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Continuous stockpile management to reduce waste in the mining industry

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Abstract

Australia's economy depends upon mining exports. Ore is a once-only resource. Physical and social environments require extraction with minimum waste. This paper shows how simulation modelling of the production system, supplemented by a decision-support system, can reduce waste, extend the life of existing mines (and their associated communities) and delay the necessity to develop new mines. The example is iron ore mining, but the principles and methods apply to other extractive industries, including coal mining. Iron ore composition must lie within a tolerance, not only in iron, but also in several contaminants. Ore is mined, railed to the port, crushed, stockpiled and shipped. Traditionally, each stockpile is built to target the specified composition. The excessively tight coupling between mine and port causes oscillatory "hunting", and loss of control. Stockpiles then tend to average better than target grade, to avoid shipping unacceptably low-grade ore. Shipment of ore above target grade is an opportunity cost, causing unnecessarily fast depletion of the natural resource. We describe how this wastage was reduced. Firstly, a symmetric multi-dimensional objective function was proposed and adopted. Secondly, building individual stockpiles to target (batch) was replaced by maintaining the composition of an exponentially smoothed continuous stockpile (flow). Thirdly, information was extracted from immediate, but inaccurate, sampling data combined with later, more accurate, data. The methods, applied at several stages in the process, lessen the tight operational coupling between the stages, and improve their informational coupling.

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1 Introduction

Australia's economy depends heavily upon mining, with iron ore now being one of the major exports. Yearly production now exceeds 120 million tonnes, earning about US $2 billion, or four percent of the country's exports (Australian Bureau of Statistics, [1]). Most of this production is from the north west coast of Western Australia. Ore is mined several hundred kilometres inland, railed to the coast and stacked onto stockpiles. These stockpiles are recovered and loaded onto ships for export to Japan, China, South east Asia and Europe.

Dependency upon mineral exports has to be tempered with the realisation that ore represents a once-only resource. Extraction and shipment inevitably involves some environmental degradation, but a responsible mining company must ensure that the detrimental environmental impact of its operations are minimised. Fortunately, it has become increasingly apparent that environmental responsibility often correlates positively with economic efficiency. The physical and social environments require that the necessary extraction is carried out with minimum waste: this is commonly equivalent to minimising long-term cost, and often short-term cost as well. We shall show how this relation between environmental responsibility and economic efficiency applies to the extraction of iron ore, but the principles and methods are applicable to other extractive industries, including coal mining.

An earlier paper (Everett [2]) showed how simulation of stockpile building at the port can be used to develop policies to improve the product quality while lessening the handling and stockpile sizes, thus reducing the environmental impact of dust pollution and land degradation. Here we show how simulation modelling of the production system for iron ore, supplemented by a suitable decision-support system, can reduce waste, extend the life of existing mines (and their associated communities) and delay the necessity to develop new mines.

Iron ore shipped must lie within a specified composition tolerance, not only in iron, but also in several contaminants, notably phosphorus, silica and alumina. (With coal, the other components, apart from carbon, may include ash and sulphur.) Consumers depend upon uniform composition for efficiency in the blast furnaces that the ore is fed into. Iron ore production is a competitive market, with supply contracts and their renewal being strongly influenced not only by price and reliability but also by quality, as measured by composition uniformity. Quality is closely monitored by customers. For example, ship-to-ship variability of ore from the world's 28 major suppliers, for each element, was collated by the Japan Iron and Steel Federation's "Steel making raw materials quality investigation" committee, and published annually (TEX [3]). This information is no longer published, but is presumably still closely monitored. Methods that can improve the product uniformity are therefore of value to the producer.

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Ore is mined, railed to the port, crushed and stockpiled prior to shipment. Traditionally, each stockpile is built to target the specified grade. This can lead to excessively tight coupling between mine and port, oscillatory "hunting", and loss of control. Consequently, stockpiles tend to average better than the target grade, to avoid the shipment of unacceptably low-grade ore. The resulting shipment of ore above target grade is an opportunity cost, causing unnecessarily fast depletion of the natural resource.

