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Optimizing concentrate allocation to Anglo Platinum smelters

G.A. GEORGALLI and D.K. ANDERSON
Anglo Platinum

Anglo Platinum has three smelters and approximately twenty sources of concentrate, spread out over a very large area. Much of the concentrate is transported to the smelters by road and optimizing this distribution to minimize transport costs, while still maintaining the correct blend for the furnaces, is a combinatorial optimization problem. This paper describes a model which uses the Monte Carlo method and the simulated annealing minimization algorithm to determine the optimum distribution of concentrate to the three smelters. The model uses the transport cost as the main objective function, with penalties levied when certain blend parameters fall outside of the desired range. When applied retrospectively to the January to December 2009 concentrate distribution, the model was found to result in a 22% transport cost saving.

Keywords: Optimization, Monte Carlo, simulated annealing, distribution.

Introduction

Anglo Platinum is the largest platinum producer in the world, accounting for approximately 40% (Anglo Platinum Limited, 2009) of the world's annual platinum production. Including material from joint ventures (JVs), Anglo Platinum smelts material from approximately twenty concentrators in its three smelters. The concentrates are sourced from three different orebodies, Merensky, UG2 and Platreef, which have different mineralogies. The operations cover an extremely large area as can be seen in Figure 1.

Prior to the large expansion undertaken by Anglo Platinum starting in the late 90s, which included the construction of Polokwane smelter in order to process the material produced from the new Eastern Limb concentrate sources, the majority of Anglo Platinum's concentrate was piped in to either the Waterval or Mortimer smelter from adjoining concentrators. Most of the concentrate treated was also sourced from the Merensky Reef with the smaller fraction being from the UG2 Reef with its associated high chromium content. With the decrease of Merensky

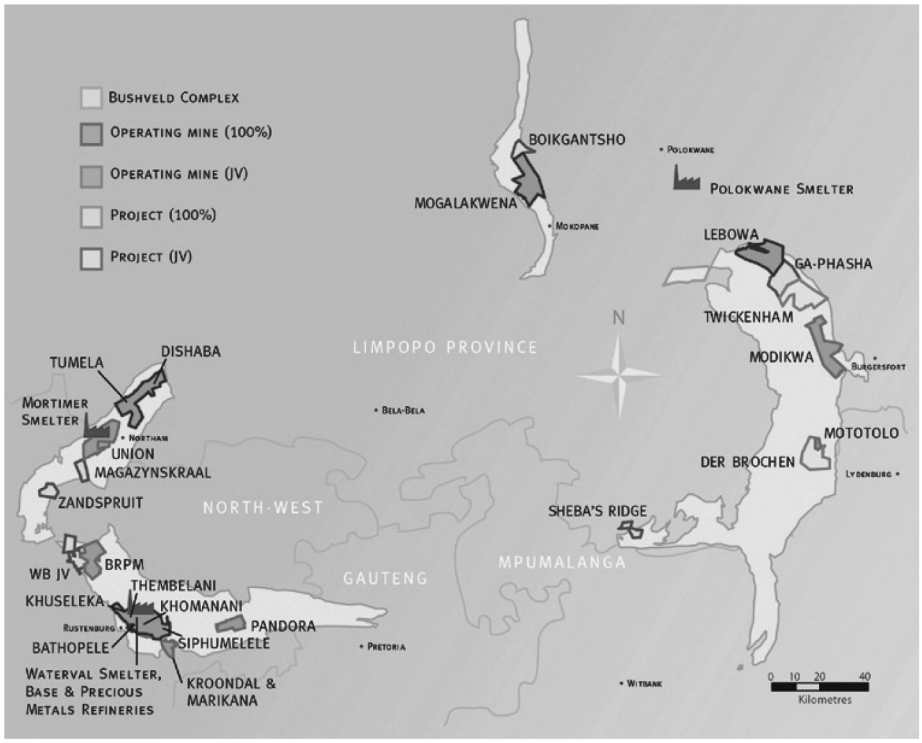

Figure 1. Anglo Platinum operational map

concentrate, the increase in UG2 concentrate and the introduction of Platreef material, blending has become an important issue and concentrates can no longer simply be transported to the nearest smelter.

