Calculating the Value of Iron Ores in Ironmaking and Steelmaking

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ABSTRACT
At present we are witnessing large investments in the iron ore industry, fuelled by demand from Asia. At the same time, there is a changing landscape in pricing of iron ores, with the recent demise of the benchmark system and the evolution of market based index pricing systems. From a customer perspective, it is the behaviour of iron ores in downstream processing that gives them their value; their impact on the sintering or pelletising process and subsequently blast furnace ironmaking. It is therefore important to consider this value when developing projects, making mine planning/cut-off grade decisions, and in setting quality price differentials.

This paper describes the use of the Marx value in use (VIU) model to quantify the downstream value of iron ores. The Marx model consists of heat and mass balance modules for sintering, pelletising and a rigorous two-stage heat and mass balance model of blast furnace ironmaking. Mass balance and cost models are applied for steelmaking, casting and rolling. The use of a heat and mass balance allows accurate comparison of the impact of raw material properties on blast furnace operation. The impact of minor elements, such as alumina, silica and phosphorus, and metallurgical properties on ironmaking is described, and examples given for the relative value of haematite, Marra Mamba, and channel iron deposit (CID) ores.

INTRODUCTION
With high demand for raw materials from China we are witnessing continuing large investments in iron ore capacity from the major iron ore producers, for example Rio Tinto has announced expansion to 333 Mt/a (Albanese et al, 2010), BHP Billiton to 240 Mt/a (Henry, 2010), Fortescue Metals Group (FMG) to 155 Mt/a (FMG Annual General Meeting, 2010) and many junior miners are now developing and operating their deposits.

An outcome of the high demand has been the emergence of a vibrant spot market for iron ore. With spot prices exceeding the benchmark price by significant margins, the annual benchmark pricing system has now been superseded by market based index pricing, either on a quarterly average or even a monthly average basis. All of the index providers use an index ore as a reference, eg 62 per cent Fe Platts daily index. Penalties/premiums for an actual iron ore can be calculated taking into account differences in iron content or other elements in the chemical assay. In long-term contracts the buyer would seek to have penalty clauses in the contract for undesirable analytes such as silica, alumina, phosphorus and iron levels that are below the contract minimum. These penalties are designed more to minimise variability than to compensate for long-term additional ironmaking processing costs and provide the customer with a contract termination clause if the guarantee levels are breached, eg three strikes and you are out.

This information can then be used in decisions during exploration, expansion projects, mine planning and operations. However, it is prudent to always consider the behaviour of ores in downstream customer processes as this, in conjunction with the overall balance of supply and demand, will determine the long-term value of the ore. The physical and metallurgical characteristics of ores then become important in addition to the chemical assay. One essential tool for comparing ores is the technical value in use (VIU) of an ore in customer processes, taking into account the impact of the whole chemical assay of the ore and any relevant physical and metallurgical properties. This can be done using a VIU model, based on a heat and mass balance model of the customer processes in question. The Marx VIU model, described in this paper, is an example of this approach.

BEHAVIOUR OF IRON ORES IN CUSTOMER PROCESSES

Ores aint ores
There is a wide range of physical, metallurgical and chemical properties which determine the process behaviour of iron ores in customer processes. Variations in hardness and mineralogy for BIF derived ores determine the amount and quality of lump ore produced from a deposit (Kneeshaw et al, 2003). Lump ores can be direct charged to the blast furnace and typically demand a premium price because of this. Fines cannot be charged to a blast furnace without first being agglomerated in a sinter strand. For magnetite and itabirite deposits, the ore is typically fine grained and intermixed with gangue, and grinding and beneficiation are therefore required to produce a suitable product. The very fine size distribution

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of concentrates is detrimental to the permeability of the sinter bed and impacts on sinter plant productivity and quality. Instead, these ores are typically pelletised.

**Sintering of fine iron ores**

Sinter is the predominant blast furnace feed material in Asia, due to the availability of sinter fines and the ability to control the sinter chemical, physical and metallurgical properties. Figure 1 is a schematic diagram of the sinter process. The main steps in the sintering process are:

- **Blending** – a range of iron ore fines from different suppliers are blended with steelworks recycle materials.
- **Mixing** – a reductant such as coke breeze or anthracite, and fluxes such as limestone, dolomite, or serpentine are added to the blended ore and the combined materials are mixed. Typically ironmakers add all of the fluxes required for blast furnace operation at the sinter plant, with sinter ratios (CaO/SiO₂) of around 1.9 being typical. Careful control is usually exercised over the total SiO₂ content of the mix, and other deleterious elements such as Al₂O₃ and TiO₂.
- **Granulation** – the mixture of ores, reductant and fluxes is granulated with water in one or more granulation drums. This is done to narrow the size distribution of the mix and thereby improve the permeability of the material on the sinter strand to air flow. Ore properties that are critical to the granulation process are the size distribution, porosity, shape and mineralogy (Loo, Penny and Witchard, 1996).
- **Sintering** – the granulated mix is ignited and fans pull the air flow. Ore properties that are critical to the granulation process are the size distribution, porosity, shape and mineralogy (Loo, Penny and Witchard, 1996).
- **Cooling and screening** – the sintered material is cooled and screening of the sinter into suitable sizes to charge to the blast furnace.