The methods described show how this wastage was reduced. Firstly, a symmetric composite of the multi-dimensional objective function was proposed and adopted. Secondly, building individual stockpiles to target (batch production) was replaced by a policy of maintaining the composition of an exponentially smoothed continuous stockpile (flow production).

The methods are applicable at several stages in the process, with a lessening of the tight operational coupling between the stages. A reasonably sophisticated information system is required, coupling the production stages. A particular challenge is to extract information from immediate but inaccurate sampling data combined with subsequently available more accurate data.

2 The Objective Function - "Stress"

Exported iron ore aims at a target composition, specified not only for iron but also for other minerals such as phosphorus, silica and alumina. Departures in either direction from the specified composition reduce the quality of the product. It is true that the customer will complain more readily if there is a shortfall in iron or excess in the other contaminating components than if the reverse occurs. However, the export of high iron or low contaminant ore represents an opportunity cost to the producer, since the ore could have been used to improve other poorer quality ore.

Consequently, the goal for each mineral can be taken as symmetric about a target specification, with ore equally below or above target being equally unsatisfactory. We can define a "stress" function as being proportional to the distance from target composition. The absolute stress for each mineral provides an objective function to be minimised. Because several minerals are involved, the objective function is multi-dimensional. Operationally, it is preferable to work with a single aggregate objective function. This was achieved as follows:

For the mineral "i", let the target percentage composition be T_i. Consultation with the marketing staff generated an "allowable" discrepancy D_i, such that the allowable discrepancy for each mineral caused equal distress to the customer. If the actual percentage composition for the mineral is C_i, we can define the mineral's "stress" component S_i:

$$S_i = (C_i - T_i)/D_i. \qquad (1)$$

We can now compute an "aggregate stress" vector $\underline{A} = \{S_i\}$, with amplitude:

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$$A = \sqrt{\Sigma S_i^2}. \tag{2}$$

The amplitude A of the aggregate stress is an overall objective function to be minimised. This not only combines the stress components, but also has the intuitively attractive property that two units of stress in one component creates a bigger aggregate stress than does one unit of stress in each of two components. Marketing staff verified that this property matched customer attitude.

3 The Production Sequence

Production at a mine is scheduled to select material from a number of current mine blocks. A sequence of train loads from one or more mines can be scheduled for dispatch to the port. At the port, trains are unloaded and stockpiled. One or more stockpiles may be built at a time: each is completed before it is available for shipping. Finally, each shipment is loaded from one or more available completed stockpiles. Figure 1 shows the production sequence from mine to ship.

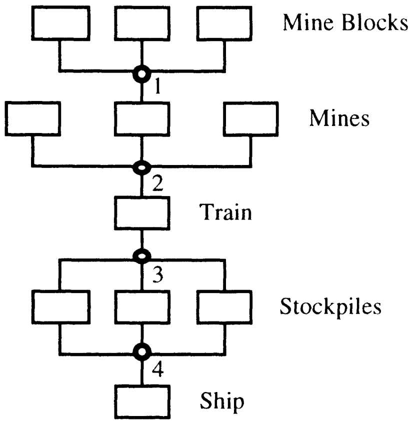

Figure 1: The Production Sequence

Four stages in the ore handling provide opportunity for scheduling choices:

1). Selecting the order in which mine blocks are mined at a particular mine.

2). Selecting the sequence of trains taking ore from source mines to the port.

3). Selecting the stockpile to which an incoming train load is to be stacked.

4). Selecting the stockpiles from which a particular ship is loaded.

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Scheduling of Stages 1) to 3), must consider the effect on future decisions, because a decision for short term optimisation may block longer term optimisation. The ore composition exhibits strong serial correlations in each mineral and strong cross correlations between the minerals. These correlations are complex, and the composition is not stationary. So for Stages 1 to 3, analytical solution is not appropriate, nor can we construct synthetic data series that adequately represent the real fluctuations in composition. Heuristic solutions were used for these stages. These solutions were developed and evaluated using simulation models with data from several years of production. The simulation models were constructed using Extend™ (Diamond and Lamperti, [4]).

Not all iron ore mining operations in Western Australia have the full complexity of Figure 1. For some, the supply may come from only one mine. In others, only one stockpile is being built at a time. However, in every case the objective is to minimise variability in composition. Appropriate choices at some or all of the Stages 1 to 4 can be used to help in this objective.