The most important variables to control through blending are the chromium content and the matte fall. Chromium has been the largest issue in PGM smelting in South Africa in the last decade and has resulted in an increase in the operating temperatures of the smelting furnaces and shortened furnace life, along with other issues such as increased slag viscosity, poor matte-slag separation, and decreased available furnace volume (Barnes and Newall, 2006; Coetzee, 2006; Nell, 2004; Nelson *et al*., 2005).

High intensity smelting was introduced to handle the high chromium concentrates, but has proved only partially successful in dealing with this problem.

With regards to matte fall, too low a matte fall will result in matte losses to the slag through entrainment due to minimal coalescence of matte droplets in the slag layer resulting in poor matte settling. This is particularly true of lower-intensity, low power smelting operations. Too high a matte fall can also be dangerous when running a furnace with water-cooled copper coolers if the matte level in the furnace is allowed to rise faster than it can be tapped, resulting in a matte hit on a copper cooler which can cause a catastrophic explosion.

The three main types of concentrate treated by Anglo Platinum can be characterized as follows;

- Merensky: high matte fall, low chromium
- UG2: low matte fall, high chromium
- Platreef: very high matte fall, very low chromium.

Ensuring that the concentrate is distributed in the most cost-effective manner while still maintaining the correct blend required for the furnaces is a combinatorial optimization problem and cannot be solved analytically. Thus a numerical optimization tool was required which needed to meet the following criteria;

- It must be user friendly so that it can be used with minimum effort by someone other than the person who created it.
- It must be flexible enough to be able to handle changes, i.e. extra concentrate sources.
- The input information must be easily accessible and not overly complicated as this would discourage the use of the tool or result in errors due to bad assumptions.

Keeping these criteria in mind a program was created which solves the concentrate distribution by minimizing the transport costs in a Monte Carlo fashion using the simulated annealing minimization algorithm. The blending parameters described above are taken into account in the model by levying penalties to the objective function for any excursions outside of the desired range. The model, which will be fully described in the subsequent sections, was evaluated by comparing its optimum concentrate distribution to the actual distribution for the period January to December 2009.

Objective function

As mentioned in the introduction, the aim of this work is to minimize the transport costs related to concentrate distribution while ensuring that the blend of concentrate allocated to each smelter falls within certain parameters. Thus, in order for the model to meet these criteria these goals need to be reflected in the objective function which will be minimized in a Monte Carlo fashion using the simulated annealing algorithm.

Three variables (transport cost, chromium concentration and matte fall) need to be taken into account when constructing the objective function. This can be done by constructing three objective functions, one for each variable, but this will result in a multiple-objective combinatorial optimization problem which can become extremely complicated to solve (Czyzak and Jaszkiewicz, 1998). Thus, the approach adopted in this work was to minimize the transport costs while adding penalties for any excursions outside of the desired blend compositions.

The objective function O is calculated as follows:

$$O = TC + (\alpha \cdot P_{Cr} + \beta \cdot P_{MF}) \cdot TC \quad [1]$$

where TC is the total transport cost, P_{Cr} and P_{MF} are the chromium and matte fall penalties respectively, α is the chromium penalty coefficient and β is the matte fall penalty coefficient. From this equation it can be seen that the penalties are levied as a fraction of the transport costs and the magnitude of each penalty is determined by the coefficients α and β, which can be adjusted by the user until they are satisfied with the outcome.

The transport cost is calculated using Equation [2].

$$TC = \sum_{i=1}^{n}\sum_{j=1}^{3} C_{ij} \cdot M_{ij} \quad [2]$$

where i and j are the concentrate and smelter indices respectively, n is the number of concentrates, C_{ij} is the transport cost of concentrate i to smelter j and M_{ij} is the mass of concentrate i going to smelter j.

$$P_{Cr} = \begin{cases} \sum_{j=1}^{3} \left(Cr_j - Cr_{\text{limit } j}\right)^2 & \text{for } Cr_j > Cr_{\text{limit } j} \\ 0 & \text{for } Cr_j \leq Cr_{\text{limit } j} \end{cases} \quad [3]$$

$$P_{MF} = \begin{cases} \sum_{j=1}^{3} \left(MF_j - MF_{\text{limit } j}\right)^2 & \text{for } MF_j < MF_{\text{limit } j} \\ 0 & \text{for } MF_j \geq MF_{\text{limit } j} \end{cases} \quad [4]$$

