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Multi-level grade control in a mining supply chain DEM

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Abstract: A complex discrete event model was constructed to model an entire pit-to-port iron ore mining operation, including multiple mines, two rail lines and two ports. Inputs to the system included an 18-month block-level mine plan with estimated grades. The purpose of this model was to evaluate the trade-off between annual tonnes produced and grade quality, in the face of ore body depletion and changing customer requirements, in order to maximize tonnes per annum while minimizing any export grade penalties. The problem of managing ore grade with variability and uncertainty across the entire operation required the use of a global optimization, which calculated and updated a schedule of production every 24 hours of model time, with a look ahead of 30 days. The LP solver was integrated into the model code and acted as the intelligent driver of all ore handling activities. This approach allowed the evaluation of selected grade targets and production volumes in the context of an 18-month time horizon, including realistic operating conditions such as weather interruptions and equipment down times. The result was a dramatic reduction in export grade variability, with no loss of throughput compared to the case of no grade control. This work showed the feasibility of modeling the effects of grade control at an enterprise level, managing the variability and uncertainty inherent to any mining operation to achieve the best possible grade outcomes.

Keywords: *Discrete event model (DEM), Optimisation, Iron ore, Grade control*

1. INTRODUCTION

Iron (chemical element Fe) is the fourth most common element in the earth's crust, accounting for about 5% of its mass, and is the most used metal on the planet. It occurs in ores such as hematite (Fe_2O_3) and magnetite (Fe_3O_4) which are refined to make pig iron and ultimately steel. Since the 1960s, iron ore exports have become a significant factor in the economy of Australia with almost all of the iron ore exports coming from Western Australia.

The process of producing iron ore for export involves a great deal of planning and heavy equipment. Geological surveys and drill samples first indicate where commercial deposits are located. Mine planners calculate a sequence of digging that, in the case of an open pit mine, expands the mine pit over time to recover the ore while minimizing the amount of uneconomic waste that has to be removed. The excavated rocks are then fed to a crushing machine which reduces the material to one of two sizes, approximately 7mm to 25mm which is 'lump', and under 7mm which is called 'fines'. The reason for this is that blast furnaces need material of this size to operate efficiently.

The commercial proposition of an iron ore mine depends on many factors: how many tonnes of ore can be produced; what the Fe concentration is; and what impurities are present such as silica, alumina, phosphorus and sulphur, all of which have a detrimental effect on the refining process. Steel mills require processed ore of a pre-defined quality in order to operate effectively, and this highlights the difficulty of turning an ore deposit into a useful and valuable export product.

This paper addresses: the significance of grade issues prior to commencing mining operations; the rationale for using a Discrete Event Model approach to investigate the associated problems; the methodology adopted and findings; and concludes with a brief discussion with respect to the relevance of those findings and their importance to the long term planning for the iron ore mining business in Australia.

2. GRADE ISSUES OF AN IRON ORE MINE OPERATION

The mining supply chain encompasses all of the ore handling operations, from the diggers in the open cut mine pit to the barges that carry the ore to the offshore ship loader.

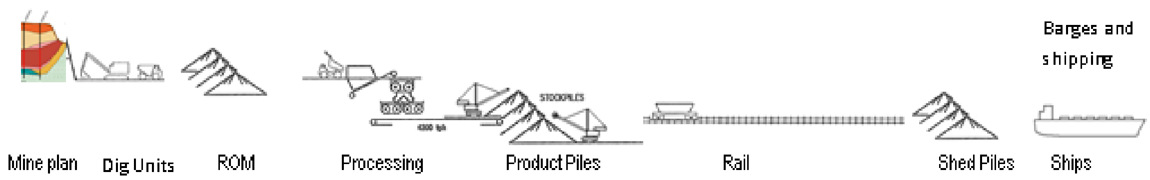

Figure 1 - Typical mining supply chain

Before any mining begins, the only data on the hidden ore body comes from core samples taken during exploratory drilling. As these holes are expensive to drill, their number is limited. This means that the grade of the entire ore body must be estimated from these samples. When the block-level mine plan is created there is a degree of uncertainty in the ore grades. It is only after digging and crushing that samples can be analyzed and the actual grade is known. Figure 2 shows the grade variability that can exist in a block-level mine plan of 18 months duration.

Another source of variability is in the equipment used at all stages of the operation. Mining equipment works hard and needs regular maintenance. There are also equipment breakdowns. Taken together, these maintenance and down times reduce the equipment availability, affect the interactions between different areas of the operation, and must be factored in to any plan.