The studies reported in Everett [2], considered only one producing mine. Ore was not crushed until it reached the port, and multiple stockpiles could be built in parallel at the port. So for this study, scheduling policies in Stage 3 and Stage 4 were developed and applied to obtain an verified improvement in export quality.

For the BHP Iron Ore operations discussed here, operational constraints precluded the building of multiple stockpiles at the port, so improvements in Stage 3 and Stage 4 scheduling were not feasible. But train loads of ore from each of three mines were crushed and transported to the port. Examining the sequencing policies at Stage 2 enabled development of a scheduling procedure which substantially improved the ore quality for this operation.

4 Scheduling from Mine to Train (Stage 2)

The use of scheduling to improve composition uniformity of the output at each stage depends upon having some knowledge of the input composition for that stage. At Stage 1, the composition of not yet mined ore can be roughly estimated from samples taken from exploration or shot hole drilling. The mined ore cannot be assayed until it is crushed (which may be before or after its train journey to the port). When the ore is crushed, it has to be dealt with before the assay results are known. Consequently, decisions at Stage 2 have to be based on estimates or forecasts of the ore composition.

In BHP Iron Ore's operation at Newman, ore is mined from three mines, sufficiently close to be served by a single rail line to the port. The Whaleback mine is very high in iron, and low in the other minerals. The other two "Satellite" mines are of lower grade. Train loads from the mines are sent in sequence to the port and stacked to the same stockpile. The sequence in which

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trains from the three mines are dispatched is controlled by a Quality Control officer (Figure 2).

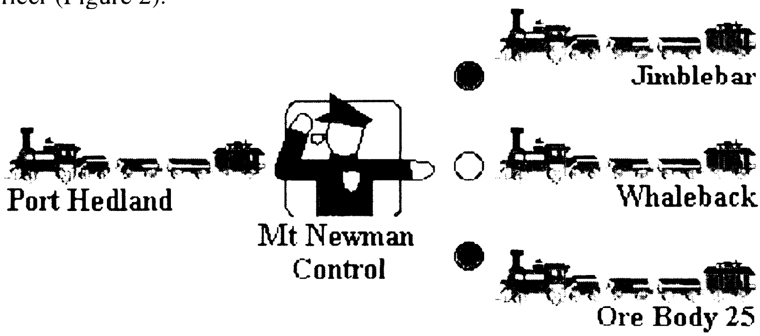

Figure 2: Newman Quality Control

This study arose from coordination problems between the Quality Controller and staff at the port. Requests for train loads of a composition to correct partially completed stockpiles were being sent up to the Quality Controller. Between mine and port, trains were delayed or arrived out of order, so the intended solution to one problem might often end up being the cause of another problem. Also, trains were chosen so as to maintain a moving average composition close to target. But with a moving average, all past trains are given equal weight until they reach a certain age, and then given no weight at all. Consequently, an extreme value not only causes a disturbance when it occurs, but also causes an equal and opposite spurious disturbance when it leaves the moving average a fixed time later. Both causes, the delayed reaction to emergencies and the use of moving averages, gave rise to "hunting" or swings caused by positive feedback and over-compensation.

We considered the problems might be lessened by reducing the tight coupling between port and mine, and by adopting an exponentially smoothed continuous stockpile of dispatched material, in which the effect of new data steadily and smoothly dies away. The Quality Controller would aim to maintain the smoothed continuous stockpile composition close to target, instead of reacting to short-term requirements at the port. Simulation models, using the past couple of years' data, were constructed to evaluate the proposed method before it was adopted.

The simulation model selects from the actual sequence of train loads from each of the three mines, so as to minimise the smoothed output aggregate stress. Because train loads vary, consistency requires the exponential smoothing constant, alpha, to depend on tonnage. Alpha is specified using an alpha per kilotonne. For alpha per kilotonne "k", and weight of a train load "w" kilotonnes, alpha is calculated as $[1-(1-k)^w]$, which is approximately equal to kw if $kw<<1$.

