Virtual Smelter Modelling for Metal Flow Management

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Abstract

The production of aluminium is an extremely expensive process because of the vast amounts of energy it uses. It is also a continuous, large scale process, thus it is very hard to experiment with. Metal flow management provides an opportunity to increase revenue without altering the base processes which produce the metal. Metal flow management means utilising the smelter's resources as efficiently as possible to produce the most profitable types of aluminium possible.

Metal flow through a smelter is extremely complex with many interactions which are difficult to model analytically. However this can be overcome by utilising simulation. This enables us to experiment with a smelter for very little cost. It also allows us to analyse the complex interactions of different parts of the metal flow process so that we understand the process better, thus we are be able to produce better optimisations for aluminium smelters. In this paper we describe how we developed what we believe is the first metal flow simulation for an aluminium smelter which utilises optimisation at several stages of the process and the results we obtained.

Key Words: Aluminium, alumina, metal, crucible, smelter, cell, furnace, cast house, batching, scheduling, VSmelter, LMRC (Light Metals Research Centre), metal flow, metal flow management.

1 Introduction

To model the flow of aluminium through an aluminium smelter it is important that we understand what aluminium is and how it is produced.

Aluminium is light metal produced in a smelter from aluminium oxide, commonly referred to as alumina. Bauxite is the primary ore for alumina; this means that alumina is obtained from the mining of bauxite ore. Bauxite comprises of many different minerals such as gibbsite ($Al(OF)_3$), along with some impurities. Bauxite is purified by the Bayer process and alumina is produced.

In an aluminium smelter the metal is produced using the Hall-Héroult process, this is a process of electrolytic reduction of alumina into aluminium. The alumina is dissolved into molten cryolite (a rare mineral) where it undergoes electrolytic reduction to obtain pure aluminium. This process takes place in reduction cells constructed out of steel and refractory bricks. The process is extremely energy intensive; a direct current of 150,000 to 250,000 Amps, depending on the type of cell is passed between an anode and a cathode within a bath of hot cryolite (around 960 ˚C).

Aluminium smelting is a major industrial process. The reduction part of the process consists of multiple pot rooms which in turn consist of multiple cell lines. Each cell line contains anywhere from 50 to 150 cells. The cells are tapped once a day to remove the produced aluminium.

The tapped metal then undergoes firing in the furnace where its chemical composition is altered to increase its value for sale. The aluminium will then undergo casting to create products for sale on the global market. The primary products are ingots and billets of different quality aluminium. These are then used as raw material in the production of goods which utilise aluminium, such as nails, bikes, cars and even airplanes.

The nature of the world aluminium market is such that as the purity increases, the price obtained for the metal increases exponentially (Piehl, 2000). Adding additional elements to form an alloy can also have a huge impact on the price of the metal. This means in certain situations it is better to produce small quantities of expensive metal than to produce large quantities of inexpensive metal. A decision must be made about how much of each type of aluminium should be produced in order to maximise profit.

Metal flow is the passage of metal through an aluminium smelter from its raw form as alumina casted products such as ingots. Managing metal flow within the smelter is critical because it will greatly affect its price in cast form. Optimal metal flow management is a necessity for an aluminium smelter to function at its peak efficiency.

Simulation is needed to model metal flow. This is because currently the only test to determine the effect of metal flow management decisions is to apply them to a smelter..

The different areas of metal flow management involve separate processes but the decisions that are made are intertwined and therefore have upstream and downstream effects on what and how the metal in the smelter is being produced.The simulation of a smelter will allow us to identify whether the optimisations are working in the real world and how they affect the smelter's overall efficiency.

There have been mathematical models developed of aluminium smelters previously (Duncan & Nicholls, 1993). These models have not been able to model the complex real world constraints. The only way to truly do this is through an aluminium smelter simulation.

Simulations and optimisations can also be used together for mutual improvement. As the simulation improves the feedback it allows the improvement of optimisations and vice versa.