The question then is how to predict what the production of an iron ore mine will be in terms of tonnes over time, and also what can we expect the grade of the final product to be, given the inherent variability of the ore body? And how can we look forward one month, one year, or even 10 years?

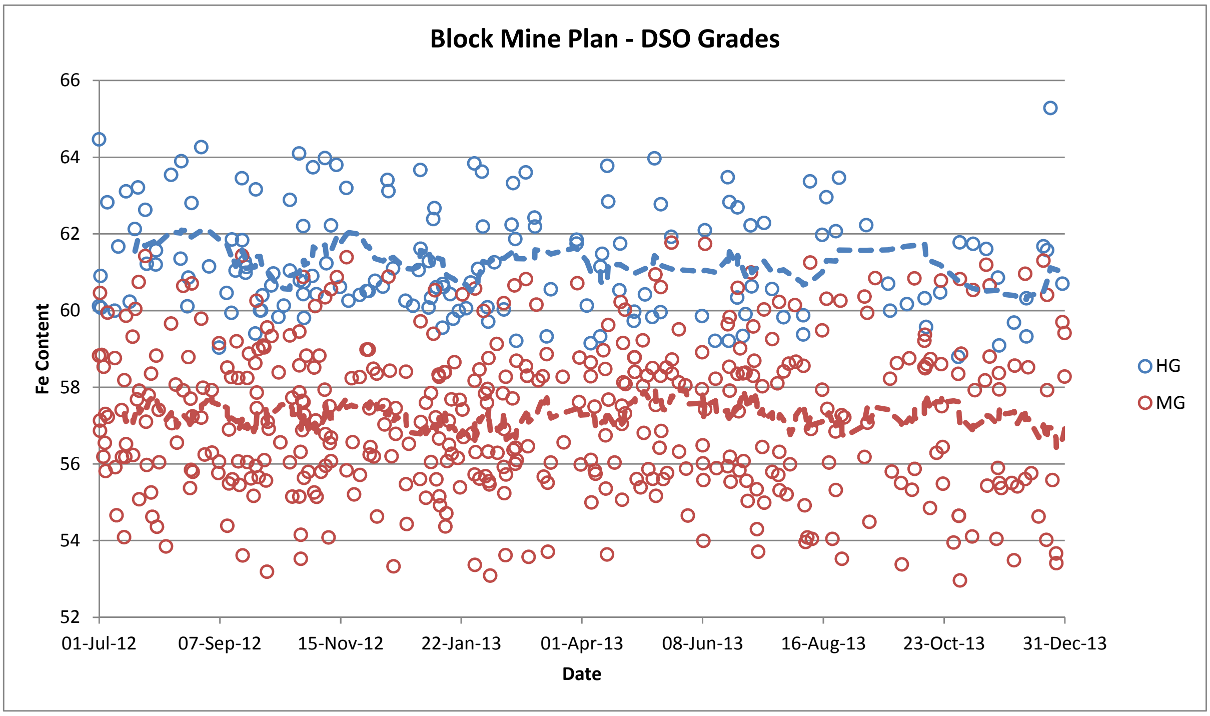

Figure 2 - Estimated block grades in an 18-month mine plan

3. APPROACH: WHY WE USE A DISCRETE EVENT MODEL

Managing the grade of ore to be loaded from port stockpiles onto a ship is a relatively straightforward operation. The grades of the stockpiles are known, and it is then a simple matter of choosing from the available stockpiles using a weighted average calculation. This can be handled with a spread sheet, and often is. However, this is an operational problem with a short time horizon. A more difficult problem is: how to predict the grade of an ore shipment that is one month out, when most of the ore is still in the ground? Clearly, a more sophisticated tool is needed.

The data for all the variables of ore grades and equipment operations are known at a statistical level, and one might approximate the overall system performance using *averages*, over some time period such as a week or a month. However, the important fact is that these simplifications overlook the dynamic interactions between different parts of the system, which can have a significant effect on the final outcome.

It is for this reason that the preferred approach is to use a Discrete Event Model (DEM). In such a software model, each component of the mining supply chain, from diggers to ship loading barges, is modeled along with the flow rates, travel times and down times according to input parameters. Each parameter that can vary is related to a statistical distribution, and many model runs produce a distribution – or envelope – of the important system behaviors.