Candidate trains are selected with unknown composition, because the ore is not crushed and assayed until a train is dispatched. So choice was based

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upon the previous exponentially smoothed composition from that source. To run the model, we needed alpha values for the three sources, and for the output streams.

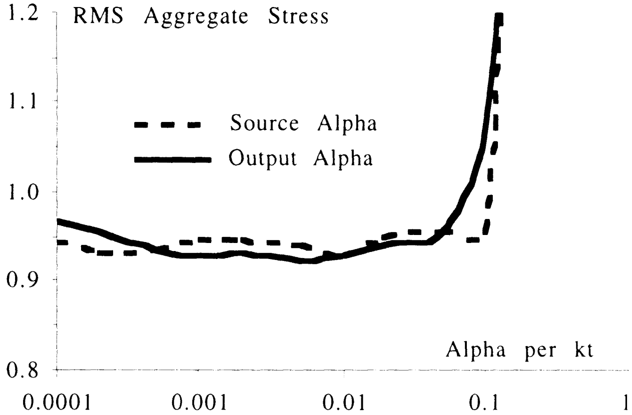

Figure 3: Choosing the Exponential Smoothing Constant, Alpha

Figure 3 shows the root mean square (rms) aggregate stress of completed 150 kilotonne stockpiles, and how this stress depends upon the source and output alpha values. The figure shows that, for both source and output alpha, the control becomes unstable if the alpha per kilotonne is of the order of 0.1 or larger, but does not change much for smaller alpha values.

Other things being equal, a larger alpha is desirable, so that the system can respond more quickly to sudden changes. Accordingly, an alpha value of 0.01 was used for exponential smoothing of the three sources and of the output. By way of comparison, the results suggest that the method would generate an rms aggregate stress of 0.92, whereas the actual train sequence used over this period had given an rms aggregate stress of 1.26.

The result for the source alpha is at first counter-intuitive. For each source mine, the best forecast is given with an alpha of about 0.1. Using the best forecast does not give the best system performance.

To check this paradox, the simulation was repeated, choosing candidate trains according to their actual composition (of course this would not be possible in reality). The rms aggregate stress increased to 1.49, worse than the 1.26 actually achieved. The reason for this surprising result, that using perfect knowledge leads to worse performance, lies in the conflict between short-term and long-term goals. Using the actual or accurately forecast composition causes any particularly "bad" train to be greatly delayed, blocking the using of "good" trains following it from the same source.

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Comparing actual to potential performance we have seen that the rms aggregate stress of completed stockpiles would be decreased from 1.26 to 0.92, a 27% improvement.

Figure 4 compares the revised to the actual train sequence. Train loads plotted below the 45° line should have been despatched earlier than they were, and vice versa.

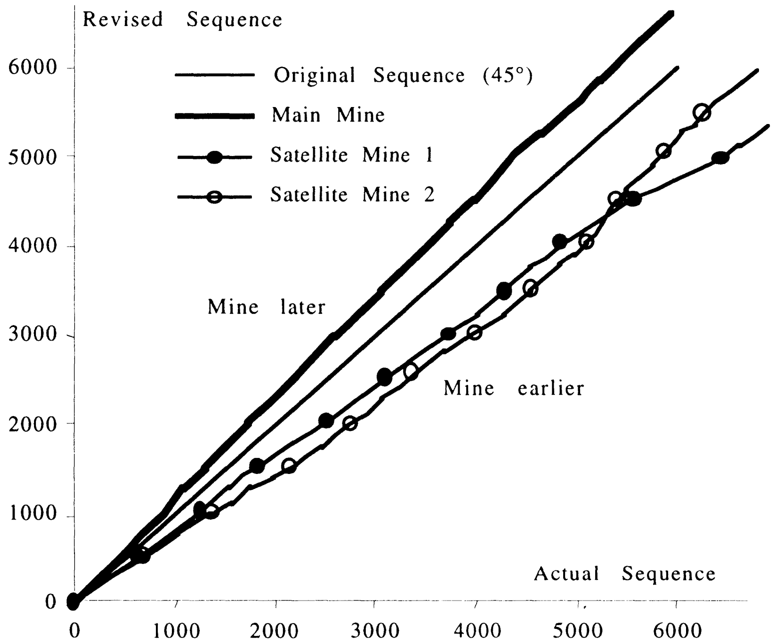

Figure 4: Actual Compared to Improved Production Sequence

The revised train schedule shows that more of the low-grade, lower-cost satellite mine ore could have been used, providing an ancillary benefit to the improvement in grade control. This means that the life of the high-grade Whaleback mine could be extended by about 20%. Since Whaleback is unique, but is surrounded by a number of potential low-grade satellite mines, the finding is of considerable potential economic benefit.