2 Metal Flow

This section describes metal flow through an aluminium smelter. Before simulation or optimisation this flow has to be understood. This flow should be understood because if the flow isn't simulated improperly it will lead to invalid results. It is also necessary to understand metal flow so we know how to implement the optimisations within a smelter. To do this we have to understand how decisions are currently being made.

Metal flow though an aluminium smelter is a continuous process. Keeping the flow of metal through the smelter constant enables the production of high quality metal. This is because reduction within the cells is a carefully balanced process. Production can't be ramped up or slowed down without affecting the quality of the metal being produced. This is because it would affect the bath chemistry of the cell causing the process to become unbalanced. In addition if molten aluminium is left too long below its melting point it becomes solid thus ruining the vessel that contains it.

2.1 Feeding

This is the process of adding alumina into a cell at a rate which tries to maintain constant bath chemistry. The cells are being tapped at a rate of once per day. The quality of the alumina affects the purity of the aluminium being produced but other factors also affect aluminium quality; these include the current flowing into the cell (whether the current is constant) and the quality of the carbon in the anode. These factors are largely determined by the manner in which the cell has been operated during its life. The composition of the metal within a cell can also be affected by impurities such as iron, silicon and gallium. The same alumina is typically fed into every cell throughout a cell line so this will not influence the variation in purity between cells.

2.2 Cell Batching

The cells in a cell line are tapped once a day. Tapping is the process of extracting metal from a cell and loading it into a crucible . Smelter workers prefer to tap cells sequentially in batches (groups of 2 or 3 cells) to fill a crucible.

The choice of which cells are put into the same crucible affects the purity of the aluminium the crucible contains. If the cells are tapped sequentially the composition of the metal which fills the crucible has not been optimised and is effectively random. In this report the metal contained within the crucible is called a cell batch.

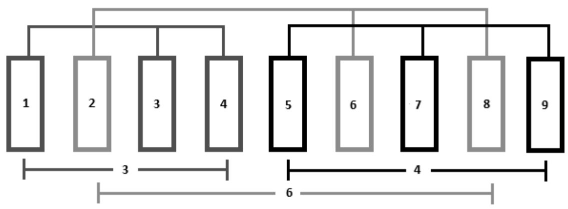

Figure 1, Cell Batch Spread

The spread of the cells in a batch is what defines the distance travelled when the workers are tapping.

2.3 Furnace Batching

Cell batches arrive at the furnace in crucibles, they are then completely emptied into the furnace. A furnace batch is the metal created when cell batches are mixed in the furnace. The process where the furnace is filled by these cell batches is called charging. The choice of cell batches within a furnace batch affects the purity and therefore the price which can be obtained for the metal produced by the furnace batch.

The furnace batch is then heated and alloying elements may be added to create the requisite metal type. The process of heating the metal within the furnace is called settling. The metal is then poured from the furnace into loads to be used in the cast house. Furnace batches are emptied from the furnace in lots called furnace pours. It is impossible to empty a furnace completely; a small amount of metal is left which will contaminate the next furnace batch.The small amount of metal left in a furnace after it is poured is called the heel.

2.4 Cast House

The cast house receives pours of metal from the furnace. From this the cast house produces products such as billets, ingots and cast rods. The products that a cast house can produce are determined by the machinery that it contains. The processes which take place within the cast house are casting, rolling, and extruding.

3 Literature Review

The first approach to the cell batching optimisation problem was described in Tuck (1997). The cell batching problem was applied to the New Zealand Aluminium Smelter (NZAS) at Tiwai point. Ryan (1998) states that the cell batching optimisation can be formulated naturally as a set partitioning problem (SPP). However Ryan (1998) does not take into account that this is part of a larger smelter scheduling problem which he states in his conclusion.

Ryan (1998) and Piehl (2000), who worked on a similar problem, both make the assumption that the tapping weight across a cell line is the same from every cell. In reality the planned tapping weight for every cell in a cell line is one of a set of maybe four or five choices depending on the cell's condition. For example the planned tapping weights could either be 0 kg, 1500 kg, 1800 kg, 2000 kg or 2200 kg. The composition of the metal in a cell batch could vary significantly from predictions if the tapping weights of each cell were assumed to be the same. The actual weight of the metal tapped from the cell is never exactly that planned, rather it is normally distributed around the plan. This can only be shown using a simulation or a stochastic solution.