And yet, even this is not sufficient. A software model may well be able to represent each vehicle or piece of machinery faithfully, but such a system would be simply a collection of autonomous entities, each operating independently. This is what one might expect from a simulation of, say, an airport. Planes arrive and leave, passengers disembark, pass through customs and security control points, collect their baggage, and so on. Plane schedules are determined, and apart from that there is no overriding control of passenger flow.

For the purposes of a strategic plan, what we need in our modeling of an iron ore mine requires some degree of system level control, primarily of the target tonnes and grade that are to be produced and shipped. For this reason, we need a global view that can take in all the information about the entire operation and make decisions that direct and guide the model execution.

For this we incorporate a mathematical solver in the model, which is described in the next section.

4. WHAT WE DID

A discrete event model of a mining supply chain was built using the simulation language SLX. This model included all of the diggers, crushers, trains and barges used to deliver processed ore to the ships at anchor. The movement of ore progresses in stages, first being dug and placed onto rough piles of recovered ore material (ROM), from where it went into crusher feed piles. Output from the crushers went into post-crush piles at the rail load out points. Trains then carried the selected post-crush ore (by now with actual grades) to the shed at the port, from which the ore would be either stockpiled or bypass the shed and be loaded directly onto the barges, which carried the ore to the waiting ships at an offshore loading point. The shallow waters of the coastal area required the large ships to anchor off the shore.

The model used over 1000 input parameters, giving an indication of the level of detail involved. These parameters covered all of the normal equipment operations such as digging rates, crusher flow rates, train loading and unloading times, train travel times (including dynamic passing delays), barge loading and unloading times, etc. Most of these parameters were provided by the client based on current operational data. Also included were planned maintenance times and historical downtimes. After the initial model was built, a model validation phase was undertaken during which time the model parameters were tuned to match the actual mine operations over a 3 month period.

Once the model was validated, modeling was extended to look at a longer time horizon to support strategic planning. The mine plan for this phase contained 18 months of data, with an expected production rate of about 6 million tonnes per annum (Mtpa).

The export ships were assumed to all be of the cape size class with a capacity of 169,000 tonnes. The capacity of the port in the model meant that 3 ships of this size could be expected to be serviced each month, so the goal was to optimize the grade and tonnes of each of these 3 ships. A list of export ships was generated automatically by the model, with a total look ahead of 3 months. There is never enough post-crush ore ready at any time to fill 3 ships, so the planning had to look back into the supply chain, even back into the mine plan itself. Thus, given the uncertainty of ore grade past the first month, the planning of ships in the second and third months was based only on available tonnes.

The model was driven by a daily consignment plan, which contained the tonnes of each product required from each stockpile in the entire system to meet the demands of the first 3 ships in the queue. For example, a train arriving at a mine load out station would be loaded with product for ship 1 first, according to the plan, and if no more material was needed for ship 1, then ship 2 material would be loaded. In this way, the operations of the mine model could be directed on a daily basis to meet the ultimate goal of exporting the correct tonnes at the desired grade.

These plans were produced using a linear program (LP) formulation of the global grade control problem, written using the mathematical programming package AIMMS and accessed from SLX. In addition, the same LP in a reduced form was used to solve the local problem of producing feed piles prior to crushing.

The objective function of the LP was based on the sum of all penalties for deviations from the target tonnes and the target grades. Figure 3 shows the lower and upper bounds for a particular grade element, for example Fe. Below this range (to the left) the penalty weight increases dramatically, and also above this range (to the right). Within this range, there is a slight bias towards the lower end of the range. For impurities such as alumina or silica the bias is reversed.

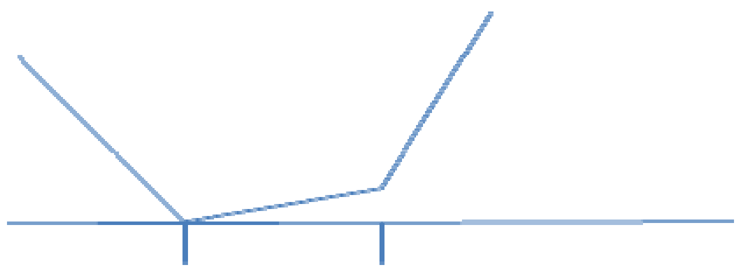

Figure 3 - Penalty function for grade targets

Figure 4 shows the lower and upper bounds for a tonnes target. The actual target is in the middle, and below that (to the left) say at -10% the slope of the penalty function is very high, but within this range the slope is small and meant only as a bias. The effect of this shape is to bias the solution towards the target from both sides, but impose a high penalty for exceeding the upper and lower bounds. Obviously, ships have a limited capacity and thus the very high penalty to avoid over-loading.