It is normal to carry out laboratory scale investigations into the behaviour of iron ore fines in a sinter blend using sinter pot tests at suitable metallurgical testing laboratories. This allows the prediction of important sinter plant process parameters such as productivity, fuel rate, and yield, as well as measurement of sinter metallurgical properties. As there are many possible blend and operating variables, these sinter pot programs require careful definition and interpretation of results.

**Pelletising of iron ores concentrates**

Magnetite or haematite concentrates typically have an ultrafine size distribution, for example 80 per cent passing 45 μm. This material cannot be used directly in the blast furnace and is also problematic in sinter production, so it is normally used in the manufacture of pellets. The three stages of pellet production are raw material preparation, green ball formation and induration:

1. The iron ore must have a suitable size distribution or specific surface area (m²/g or ‘Blaine index’) to form good pellets. In some cases the ore will already be at a suitable size after beneficiation. If not, further grinding is required.
2. The ore is then mixed with water and additives and formed into green balls using a drum or disc pelletiser. The objective of this stage is to form balls of a uniform size with sufficient strength to survive handling to the induration stage. Bentonite is typically added as a binder to improve the strength of the green pellets. Other additives are used to improve the metallurgical properties of the pellets, eg limestone and dolomite.
3. Finally the pellets are dried and fired at induration temperature to form strong bonds between the concentrate grains due to recrystallisation and melting of gangue phases. Magnetite concentrates undergo oxidation to haematite during firing, and form bonds at lower temperatures than do haematite concentrates, substantially decreasing the fuel requirements of the firing process. The pellets are then carefully cooled.

Pellet induration is accomplished using a number of technologies, such as shaft furnace (eg Grange Resources at Savage River), straight grate (eg Corus Ijmuiden) and grate-klin (eg OneSteel Whyalla).

Pellets are manufactured to strict quality requirements, such as physical strength (cold crushing strength and tumble index), reducibility, and swelling index. Swelling of pellets during blast furnace ironmaking can occur due to a volume...
change on reduction from haematite to magnetite, particularly for pellets with a CaO/SiO₂ ratio of between 0.1 and 0.7 (Meyer, 1980). For this reason additives such as lime or dolomite are often added to the iron ore prior to pelleting. Pellets with a low basicity are known as ‘acid’ pellets, whereas pellets with added lime or dolomite are known as ‘fluxed’ pellets.

Pellets are a high value blast furnace burden due to their uniform size, high in-furnace permeability, high strength, high reducibility, low reduction degradation index and good softening and melting properties (Meyer, 1980; Zhang et al, 2009).

Raw material requirements and pellet metallurgical qualities are best determined by laboratory balling tests and pilot scale ‘pot grate’ testing at an appropriate metallurgical testing laboratory.

**Blast furnace ironmaking**

The blast furnace is a continuous counter-current shaft reactor. Solid ferrous burden, including sinter, lump iron ores and pellets are charged at the top of the furnace in alternate layers with metallurgical coke. A hot air ‘blast’ is introduced at the bottom, typically with some oxygen enrichment and pulverised coal or other fuels. This blast generates carbon monoxide reducing gas and supplies heat for chemical reactions and melting. Liquid products are tapped from the bottom of the furnace and gaseous products and dust exit at the top.

The role of the blast furnace is to reduce iron oxides to molten metallic iron (hot metal), and to remove impurities (often called gangue elements) into a separate slag phase. All of the Al₂O₃, CaO, MgO contained in the iron ore report to the blast furnace slag. The majority of the SiO₂ also reports to the slag, with a small proportion being reduced to Si and dissolving in the hot metal. Elements such as sulfur and manganese are partitioned between the hot metal and slag, and essentially all of the phosphorus reports to the hot metal.