Ryan (1998) and Piehl (2000) both use column generation to limit the spread of the potential tapped batches in the cell batching optimisation problem. Ryan (1998) has a spread limit of 6 cells which can be violated a small number of times. When this happens the spread is limited to 10 cells. This reduces the problem size from 20825 variables to 3000 variables, Ryan (1998). The cell batching optimisation used in the Virtual Smelter does not use this spread limiting constraint instead only using a priori variable generation.

Tuck (1997), Ryan (1998) and Piehl (2000) all use the same alloy codes to obtain the premiums for the metal produced by each cell and each cell batch. Pascal Lavoie of the LMRC (Light Metals Research Centre) has advised that these codes are similar enough to the present situation and thus can be used for valuing the metal produced (Lavoie, 2010).

As mentioned earlier research in developing a mathematical model for an aluminium smelter has occurred (Duncan & Nicholls, 1993) (Nicholls, 1997). The models developed had different levels of aggregation as do the optimisation models put forward in this report (Nicholls, 1997). These papers mostly investigated the level of linking between sub models to develop one core model. Nicholls (1995) shows the core integrated model to be a nonlinear bi-level problem. The simulation utilised within a virtual smelter will allow for an investigation into the value of the improvement arising from this.

4 Simulation

The simulation, the optimisations and the supervisory framework are all part of VSmelter, a program created to simulate an aluminium smelter. Python was used as a base language because the simulation package SimPy and optimisation package PuLP were both available for python so could be easily linked. SimPy is a package available for python which easily allows creation of a discrete event simulation. The simulation's purpose is to model metal flow through a smelter based on the metal composition at each point within the smelter.

4.1 Recovery Heuristics

Recovery heuristics are simple decisions initially put into the supervisory framework which enable the smelter to run without any optimisation. They will be employed if an optimisation fails within the simulation. This simulates reality where if an optimisation fails the smelter continues to function.

There are four areas of decision making within the simulation:

- Providing a list of cells to be tapped in their batches to the cell line
- Determining which furnace to send a crucible to
- Determining when to start the furnace settling and stop receiving crucible.
- Determining which cast house to provide with the pours from a furnace.

The recovery heuristics implemented initially to make sure the simulation ran:

- Tapping cell lines in sequential batches i.e. (1,2,3) , (4,5,6).
- The crucible will be sent to the first furnace found to be charging.
- Stop the furnace loading when it reaches a set mass.
- The furnace pour will be sent to the first cast house determined to be free.

5 Optimisation

It is possible to perform optimisations at key decision areas within the metal flow of a smelter. These key areas include cell batching, furnace batching, furnace scheduling, cast house scheduling, and the usage of scrap or recycled metal, metal storage and sales and marketing The metal flow model is extremely complex which means it is extremely hard to model as whole, but it is possible to model these decisions individually. The metal flow model as whole is nonlinear (Nicholls, 1995) and solving it would be far too time consuming. However aluminium smelters might not even be implementing local optimisations so these implementations should be modelled within VSmelter to prove their viability.

5.1 Cell Batching

The batching problem has been researched and applied to NZAS. For this reason it was the first optimisation applied to the VSmelter. Cell batching has been applied to a smelter and is still in use therefore the conclusion can be reached that it has been a profitable implementation. Thus we would expect that applying the cell batching SPP (Set Partitioning Problem) to VSmelter should increase the revenue generated.

Indices

i = Cells

j = Cell Batches

Parameters

a_{ij} = 1, if cell i is included in cell batch j
0, otherwise

r_j = Represents the revenue of cell batch j, which is the premium of the alloy in the possible batch multiplied by the mass

n = Total number of possible cell batches

c = The number of cells in the cell line

Decision variables

x_j = 1, if cell batch j is selected
0, otherwise

Model Cell Batching

$$\text{Maximise} \quad z = \sum_{j=1}^{n} r_j x_j$$

$$(1) \quad \sum_{j=1}^{c} a_{ij} x_j = 1 \quad for \quad i = 1, 2, \dots, n$$

$$(2) \quad \sum_{j=1}^{n} x_j \le \lceil c/3 \rceil$$

$$x_j \in \{0, 1\}$$

Explanation

The objective is to maximise the revenue. Constraint (1) limits one cell to one cell batch. Constraint (2) sets a maximum number of batches.

