Reducing the environmental and economic costs of handling iron ore

J.E. Everett

Department of Information Management & Marketing, University of Western Australia, Australia

Abstract

Iron ore is shipped out in large quantities from northern West Australian ports. The ore is railed to the port, stock piled and then loaded on to ships. Customers require that successive shipments are uniform in composition, with respect to several elements, including iron, silicon, aluminium and calcium. Variability in composition can be smoothed out by stacking the arriving ore onto large stockpiles, which are recovered for shipment. With random stacking and recovery from a single stockpile, improved variability requires larger stockpiles, and/or increased handling of the ore. Both these involve environmental costs as well as economic costs. The larger the stockpiles and the greater the amount of rehandling, the greater the resulting dust pollution and land degradation.

This paper shows how the size of stockpiles and the amount of rehandling can be reduced by intelligent stacking and recovery procedures. The decision model discussed uses a combination of computer simulation and analysis to develop ore handling rules. Forecasts of the incoming ore composition combined with a monitoring of stockpile composition can be used to decide where ore should be stored. Similar rules are developed to choose the stockpiles from which to recover ore when ships are being loaded. We find that direct loading a proportion of the ore can further reduce environmental and economic costs, without loss of composition uniformity.

The computer simulation model is used on a microcomputer to evaluate and demonstrate graphically the considerable reduction in land use and dust pollution that can be achieved by intelligent stacking and recovery procedures. The computer simulation model not only helps evaluate alternative policies using real data, but also provides a graphical interface which has enhanced communication between managers, operators and policy advisers.
1 Introduction

Iron ore provides 5% of Australia’s exports, totalling over 100 million tonnes, or over US$2 billion dollars value, per year. Most is mined in the north west of Western Australia and railed to a few coastal ports, then crushed, stock piled and shipped out, to customers in Japan, China, Southeast Asia and Europe.

Customers are concerned about variability of composition in the iron ore. Their blast furnaces are tuned to ore of particular composition, and require considerable adjustment if composition varies between shipments. The major quality control for iron ore is therefore to minimise variability in composition, not just in the percentage content of iron (Fe), but also of silica (SiO₂), alumina (Al₂O₃) and calcium oxide (CaO). From some mines, the phosphorus content can also be important, though not in the example to be considered here. Customers are very aware of the variability offered by suppliers, from Australia and elsewhere. For example, the Japanese industry publishes an annual comparison of suppliers’ ship-to-ship variability. Improving the composition variability can therefore provide a substantial market advantage to an iron ore producer.

Figure 1 shows schematically the port facilities for a typical iron ore producer. The mine can plan the average composition of ore that it produces, but there will still be appreciable variation in what is mined from day to day. The ore arrives by train, is crushed, sampled for assay and stacked on stock piles. These stock piles are then reclaimed and loaded on ships for export. It is also possible to direct load some of the ore, bypassing the stock piles.

![Diagram of ore handling facility]

Figure 1: Layout of the ore handling facility.

Stock piles provide an effective means of reducing ore variability. Ore is stacked by laying the ore back and forth in one direction. Operationally, a stock pile cannot be reclaimed until it has been filled. The ore is reclaimed by...
cutting slices at right angles to the direction of stacking. So it can be assumed with reasonable confidence that ore reclaimed from a stock pile is of uniform composition. Clearly, the larger the stock pile, the greater its averaging or smoothing effect on composition. In effect, the stock pile is a low pass filter.

There are environmental as well as economic costs incurred in the port handling of iron ore. The stock piles occupy (but do not beautify) a large area of prime coastal land. The handling process, stacking and reclaiming of stock piles, creates dust which is environmentally deleterious.

This paper will show how computational procedures can be used to enhance the handling process to achieve as good or better quality control while using less volume of stock pile. It is also shown that a portion of the ore can be direct loaded, bypassing the stock piles, with no loss of quality. Both improvements can be expected to reduce the environmental and economic costs, by reducing the volume of the stock piles used, and by reducing the amount of ore handling.

