the fluctuations in iron and silica. In the early period of the month it is evident that the low alumina stockpile pair were fully depleted of ore because the pit was running high alumina and there were insufficient tonnes in the stockpiles. The resulting crusher grades cannot be shown because these stockpiles are blended with stockpiles from other hubs as they go through the crusher to achieve the desired target grade, taking into account the variability coming out of these pits.

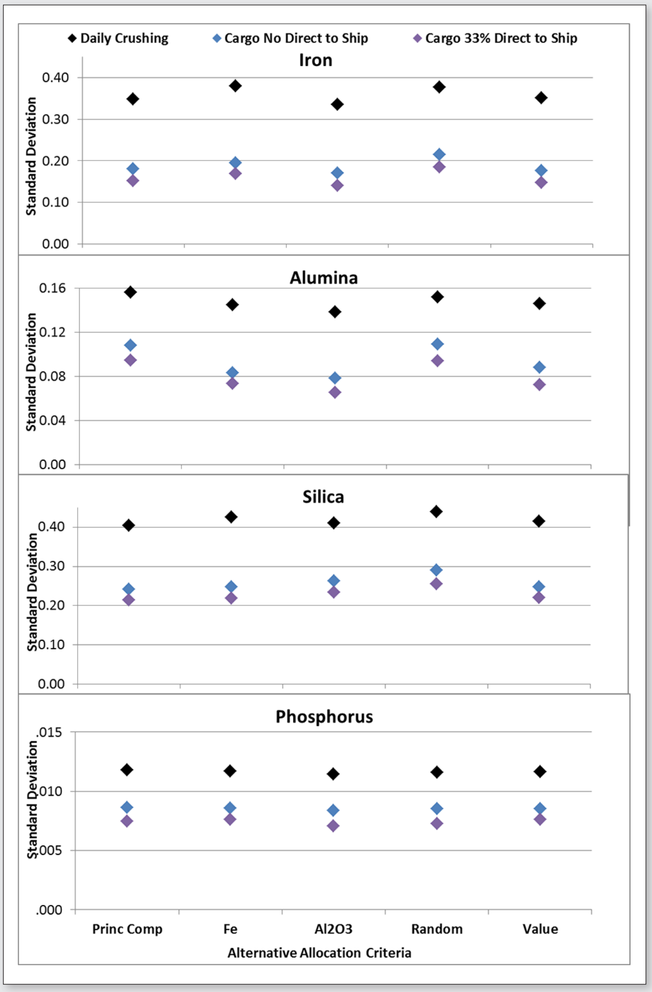

Figure 9. The standard deviation of daily crushing and shipping showing influence of the various pre–crusher allocation methods on the finished product.

We can conclude that, if the pre-crusher stockpiles are managed correctly and built to the correct size, they can provide a significant opportunity for reducing grade variability and serial correlation. However, this is dependent on using the correct allocation criteria to separate the stockpile pairs.

Conclusion

There is a low-cost opportunity to maximise the effectiveness of pre-crusher stockpiling to assist in controlling short-term grade variability. The benefit of variability reduction into the crusher will flow through the production process and eventually to the customer.

A significant reduction in short-term variability can be achieved by the use of adequately sized BIBO paired stockpiles using a grade differentiation system that best matches the grade and cross correlations characteristics of the ore. The ideal size of the stockpiles is dependent on the serial correlation of the extracted ore as well as the crusher and shipping variability requirements on a monthly basis. Simulation modelling can assist in determining the most appropriate stockpile sizes and grade allocation methods to meet operational and organisational requirements.

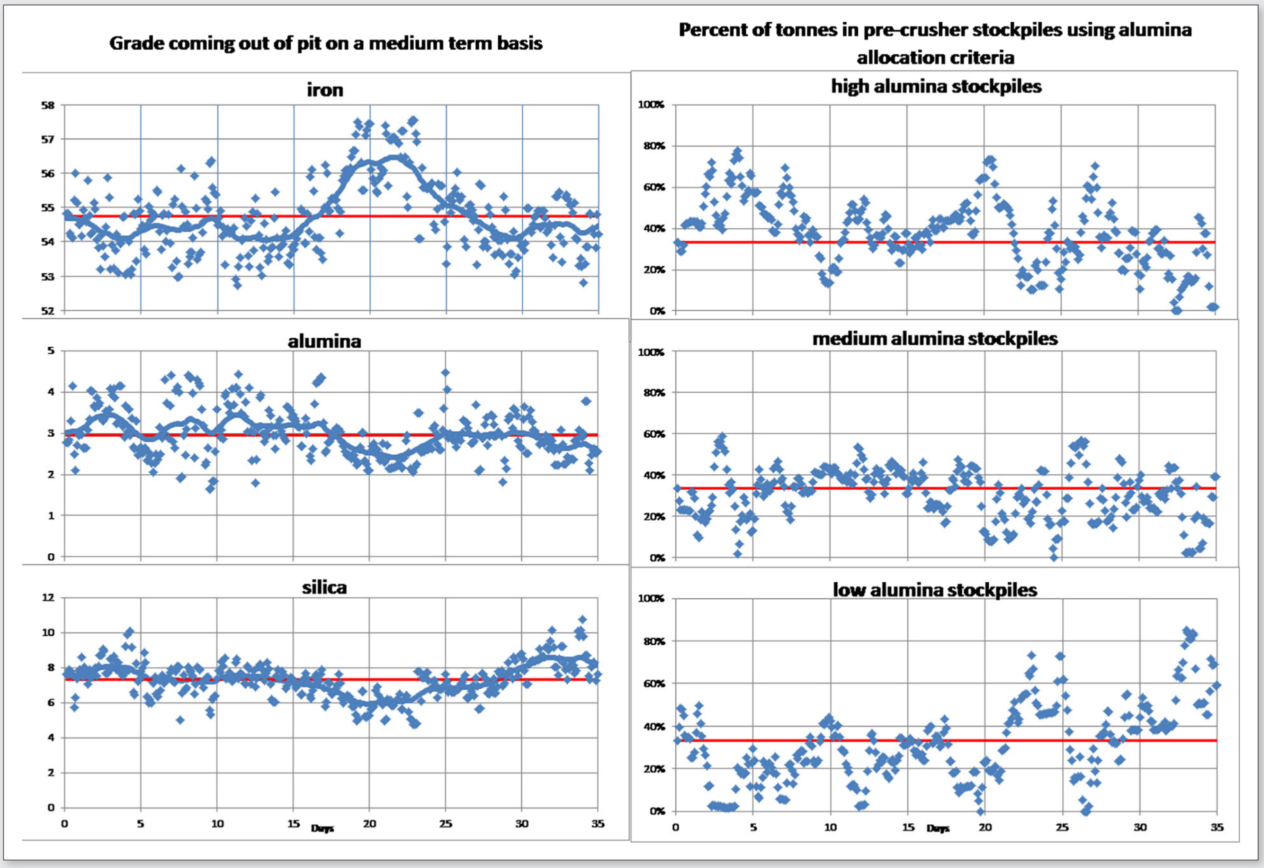

Figure 10. Grades coming out of a pit on the left hand side and pre-crusher stockpile tonnage distribution in response to ore coming from pit and requirement to crush ore to attain target grade for all analytes. Red lines are average grade and average percent ore distribution.

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