As a counter-current shaft reactor, the permeability of the ferrous burden and coke layers is critical to efficient and stable operation. The productivity of the blast furnace is largely limited by its permeability and the amount of hot blast that can be introduced. The physical strength of the sinter, lump and pellets is therefore important, along with their ability to withstand thermal shock and stresses due to reduction reactions. These properties are measured in the laboratory using a number of standard tests:

- **Tumble and shatter tests.** These tests measure the physical strength of the ferrous materials and indicate the likely size degradation during transport and handling.
- **Decrepitation index (DI).** This test measures the resistance of a sample to thermal shock.
- **Reduction degradation index (RDI).** This test measures the resistance of a sample to size degradation due to a combination of heating and reaction with reducing gas.

Poor properties in these tests would lead to generation of fine material which would decrease the permeability of the blast furnace. For a more detailed description of these tests, refer to Angove (1997). A second constraint on blast furnace permeability is the behaviour of the ferrous material during softening and melting’ in the cohesive zone of the blast furnace. There are no internationally agreed standard tests to measure this property.

The formation of a suitable slag is also a critical component of successful blast furnace operation. As described above, most of the gangue components of the ferrous burden and ash from coke and coal end up in the blast furnace slag. This slag by itself would not have suitable properties, so the ironmaker adds an appropriate quantity of flux to meet the following requirements; the slag should be liquid at operating temperatures, have a low viscosity so that it will flow readily, have a high capacity to absorb sulfur, and a suitable composition to control the partition of silicon between the slag and the hot metal. Normal practice is to target a CaO:SiO₂ ratio in the slag of 1.0 - 1.2, necessitating the addition of significant quantities of limestone to the sinter. It is also normal practice to limit the Al₂O₃ content of the slag to below around 15 per cent to control the slag viscosity. The content of SiO₂ and Al₂O₃ in iron ores are therefore of great importance to the operation of the blast furnace.

The reduction reactions and melting of metal and slag require significant amounts of energy, which is supplied by the hot blast and by combustion of reductants (coke and other fuels, eg pulverised coal injection). Over recent times there has been a trend to decrease the usage of metallurgical coke and to use greater amounts of pulverised coal injection for cost reasons. In addition, the total reduction addition rate is now under significant pressure with the relatively high price of metallurgical coal and the introduction of a price for carbon in many countries (Ueda et al, 2010). The reducibility of the ferrous burden is therefore an important consideration, and can be measured in the laboratory using the standard relative reducibility test (RI, refer to Angove, 1997). The reducibility of pellets and sinter is maximised during their manufacture. The reducibility may impact the relative value of lump ores.

Sulfur and phosphorus have negative impacts on steel properties and must be removed in a hot metal pre-treatment stage prior to steelmaking or during the steelmaking process itself.

**VALUE IN USE MODELLING**

The previous section has given a brief process description and outlined some of the key factors affecting economic blast furnace operation. The fact that there are several process steps each influenced by multiple raw material properties makes the use of a process model one of the vital tools required to perform an analysis of the value of different ores.

A useful approach to blast furnace simulation is the one dimensional static model of the furnace, with a conceptual division into two stages through the chemical reserve zone to allow a unique solution of the heat and mass balance equations (Rist and Meysson, 1966; Peacey and Davenport, 1979; Kundrat, 1989). These models are still useful today for operator guidance, ‘what if’ studies and raw material analysis (Hooey et al, 2010). The Marx model developed by Creative Process Innovation incorporates a rigorous two-stage heat and mass balance model of the blast furnace, shown schematically in Figure 2. This allows prediction of fuel rates, hot blast requirements, slag and hot metal production rates, partitioning of elements such as phosphorus and sulfur between slag and hot metal, and top gas temperature and composition based on selected raw material inputs and operating constraints. Iterative heat and mass balance calculations are performed to simulate the operation of the sinter plant, ensuring the sinter is able to meet blast furnace fluxing requirements and calculating the flux and fuel requirements at the sinter plant. A pellet plant heat and mass balance module is also included. Mass balance and cost calculations are performed for hot metal pretreatment, steelmaking, casting and rolling. The majority of thermophysical data is sourced from the Outotec HSC Chemistry program (Roine, 2009).
The Marx model can be calibrated to simulate a particular blast furnace operation, or to represent a broader market segment. For the purposes of this paper, the model has been set up to simulate a typical coastal Asian blast furnace (Naito, 2006). These are typically large furnaces (4000 - 5000 m³ inner volume), operating at high productivity (>2 t/m³/day), with high rates of pulverised coal injection (eg 150 kg/t hot metal). The raw material blend is made up of imported seaborne iron ores and the slag composition is very close to the accepted limits of slag Al₂O₃.