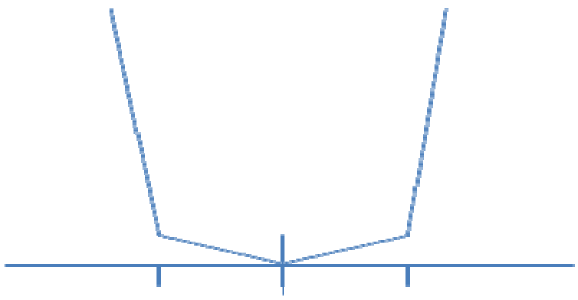

Figure 4 - Penalty function for tonnes targets

Because the grade optimization was used at the local level for feed piles, and at a global level for ship-based consignments, this approach delivered multi-stage grade control over the whole system.

5. WHAT WE FOUND

If the mined ore were processed and exported as specified directly by the mine plan, giving priority to tonnes and without any decisions taken on the basis of ore grade, then the outcome would be driven solely by the digging order. Such an outcome is shown in Figure 5, for a period of one year. The data points for Lump and Fines come as pairs, as each ship carries a cargo composed of both products. For this graph, there were 34 ships that carried 5.52 Mt over the year. The actual Fe grades have been obscured to protect the source data, but the major increments are 1% Fe. From this it can be seen that the Lump grades vary over a range of 4.5% and the Fines grades vary over a range of 5.5% Fe. This is the result of directly shipping whatever comes out of the mine according to the mine plan.

Figure 6 shows the result of applying local and global grade control. Again, the major increments are 1% Fe. However, the results are impressive. The Lump and Fines shipped grades vary by only +/- 0.5% Fe, and with no loss of overall tonnes exported.

This is perhaps the most significant result of this modeling. Using the same mine plan and the same equipment fleet, by applying a daily plan based on a grade optimization, the shipped grades can theoretically be controlled to within 0.5% Fe. More importantly, this achievement of grade control did not come at the expense of tonnes, as the total tonnes exported in the year was within 0.5% of the uncontrolled runs.