2 Measure of Performance

The objective is to ship out ore of minimum variability. For each mineral there is a target percentage, and a tolerable range. The tolerable range was established by discussion with the marketing staff. For example, if the \{Fe, SiO₂, Al₂O₃, CaO\} targets were \{57.29%, 5.35%, 2.64%, 0.56%\}, and the tolerable ranges were \{0.40%, 0.30%, 0.14%, 0.30%\}, then an Fe content of 56.89% or 57.69%, or an SiO₂ content of 5.05% or 5.65% would all be equally distasteful to the customer. It is convenient to define a “stress” for each mineral:

\[
\text{Stress} = \frac{\text{Actual} \%- \text{Target} \%}{\text{Tolerance} \%} \tag{1}
\]

The aggregate stress (A) can then be defined by:

\[
A^2 = \text{Stress}^2(\text{Fe}) + \text{Stress}^2(\text{SiO}_2) + \text{Stress}^2(\text{Al}_2\text{O}_3) + \text{Stress}^2(\text{CaO}) \tag{2}
\]

The individual mineral stresses can be positive or negative, but the aggregate stress must be positive. The aggregate stress provides a suitable measure of the quality of a shipment of iron ore. The objective is to despatch shipments of iron ore for which the root mean square (RMS) aggregate stress is minimised.

3 Data Source

This study was carried out in cooperation with Robe River Iron Associates, who export 30 million tonnes of iron ore yearly through their port facility at Cape Lambert., on the northwest coast of Western Australia.
Incoming iron ore is sampled for each four-hour period of production. The incoming tonnage and assays for iron, silica, alumina and calcium oxide are recorded. A data file of 2,014 such records was supplied, spanning about a year of operation of the port facility, and was used as the basis for this study.

Each four-hour period of incoming ore averaged close to 12,500 tonnes. The median ship capacity was about 150,000 tonnes. For the purpose of the simulation studies to be reported here, it will be assumed that each four-hour production is exactly 12,500 tonnes, and each ship has capacity 150,000 tonnes.

Table 1 shows statistics for the year’s production. The four mineral stresses have quite strong cross correlations, and each exhibits strong serial correlation.

4 Simulation Models

To investigate the effectiveness of alternative ore handling procedures, the system of Figure 1 was modelled using the graphical simulation package Extend². The model allowed up to three stock piles to be built concurrently from incoming ore, and for ships then to be filled from up to three stock piles simultaneously. We will discuss various procedures for determining how to build the stock piles, and how to recover ore from them to load the ships.
5 Single Stock Piles

The simplest procedure is to build a single stock pile to completion before the next is started, and to recover from a single completed stock pile to fill each ship. If the incoming stresses were not serially correlated, then the RMS aggregate stress of the completed stock piles would be inversely proportional to the square root of the stock pile size. Because of the strong serial correlation, the stress does not fall off quite so fast. Figure 2 shows how the root mean square aggregate stress decreases with increasing stock pile size. For comparison, the broken line shows the behaviour that would occur if the stresses had no serial correlation. Since ships are being filled each from a single stock pile, the RMS aggregate stress applies both to completed stock piles and to filled ships.

Figure 2: The decrease of aggregate stress with increasing stock pile size.

Larger stock piles occupy more land, implying greater environmental and economic costs. If more sophisticated ore handling methods can use a lesser stock pile area, then some environmental and economic benefit is obtained.

In the following sections we will consider a range of alternative ore handling methods, and compare the stock pile capacity needed with that required to give the same level of RMS aggregate stress using the single stock pile configuration.
Multiple Stock Piles Built in Turn

We have seen that the RMS aggregate stress does not fall off as quickly with stock pile size as it would if there were no serial correlation. Serial correlation can be reduced by building multiple stock piles in turn, to increase the building time each stock pile spans. Consider building simultaneously three stock piles, each of 300,000 tonnes. Since it would be operationally infeasible to change the destination stock pile every four hours, we shall assume that the destination is changed three times per stock pile. This corresponds to changing the destination stock pile each 100,000 tonnes, or 32 hours, of production.

Building the three stock piles could be done in a number of different sequences. Table 2 shows the sequence used, which ensures that each stock pile spans nine changes, the maximum possible. Maximising the building span of each stock pile reduces the serial correlation. Pile “3” is started when pile “1” is two-thirds full and pile “2” is one third full. The next 100,000 tonnes goes to pile “2”; then pile “1” is completed; pile “4” is commenced, and so on.

Table 2. Stock pile building sequence to maximise span (“three in turn”).

<table>
<thead>
<tr>
<th>Stock Pile</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Period</td>
<td>{9</td>
<td>12</td>
<td>15</td>
<td>18</td>
<td>21</td>
<td>24</td>
<td>27</td>
</tr>
<tr>
<td>{5</td>
<td>8</td>
<td>11</td>
<td>14</td>
<td>17</td>
<td>20</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>{1</td>
<td>4</td>
<td>7</td>
<td>10</td>
<td>13</td>
<td>16</td>
<td>19</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 compares building 300,000 tonne stock piles singly, with building three in turn (as in Table 2). Building three stock piles in turn gives considerable reduction in aggregate stress, equivalent to single stock piles of 706,000 tonnes. However, the single stock pile system averages two stock piles half full. If we build three stock piles in turn, and fill ships from the last stock pile completed, on average four stock piles will be half full. Taking this into account, building the three stock piles in turn gives 15% saving in storage space.