This is a pure set partitioning problem; however we limit the spread to a maximum number of cells within the batches by generating the variables a priori. The spread is limited to make tapping easier for the staff at a smelter. Because the spread is limited during a priori variable generation the spread is an implicit constraint. This means that a spread constraint is not added to the problems' formulation.

At this point the value of the simulation presents itself. The simulation can be used to analyse how changing the spread constraints affect the revenue of the smelter, the amount of distance travelled and the quantity of work done by the staff. Changing the maximum spread can be experimented with in the same way. The simulation could be used to determine whether the expense in time and staff of tapping extra batches is justified by the extra revenue produced.

5.2 Furnace Batching

This model defines a group of cell batches a priori then combines these into furnace batches to maximise revenue. The cell batches can be defined using any optimisation or even a simple heuristic. This will allow an analysis to be carried out to determine if cell batching before furnace batching provides additional revenue over and above using sequentially tapped groups. This optimisation will produce metal with a higher premium then creating furnace batches without any guidance.

The spread within a furnace batch is defined by the difference of the position of lowest and highest positioned batch, where the position of a batch is defined by the position of the lowest cell in that batch. This models a time constraint ensuring that furnace batches don't take too long to be collected, so that the furnaces run effectively with minimal wait times. The spread has a direct correlation to the work done when tapping the cell batches. If the spread is too large the workers on a line will have to travel the whole line to gather the taps, this takes extra time and is not efficient.

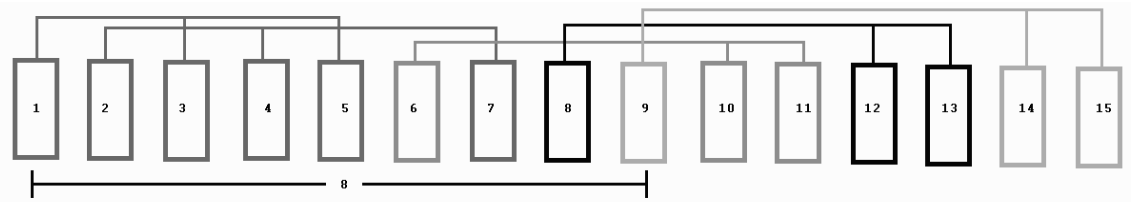

Figure 2, Furnace Batch Spread

As with cell batching the change in spread used in simulation can be used to analyse the extra time and work taken to collect the furnace batch. This allows experimentation, greater revenues may occur when a larger spread in furnace batching is used. As with in cell batching, variable generation a priori is used in this form of furnace batching to limit the spread of the furnace batches. This also has the effect of limiting the number of possible furnace batches and therefore significantly reduces the time required to generate these. This form of furnace batching was implemented.

Indices

j = Cell Batches
k = Furnace Batches

Parameters

b_{jk} = 1, if cell batch j is included in furnace batch k
0, otherwise
r_k = Represents the revenue of furnace batch k, which is the premium of the alloy in the possible batch multiplied by the mass
m = Total number of possible furnace batches
h = The number of cell batches
f = Maximum number of furnace batches allowed per day

Decision variables

y_k = 1, if furnace batch k is selected
0, otherwise

Model Furnace Batching

$$\text{Maximise } z = \sum_{k=1}^{m} r_k y_k$$

$$(3) \sum_{k=1}^{h} b_{jk} y_k = 1 \quad for \ j = 1,2,\dots,m$$

$$(4) \sum_{k=1}^{m} y_k \leq f$$

$$y_k \in \{0,1\}$$

Explanation

The objective is to maximise the revenue. Constraint (1) limits one cell batch to one furnace batch. Constraint (2) sets a maximum number of furnace batches.