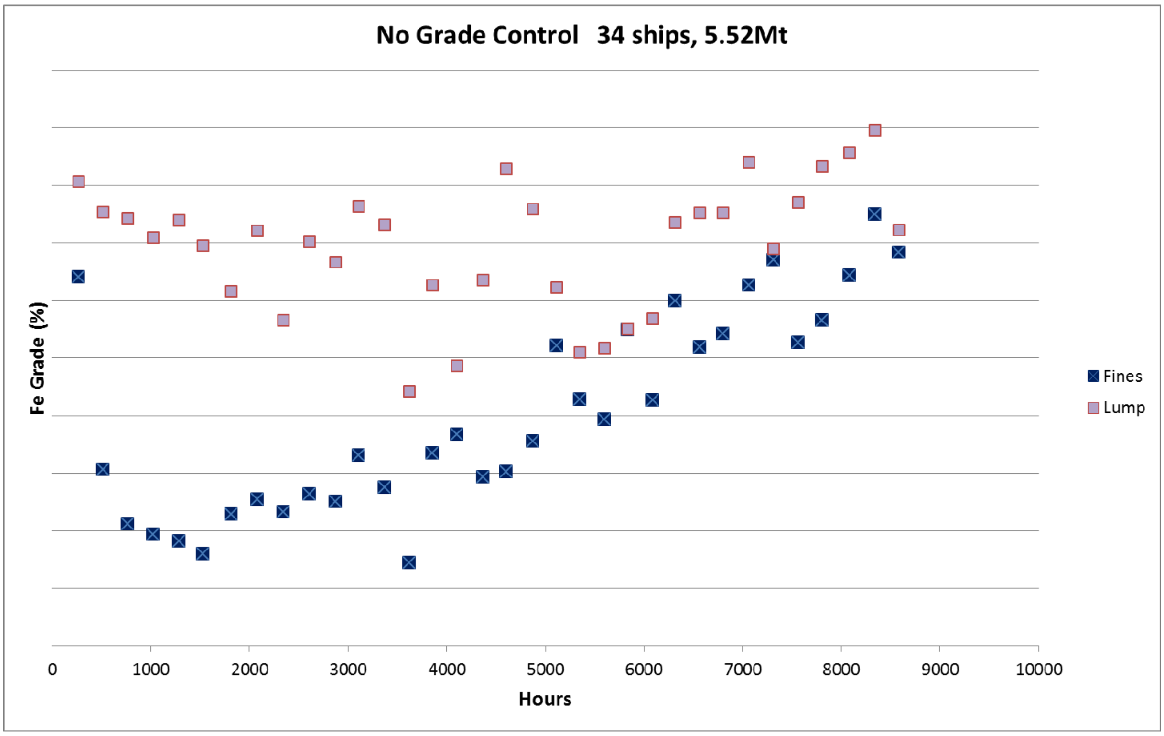

Figure 5 - One year of ore exports, no grade control

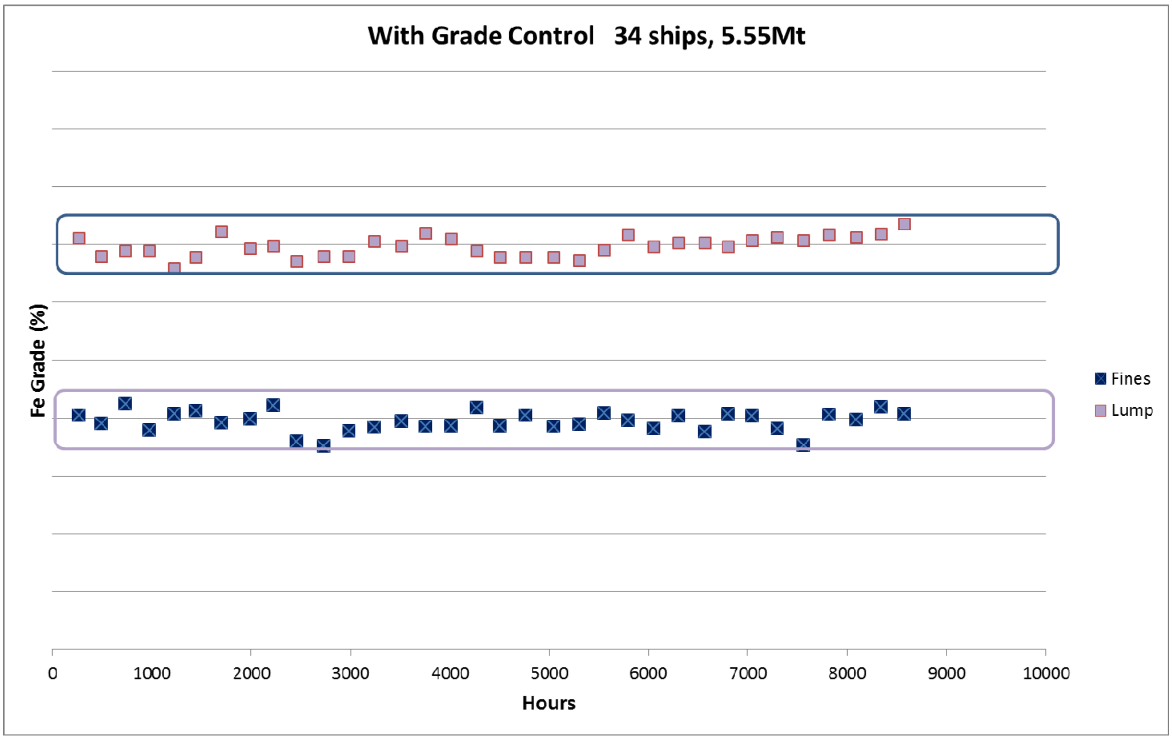

Figure 6 - One year of ore exports, with grade control

6. DISCUSSION AND CONCLUSIONS

The use of a DEM in conjunction with built-in optimization control showed that it is possible to operate an iron ore mine in such a way that tight grade control is possible, using the same mine equipment and the same mine plan. This result is of potentially enormous economic benefit for the iron ore mining business in Australia, especially when commodity prices begin to soften.

In addition, such a detailed, functional model allows for the evaluation of the economic benefit of alternative equipment configurations, for example more trains or larger conveyors.

Moreover, it allows us to answer strategic questions surrounding capacity and grade with a forward view of one year or more. Such a forward view makes it possible to plan a year out with some degree of confidence.

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