Table 3. RMS stress for stock piles built singly, and for three in sequence.

<table>
<thead>
<tr>
<th>Stock Pile Sequence</th>
<th>Aggregate Pile Stress</th>
<th>Equivalent '000 Tonne</th>
<th>Piles in use</th>
<th>Stock Pile Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single stock pile at a time</td>
<td>1.490</td>
<td>300</td>
<td>2/2</td>
<td>0%</td>
</tr>
<tr>
<td>Three in turn (see Table 2)</td>
<td>1.062</td>
<td>706</td>
<td>4/2</td>
<td>15%</td>
</tr>
</tbody>
</table>
7 Multiple Stock Piles Built Intelligently

If we know the stress of the incoming ore, then we can modify the sequence in which the stock piles are built, using the assay information to reduce the stress of the completed piles. We shall refer to procedures using the assay information as "intelligent" procedures. Consider a stock pile "j" containing ore of weight $W_j$, with stress components $\{S_i\}$, where $i$ goes from 1 to 4, for the four mineral stresses. We can define the "pain" $P_j$ for stock pile "j" as:

$$P_j = W_j A_j^2 = W_j \sum_i S_{ij}^2$$  \hspace{1cm} (3)

For incoming ore of weight $w$ and stress $\{s_i\}$, we need to choose which stock pile ($j = 1, 2, \ldots$) to add it to. It is sensible to choose the stock pile for which the rate of increase in "pain" per tonne added ($\partial P_j/\partial w$) is smallest.

$$\frac{\partial P_j}{\partial w} = \sum_i \left[ \frac{\partial}{\partial w} (W_j S_{ij} + w s_i)^2 \right] = 2W_j \sum_i S_{ij} s_i$$  \hspace{1cm} (4)

So an appropriate criterion in choosing a destination stock pile "j" is to select the one which minimises the criterion $W_j \sum_i S_{ij} s_i$. With a delay of several hours in processing assays of incoming ore, the stress $\{s_i\}$ is not accurately known. However, an unbiased forecast of the stress, based on previous assays, can be used instead. An exponentially smoothed forecast was used. Analysis using the SPSS Trends package found the best fit with an alpha value of 0.7.

Table 4 shows the RMS aggregate stress that would be obtained if the 300,000 tonne stock piles were built using accurate assay data, and if forecast data were used. Although the accurate assay data would not be available, the forecast data gives almost as good a result. We see that the exponentially smoothed forecast is better than a naive forecast (the previous assay). The decrease in RMS aggregate stress, obtained with intelligent sequencing using the exponentially smoothed forecasts, gives a 30% saving in stock pile space.

<table>
<thead>
<tr>
<th>Three Pile Sequence Controlled by:</th>
<th>Aggregate Pile Stress</th>
<th>Equivalent '000 Tonne</th>
<th>Piles in use</th>
<th>Stock Pile Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accurate assays</td>
<td>0.936</td>
<td>918</td>
<td>4/2</td>
<td>35%</td>
</tr>
<tr>
<td>Forecast based on:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exponential smoothing</td>
<td>0.966</td>
<td>861</td>
<td>4/2</td>
<td>30%</td>
</tr>
<tr>
<td>Previous assay</td>
<td>1.005</td>
<td>789</td>
<td>4/2</td>
<td>24%</td>
</tr>
</tbody>
</table>

Table 4. RMS stress for stock piles built using assay information.
8 Intelligent Ship Loading

We have so far assumed each ship is fully loaded from a single completed stock pile. Further improvement in variability can be achieved by intelligently filling each ship from multiple stock piles, taking account of the assay stresses of the stock piles. Filling a ship from “k” available stock piles, the proportion of load taken from each stock pile is the vector \( \{ p_j \} \), for \( j = 1 \ldots k \). The stress of stock pile “j” is given by the vector \( \{ s_i \} \), where \( i = 1 \ldots 4 \), represents the four minerals. The ship may already contain a proportion \( p_0 \) with stress \( \{ s_0 \} \). The aggregate stress of the filled ship is to be minimised, subject to the constraint that \( \sum_j p_j = 1 - p_0 \). Using the Lagrange multiplier \( \mu \), we can minimise a modified objective function “Y” with respect to each of \( p_1 \ldots p_k \) and \( \mu \):

\[
Y = \sum_i (p_0 s_i + \sum_j p_j s_i)^2 - \mu (p_0 + \sum_j p_j - 1)
\]

Solving the resulting equations gives the proportion \( p_j \) to take from each stock pile. If more is demanded from a stock pile than it contains, the stock pile is emptied to the ship, and the calculation repeated, including the next stock pile. Also, some \( p_j \) may be negative. If only one \( p_j \) is negative, the optimum is found by repeating the calculation omitting that stock pile. In the rare case of two or more \( p_j \) values being negative, then little (if any) optimality is lost by omitting the stock pile with the most negative \( p_j \) and repeating the calculation.