In this scenario a key operating constraint is the need to dilute the blast furnace slag to maintain a fixed slag Al₂O₃ content of 15 per cent. This is required as higher slag Al₂O₃ contents adversely affects the viscosity of the slag impacting the stable and efficient operation of the blast furnace. If additional Al₂O₃ is added to the furnace raw materials in either iron ore or coke ash, additional fluxes must also be added to maintain the slag Al₂O₃ limit. This has the effect of increasing coke rates in the sinter plant and blast furnace as extra coke is required to melt the additional slag. The higher slag volume also decreases the sinter plant and blast furnace productivity, as many blast furnaces are limited by the volume of hot metal and slag they are able to produce and cast per day. This loss of production is multiplied by the marginal value of hot metal and results in a negative impact on the VIU.

Another key consideration is the behaviour of phosphorus. Unfortunately, the strongly reducing conditions present in the blast furnace mean that all of the phosphorus present in the iron ores and coal reports to the hot metal. Phosphorus is detrimental to steel quality and needs to be removed after the blast furnace in hot metal pretreatment or during the steelmaking process. This increases the cost of steel production, and can be incorporated in the VIU model as a penalty.

To perform a VIU calculation, a base case of the model is run simulating normal ironmaking practice and the costs calculated. A test ore (sinter fines, concentrate, lump or pellets) is then substituted for a reference ore and the model run again subject to a set of operating constraints. The test ore VIU is calculated as the ‘break-even’ price, ie the price a customer would be prepared to pay for the test ore to maintain the same ironmaking costs as the reference case, taking into account any changes in ore usage, coke, fluxes or penalties due to the use of the test ore. This is an ‘in plant’ VIU; freight can then be subtracted if required to calculate an FOB VIU.

As an example, a selection of typical ore types have been compared using the Marx model with grades taken from Khosa, Lu and Manuel (2007). The chemical analysis of these ores is summarised in Table 1, with two additional hypothetical ores:

1. high P Marra Mamba – the phosphorus content has been increased to 0.1 per cent to test the sensitivity of the calculation to phosphorus; and
2. high alumina CID – the alumina content of the channel iron deposit has been increased to 2.5 per cent at the expense of LOI, to test the sensitivity of the calculation to alumina.

It has been assumed that the ferrous burden comprises 70 per cent sinter, 20 per cent lump ore and ten per cent pellets, with ten per cent of the sinter fines blend made up with Marra Mamba ore in the reference case. The reference Marra Mamba ore is then replaced with each ore in turn and the impact on sinter plant and blast furnace operation calculated. The impact of this ore replacement on two of the main blast furnace variables is plotted in Figure 3.

The relative VIU of these ores is shown in Figure 4 (Marra Mamba ore is given a reference value of 100 per cent). Comparing the VIU result to a simple differential based on iron content, it can be seen that other factors that can be
calculated using a VIU model have a significant impact on the relative value.

In the case of the two CID ores, the VIU to the customer is significantly different even though the Fe per cent (dry basis) is the same. This example highlights the potential impact of raw material alumina content, for ironmakers who are constrained by slag alumina content. The normal Al₂O₃ CID ore has been calculated to have a much higher value than that suggested by a simple linear function of iron content alone. This is due to its relatively low alumina content compared to the Marra Mamba ore. The high alumina CID, on the other hand, has a relatively low value compared to the Marra Mamba ore. In this case the physical impacts on sinter plant operation would have to be carefully considered, given the significant difference in ultrafines content (per cent passing 150 μm).

The impact of changing phosphorus has been calculated to be relatively low for the Marra Mamba ore (0.07 to 0.10 per cent P).

The haematite ore has excellent chemistry and is calculated to have a much higher value than that suggested by a simple linear function of iron content. The low SiO₂ and Al₂O₃ content lead to low overall slag volumes, decreasing the fuel and flux requirements and increasing productivity.

**CONCLUSIONS**

To establish the value of an iron ore product it is important to consider its behaviour during use in customer processes. For lump iron ores this involves measurement of a range of physical and metallurgical properties in addition to chemical assay.

For fines the behaviour during sintering is important and this can be measured in the laboratory using granulation and sinter pot tests. The impact of fine ore properties on the sinter process and well as the metallurgical properties of the sinter which subsequently affect the blast furnace process must be considered. In the case of concentrates, the behaviour during pelletising and impact of pellet properties must be considered.
VIU models, such as the Marx model described in this paper, offer an important tool to quantify the relative value of an iron ore. VIU results should be used in conjunction with metallurgical testing and other market information to determine the value of ores relative to the index ore when developing a new project, making mine planning/cut-off grade decisions, and in setting quality price differentials.

ACKNOWLEDGEMENTS

This paper is dedicated to Campbell Cripps Clark, who pioneered VIU modelling within Bluescope Steel/BHP Billiton.

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FIG 4 - Relative value in use plotted against iron content (per cent value relative to Marra Mamba on a $/dmtu basis). Simple price differential based on iron content alone shown for comparison.