Simulated annealing

The method of simulated annealing (Kirkpatrick, Gelatt and Vecchi, 1983) is a technique which is suitable for optimization problems of very large scale. The method is based on an analogy with thermodynamics, specifically the way the liquids freeze or crystallize, or metals cool and anneal. It is based on the Boltzmann probability distribution (Press *et al.*, 1988). The equation, when applied to an optimisation problem, is expressed as follows:

$$P = \exp\left[\frac{-(O_2 - O_1)}{k \cdot T}\right] \quad [5]$$

where O represents the value obtained from the objective function, k is the Boltzmann constant and T is the temperature. From Equation [5] we can see that if $O_2 < O_1$ (i.e. the change made has improved the performance of the objective function) the probability is greater than unity. In these cases the change is assigned a probability of 1, and so the solution is always accepted. If $O_2 > O_1$ then the value of P is between 0 and 1. This value is compared to a randomly generated value between 0 and 1. If the randomly generated value is less than the calculated probability then the solution is accepted, if it is greater then it is not accepted. In

summary, we can see that if a solution is better, then it is always selected. If it is worse, it is sometimes selected.

As the algorithm progresses the 'temperature' is decreased, this results in the algorithm selecting less and less worse configurations. The value of the Boltzmann constant is selected is such a way so that at the starting 'temperature' approximately 50% of the changes are selected.

This method of operation allows the simulated annealing algorithm to escape from local minima and the algorithm is therefore very good at finding a global minimum. The algorithm has been used successfully in various applications including job scheduling, structural optimization, particle packing and circuit design (Suresh and Mohanasundaram, 2006; Kolahan, Abolbashari and Mohitzadeh, 2007; Georgalli and Reuter, 2008; Lin, Yi and Chang, 2002; Tong and lin Wu, 1995).

Solution algorithm

The solution algorithm for the minimization procedure followed is shown in Figure 2. The algorithm begins by reading the inputs from the user. The inputs required are;

- Mass of concentrate required by each smelter
- Matte fall and chromium limits for each smelter
- Mass of each concentrate produced
- Chromium concentration and predicted matte fall of each concentrate
- The possible distribution for each concentrate, i.e. which smelter each concentrate can be distributed to. Some concentrates are piped in to specific smelters and as such these cannot be routed to any other smelters
- Transport costs for each concentrate to each smelter
- The chromium and matte fall penalty coefficients.

Once the inputs are fed into the program, it will randomly distribute the concentrates to the three smelters, ensuring that each smelter receives it quota and that each concentrate is distributed only to a smelter which can receive it. The Monte Carlo distribution will then begin. This is done by randomly selecting two smelters, and from each selected smelter one concentrate is randomly selected. Both of the selected concentrates must be allowed to be distributed to both smelters; if this is not the case the selection is repeated. One ton of the selected concentrates are then exchanged between the smelters. Once this has been done the objective function is recalculated and compared to the value of the objective function prior to the exchange. At this point the simulated annealing algorithm is applied to assess whether the exchange is accepted or not.

This procedure is then repeated until there have been 30 000 exchanges at which stage the 'temperature' used in the simulated annealing algorithm is decreased proportionally by multiplying the current temperature by 0.95. This entire procedure is then repeated until the 'temperature' drops below the minimum limit, at which stage the program stops.

The following parameters were used;

- Starting temperature: 300
- End temperature: 1
- Boltzmann constant: 1.

While the selection of the starting temperature is arbitrary, the value of the Boltzmann constant is selected so that at the starting temperature roughly 50% of the solutions are accepted. The end temperature is selected in a similar fashion to the Boltzmann constant, and is set to a value which results in roughly 0.01% of the solutions being accepted, at which stage the problem is deemed to be solved.