Both these problems could be dealt with by quadratic programming and the simplex algorithm, with the non-negativity and stock pile tonnage constraints included. However, this would require considerable extra computational effort with little better performance than the branch and bound method just described.

Table 5. RMS stress for ships loaded using stock pile assay information.

<table>
<thead>
<tr>
<th>Stock Piles Built Using</th>
<th>Aggregate Ship Stress</th>
<th>Equivalent '000 Tonne</th>
<th>Piles in use</th>
<th>Stock Pile Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three in turn (see Table 2)</td>
<td>0.590</td>
<td>2,086</td>
<td>6/2</td>
<td>57%</td>
</tr>
<tr>
<td>4-hour exponential forecast</td>
<td>0.564</td>
<td>2,248</td>
<td>6/2</td>
<td>60%</td>
</tr>
<tr>
<td>Accurate assays</td>
<td>0.575</td>
<td>2,178</td>
<td>6/2</td>
<td>59%</td>
</tr>
</tbody>
</table>

Table 5 shows that the intelligent ship loading procedure greatly improves the RMS aggregate stress, using stock piles created by “three in turn” and by intelligent methods. Even though the system uses six stock piles that are on average half full (three being built and three being recovered to the ship), the saving in stock pile space is 60%. Although building the stock piles intelligently
gave less stock pile variability than did the “three in turn” method, we find that intelligent ship loading gives almost as good a result when it uses stock piles built “three in turn” as when it uses stock piles built intelligently.

9 Direct Loading

Referring back to Figure 1, it is possible to load some of the incoming ore directly to the ship, bypassing the stock piles. If a proportion \( p_d \) is direct loaded, the rest can be intelligently selected from stock piles as described in the previous section. The simulation was run again, for a range of proportions of direct loading. Figure 3 shows that 20% or more of the ore can be direct loaded without significant increase in variability. Indeed, direct loading about 10% of the ore gives a small improvement in performance. This can be explained by the fact that direct loading increases the span of arrival time for ore going into a ship, and thus decreases the serial correlation problems. In the limit, as direct loading approaches 100%, the performance is no better than building single stock piles of 150,000 tonnes each. Being able to direct load a portion of the ore reduces the amount of handling and therefore the amount of dust pollution generated. This provides both an environmental and an economic benefit.

![RMS Aggregate Stress of Ore Shipped Out](image)

**Figure 3:** The effect on stress of direct loading a proportion of the ore.
10 Conclusion

The study has demonstrated how some fairly simple software, easily run on a microcomputer, can be used to reduce the variability in ore composition by intelligently controlling the building of stock piles from incoming ore, and the loading of ships from multiple stock piles. The computer simulation not only helps evaluate alternative policies using real data: the graphical interface has also enhanced communication between managers, operators and policy advisers.

We have seen that the software can be used to save about 60% of the space that would otherwise have to be dedicated to stock piles. This saving in stock pile space represents a considerable environmental as well as economic benefit. The software can also be used to control the direct loading of up to 20% of the ore, without increasing the variability of the shipments. Direct loading a fifth of the ore considerably reduces the amount of ore handling and resultant dust pollution.

One great advantage of the two forms of environmental benefit - saving in stock pile space and reduction in dust pollution - is that they are both accompanied by economic benefits. Environmental savings that can be achieved with a decrease rather than an increase in economic costs are clearly far more likely to be adopted, especially in a highly competitive industry.

The software described here is now being used by Robe River Associates to guide their iron ore handling operations at Cape Lambert. In the words of their Manager of Marketing - Technical:

“... the recommendations from the work have been implemented, resulting in a measurable reduction in ship to ship variability compared to the base period. Robe has adopted your finding that preparing three simultaneous piles over a nine day period will optimise blending efficiency and the procedure has been incorporated into our Quality Management System. It was also presented to customers in Japan during our recent Technical Presentations to the Japanese Steel Mills and was well received. ... In essence, a good news story like this should not be in any way confidential.”

References