6 Results

This section will discuss the results of all the VSmelter simulation. The simulations were run under various conditions. There are three metal flow management decision areas currently able to be optimised within the supervisory framework under VSmelter:

6.1 VSmelter

A typical smelter was modelled within the VSmelter simulation framework. This smelter has two cell lines of 80 cells, 20 crucibles, 2 crucible trucks, 2 furnaces and 2 cast houses.

The cell batching heuristics including the optimisation limits the spread of the cell batches to a maximum of 9 cells. The furnace batching heuristics including the optimisation limits the spread of the furnace batches to a maximum of 25 cells.

Each situation was simulated 10 times for 20 days with the first 5 days of the simulation removed as data points, so as to remove the initial transient effects of the simulation. 150 data points were collected for each situation simulated.

6.2 Batching

Figure 3 below shows the effect of both furnace and cell batching on the average metal premium against a base of a smelter run on recovery heurisitcs.

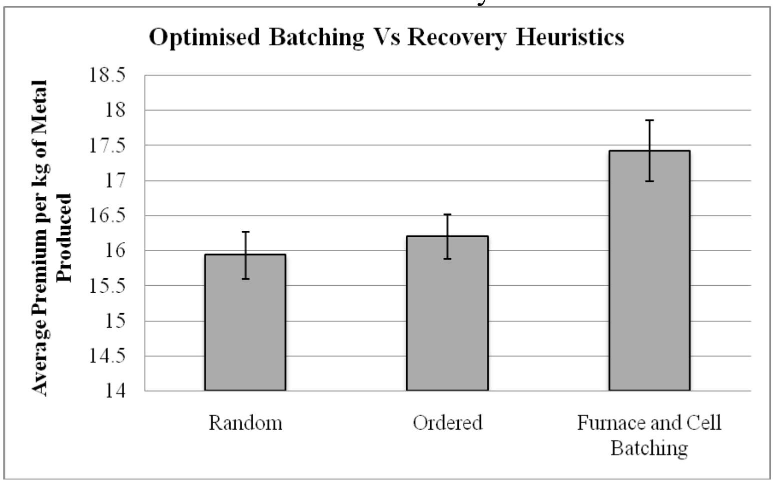

Figure 3, Effect of Furnace and Cell Batching

Utilising furnace and cell batching will yield a higher average premium than both the random and ordered situation The difference in the mean metal premium between the ordered and optimised situations is at least $0.71 per kg and a maximum of $1.71.

6.3 Furnace Scheduling.

Figure 4 below shows the effects of improved furnace scheduling heuristics on the average metal premium of the end product aluminium.

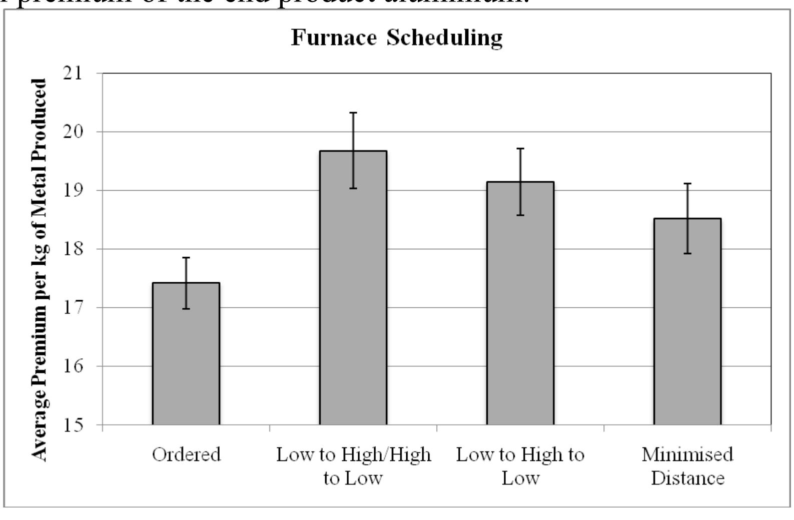

Figure 4, Effect of Furnace Scheduling

The graph and table above show that all the heuristics that aimed to improve the metal premium did. The best heuristic for ordering the furnace schedule appears to be Low to High/High to Low with an increase in the metal premium of at least $1.53 to a maximum of $2.99 per kg.