Results and discussion

In order to test the performance of the model, the concentrate distribution for January 2009 to December 2009 was solved for retrospectively using the model, and the transport costs compared to the actual costs for that period. For each month it was ensured that the total blend

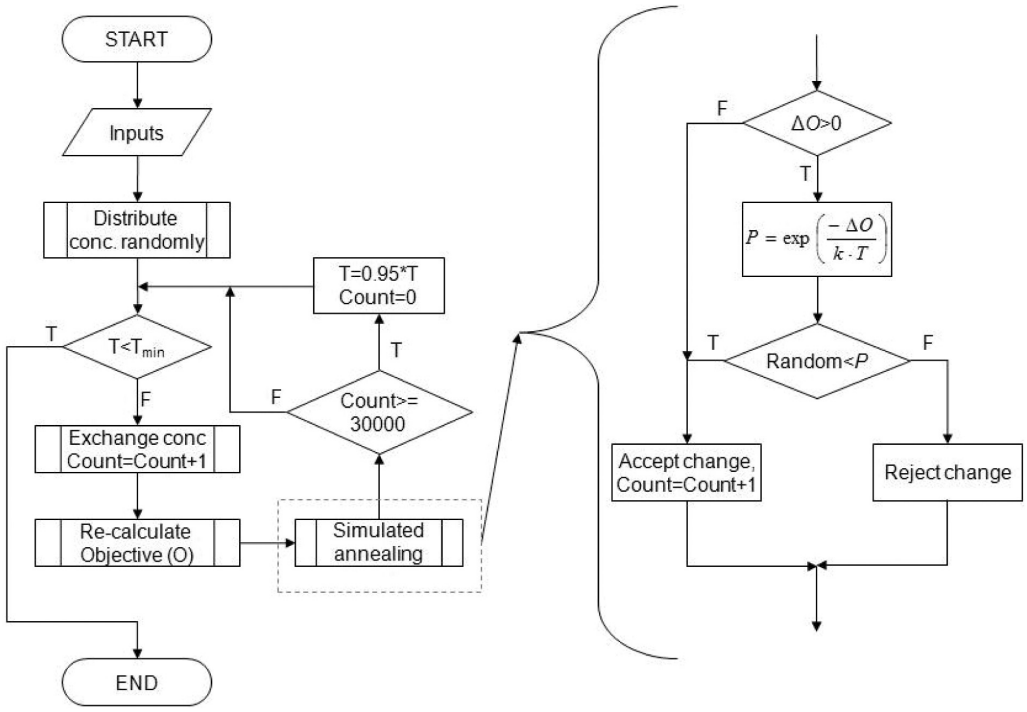

Figure 2. Flowchart of the solution algorithm. The 'simulated annealings block surrounded by the dashed rectangle is shown in more detail on the right-hand side

Table I
Performance of the model

Date	Transport cost saving (%)
Jan-09	14.2
Feb-09	20.0
Mar-09	31.0
Apr-09	37.4
May-09	23.5
Jun-09	35.0
Jul-09	29.6
Aug-09	21.6
Sep-09	21.8
Oct-09	18.5
Nov-09	-7.9
Dec-09	2.5
	22.0

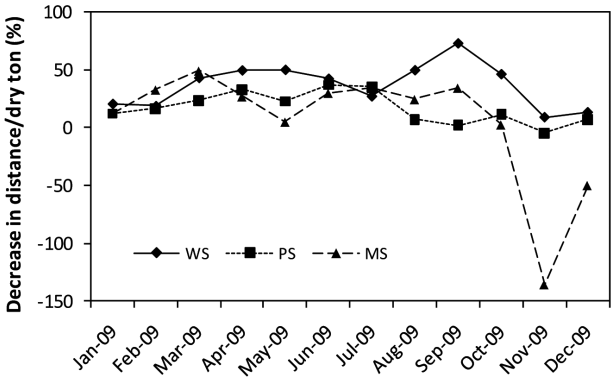

Figure 3. Model predicted decrease in transport distance per ton of dry concentrate for each smelter

of material transported to each smelter fell within the desired range for chromium content and predicted matte fall. Each smelter was also allocated the same mass of concentrate that it had received in the respective month.