The reason why the revised sequence uses the Whaleback mine more slowly becomes apparent from Fig. 5. This graph shows the cumulative distribution of the iron content of completed stockpiles, for the actual and for the revised sequence.

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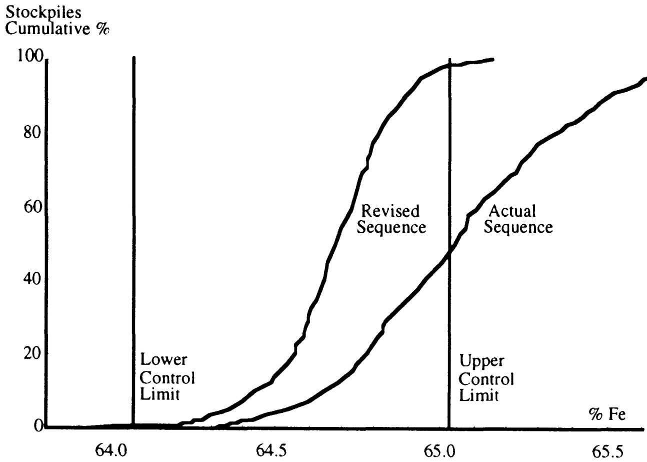

Figure 5: Cumulative Distribution of Stockpile Composition.

The upper and lower control limits in Figure 5 represent unit stress above and below the target composition. It is clear that the median composition for the revised sequence is close to target, midway between the upper and lower control limits. For the actual sequence, half the completed stockpiles lie above the upper control limit. This is because the grade control was much less precise using the previous system. Consequently, to avoid the risk of completing stockpiles too far below target, they tended to be completed above target. However, this incurred an opportunity cost, because the average grade of delivered ore was above the targeted level, so that the richer Whaleback mine was consumed proportionately quicker than necessary.

With the actual sequence, most of the out of control stockpiles erred on the side of too much iron. Similarly, cumulative distributions for the other, contaminant, minerals show that completed stockpiles erred on the side of too little of these contaminant minerals. This bias towards high iron and low contaminant presumably arose because the system was more responsive to potential customer complaint than to opportunity cost. The greater control now established enables the average iron content to approximate instead of exceeding the target value, without increasing customer complaint. Reducing the average proportion of iron, with no loss of quality, permits the proportion of production from the low-grade satellite mines to be increased, as we have seen in Figure 4.

After the simulation study was completed, it was decided that the decision support system should be adopted for use by the Quality Controller. The decision support system was implemented as an Excel workbook with embedded Visual Basic macros [5]. This medium for implementing the decision support system was chosen because Excel was available and familiar to every operator. The embedded macros were invisible to the operator.

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Six months of subsequent experience have confirmed the improvement in Total Stress of completed stockpiles, and have also resulted in 20% of the Whaleback mine production being transferred to the Satellite mines, as predicted by the simulation studies.

5 Conclusion

The economic benefits of the extension in mine life have not been evaluated. However, the 20% extension of the life of the Whaleback mine implies a 20% extension to the life of the Newman township. Extension of the life of the mining community is of clear benefit to their social environment. Delaying the need to develop high-grade mines in other locations benefits the physical environment.

Operating costs have been reduced by US $7 million per year, because the Satellite mine operating costs are lower than for Whaleback. These savings in operating costs imply a reduction in the consumption of energy and other resources, and are therefore of considerable benefit to the ecological environment.

The study shows that computer-based studies aimed at economic efficiency in Australia's resource industries can yield benefits not only to the country's economic environment, but also to its social end ecological environments.

There are clear analogies between the aspects of quality control for iron ore production and for other extractive industries. We are currently exploring applications of the methods to coal production.

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