6.4 Value of the Model

Figure 5 below shows the effects of optimisation on the metal flow process and the difference in the optimisation models predictions versus what actually happened within the simulation.

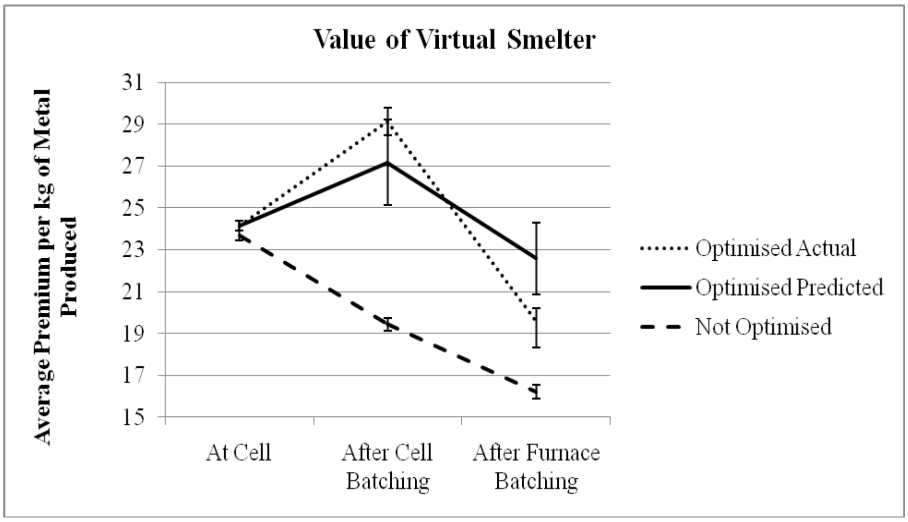

Figure 5, Metal Flow Value

The results show that a generic smelter should optimise its cell batching, furnace batching and schedule its furnaces so that they run from low to high purity and then high to low purity on alternate days. This changes the range for the mean daily production value from $3,094,650-$3,221,400 (under recovery heuristics) to $3,710,850-$3,962,400. This is a 20% increase in daily revenue. Over a year this could generate an additional $250 million of revenue.

The difference between the prodicted and actual lines show the value of the simulation as the optimisation models cannot be used to predict the value of the end product. This is because there is a significant difference the two values after the metal flow management decisions have been made.

7 Conclusions

The first simulation of metal flow through an entire aluminium smelter which incoroporated metal managmenent optimisations was created and run to analyse metal flow. Optimisations were then applied to this virtual smelter and analysed using an independent supervisory framework.

VSmelter has met its first goal. It is able to model a simple smelter and apply metal flow optimisation decisions as the simulation runs. The optimisations within VSmelter are simple but there is no reason that they can't become more complicated as research is continued into each area. VSmelter currently contains a simple simulation which is not totally realistic but is complicated enough for the analysis performed.

The simulation framework within VSmelter is able to simulate the main parts of aluminium smelter. It is also modular so the simulation's physical constraints can be changed. This is the first step to quickly being able develop simulation to simulate any smelter quickly.

Within the simple smelter modelled within VSmelter the most effective decisions heuristics were; optimised cell batching, optimised furnace batching, with a furnace schedule which ordered the batches from lowest purity to highest purity of aluminium, then from lowest to highest on alternate days.

The simple simulation within VSmelter has been used to evaluate the effect of metal flow decisions on the average metal premium, but there is no reason that the simulation could not be used to make a smelter in other areas such as energy expenditure from heat loss and input, or just utilising time and machinery more efficiently to increase production.

8 Future Work

VSmelter has immense potential to be extremely beneficial to the LMRC and the aluminium industry. As it becomes more complicated it also becomes far more useful allowing us to see in detail what effects metal flow management decisions have. The simulation could be expanded and applied to a real smelter to analyse the affects of metal flow management decisions and validate both the simulation and the optimisation models.

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