The results are shown in Table I and it is clear that the model has the potential to drastically reduce the transport costs, with an overall cost saving of 22% for the period assessed. The transport costs for eleven of the twelve months in the year were less when applying the model, with savings ranging from 2.5 to 37.5 per cent per month. The one month where the model predicted cost was higher than the actual cost (November) was due to a reduction in matte fall of some of the concentrates which meant that the model had to sacrifice performance in order to meet the blend requirements.

In Figure 3 the percentage decrease in transport distance per ton of dry concentrate is shown for each smelter. It is clear that the model reduces the distance travelled per ton of concentrate for each of the smelters for every month except for November, where an increase is seen for both Polokwane and Mortimer smelters, and December where there is also a slight increase for Mortimer Smelter.

Not only did the model predict a significant transport cost saving, but the blends received at each smelter were also better controlled. In Figure 4 the average chromium content of the concentrate blend delivered to each smelter is shown for the actual and the model predicted distribution. While the absolute values of the limits cannot be shown due to confidentiality, it is not dissimilar to published limits from other PGM smelting operations (Coetzee, 2006). Also a comparison can be made based on the fact that the scale of the axes for the two charts in Figure 4 are the same and the Mortimer smelter chromium content shown in Figure 4(b) is sitting on the chromium limit. From Figure 4(a) it can be seen that the chromium content of the actual blend delivered to Mortimer smelter was almost always higher than the recommended limit. Polokwane smelter also had two months where the chromium content of the actual blend was in excess of the limit. In Figure 4(b) it can be seen that for all the smelters, the chromium content in the model blend was always at or below the limit, with Mortimer smelter still displaying the highest chromium content, followed by Waterval and Polokwane respectively.

When looking at the matte fall of the actual concentrate blends delivered to the smelters (Figure 5(a)), both Mortimer and Polokwane smelters had some months where the predicted matte fall based on the concentrate chemistry was substantially below the recommended limit, which is indicated by the Waterval smelter line in Figure 5(b), which sits on the limit. This was once again rectified when using the model to allocate the concentrate.

It is clear that the model performs well when applying it retrospectively; however, the true test will be in using it to determine the concentrate distribution prospectively. This has not been possible thus far, due to problems with the contracted transport company which has resulted in numerous companies being used to transport concentrate to the smelters. This has resulted in a scenario where optimization is overshadowed by necessity. What is clear is that the actual savings that will be attained when using the model in the real world will definitely be less than the 22% achieved when applying the model retrospectively. A few

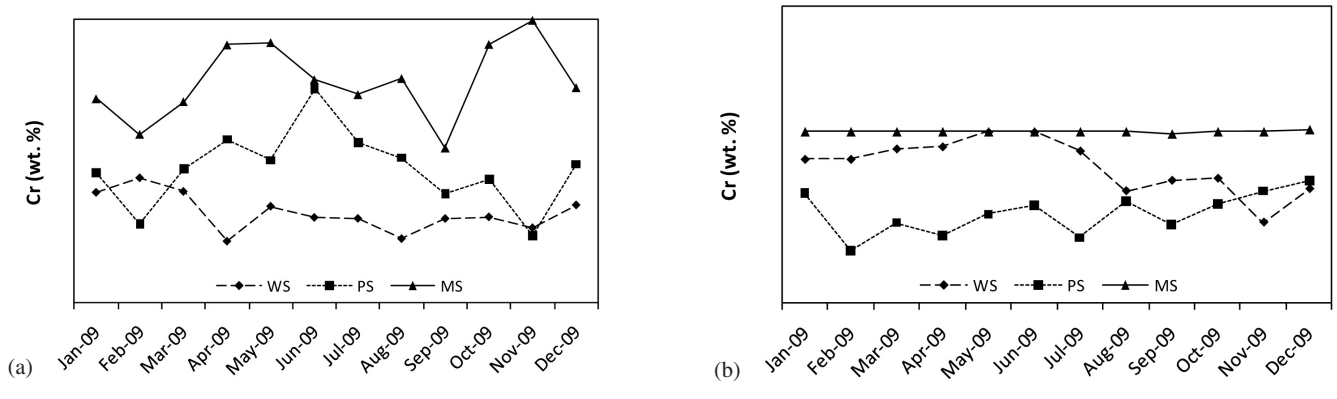

Figure 4. Comparison of average chromium content of concentrate delivered to each smelter for (a) actual and (b) model

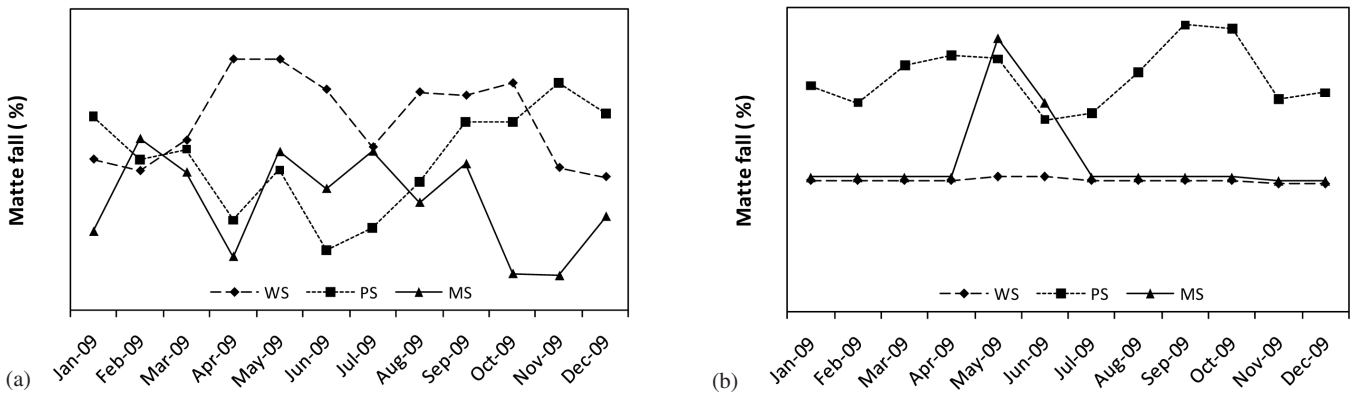

Figure 5. Comparison of average predicted matte fall of concentrate delivered to each smelter for (a) actual and (b) model

of the problems that would decrease the potential savings that can be made using the model are listed below.

- Inaccurate production forecasts: to apply the model prospectively one must rely on monthly forecasts of smelter requirements, concentrator outputs and concentrate compositions. Deviation from these forecasts will definitely occur and can result in concentrates being rerouted (at greater cost) in order to maintain the blend, avoid powering down the furnaces or generating stockpiles at individual smelters or concentrators.
- Unplanned furnace shutdowns: when this occurs the savings made by the transport optimization will be overshadowed by the cost incurred by building a stockpile at the affected site, especially if the material can be smelted at another.
- Transport problems: any disruption in transport caused by broken down vehicles, security issues or safety issues can result in a decrease in transport capacity. When this occurs optimization becomes overshadowed by necessity resulting in less efficient transport.

Conclusions

Based on the findings when the model was applied retrospectively to the period January to December 2009 the following conclusions can be drawn;

- The simulated annealing algorithm is very well suited to this type of optimization problem.
- The model has the potential to decrease the concentrate transport costs substantially, although achieving the 22% saving will be unrealistic when applying the model prospectively.
- The model was able to meet the blend requirements for each smelter while still reducing the transport costs for every month except one of the twelve months used in the retrospective assessment.

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Nomenclature

Arabic symbols

C_{ij} Transport cost of concentrate i to smelter j (ZAR/ton)
i Concentrate index (-)
j Smelter index (-)
k Boltzmann constant (-)
M_{ij} Mass of concentrate i going to smelter j (ton)
n Number of concentrates (-)
O Objective function
P Boltzmann probability (-)
P_{Cr} Chromium penalty function (ZAR)
P_{MF} Matte fall penalty function (ZAR)
T Simulated annealing temperature (-)
TC Total transport costs (ZAR)

Greek symbols

α Chromium penalty coefficient (-)
β Matte fall penalty coefficient (-)

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Gregory Andrew Georgalli

Metallurgist, Anglo American Platinum

2002-2007: Researcher, Technical University of Delft, the Netherlands
2007-2008: Researcher, Stellenbosch University
2008-present: Metallurgist, Smelting Operations, Anglo American Platinum