



# Economic modelling of a ferrochrome furnace

by W. Biermann\*<sup>†</sup>, R.D. Cromarty<sup>†</sup>, and N.F. Dawson<sup>†</sup>

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## Synopsis

All industrial processes are economically driven, resulting in the ever increasing need for process optimization in order to stay competitive and profitable. Numerous models have been published depicting the optimization of the raw material usage in an arc furnace, as well as the thermal and electrical efficiency; however, to obtain a holistic view of the cost-effectiveness of the process one needs to expand the model to include the cost of all the operational variables.

This project therefore aimed to not only include the raw material feeds and power consumption as input variables, but also the labour, maintenance, and environmental costs to generate an all-inclusive financial balance. In the end, the model was able to mathematically optimize the ferrochrome (FeCr) production process through evaluating the effect of a specified combination of input parameters. It could therefore be used as a tool to aid in managerial decision-making; to appraise and correspondingly adjust certain operational variables in order to achieve a maximum return on investment.

This paper fully describes the reasoning behind the choice of the essential model components, the assumptions made during the models development, the calculation approach, as well as the advantages, limitations, possible applications, and areas for expansion of the final model.

Through running simulations with plant data, it was found that the accuracy of final model remained fairly constant when applied to stable furnace conditions, but was met with a number of limitations when applied to more complex situations. These limitations could, however, be overcome through further development and expansion of the existing model to include a larger number of process variables.

## Keywords

carbon footprint, economic optimization, energy efficiency, ferrochrome, material balance, submerged arc furnace, triple bottom line accounting.

## Introduction

All industrial ventures strive to achieve a maximum profit margin through increasing the production of saleable products, lowering operational costs and improving operation efficiency. Although all industrial processes have these objectives in common, the means through which it could be achieved would depend on the operational variables of the specific process route.

Throughout the years the economic optimization of industrial processes has developed into a respected enterprise based on

the cost-effectiveness of the specific process route. A good example of process optimization is the semi-empirical model developed by Broekman and Ford<sup>1</sup>, which incorporated the ore supply, smelting operations, as well as the markets to predict and improve the overall cost-effectiveness of the process. Developing simulation models such as these has allowed producers to benchmark numerous operational parameters, as well as evaluate different operational conditions. Furthermore, following the global trend towards green technology, simulations could be expanded to include the cost of both the environmental and social responsibility of the producer.

Previous work done in this field was based on the principles of material and energy balances for smelting operations. According to Broekman and Ford<sup>1</sup>, the mass and energy balances were generated either from the theoretical partition ratios of the components between the product and slag mass, or through empirical relationships derived from experimental and plant data. These balances were used to predict the metal and slag constituents for a given combination of raw material inputs of known composition. Ultimately, this allowed producers to assess the influence of various raw material inputs on the power consumption, slag properties, and alloy grade.

Figure 1 indicates the theoretical minimum amount of energy and reductants required for ferrochrome (FeCr) production utilizing either AC or DC furnaces for various raw material inputs.

## Influence of charge material on power consumption

The type and combination of charge materials used would influence furnace operations and

\*<sup>†</sup> Department of Materials Science and Metallurgical Engineering, University of Pretoria.

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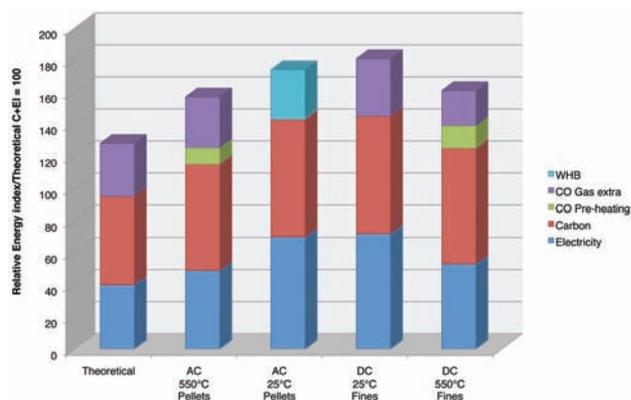


Figure 1 – Theoretical consumption of electricity and reducing agents (Daavittila and Honkaniemi, 2004)

ultimately affect the electricity consumption. The furnace feed typically consists of chromite (lumpy ore, pellets, and briquettes), reductants (anthracite, char, coke, and coal), and fluxes (quartzite, dolomite, and lime). Xiao *et al.*<sup>3</sup> reported that through careful control of the charge material's size range and composition, ideal furnace conditions could be sustained. Close control of the raw material type and size range would ensure good permeability within the packed bed, while the composition would influence the slag properties. There are, however, a number of charge pre-treatments that could be utilized in order to improve the furnace stability and productivity.

Ferrochrome smelting is an energy intensive process, with the typical electrical consumption ranging between 2000 and 4000 kWh/t FeCr, depending on pre-reduction and pre-heating of the charge material<sup>3</sup>. Figure 1 illustrates the reduction in power consumption when using agglomerated fines and sintered pellets. Daavittila also found that the maximum productivity with the lowest power consumption was achieved by the use of sintered pellets within a submerged arc furnace (SAF) setup<sup>2</sup>.

### Energy losses

In conventional furnace operations, the bulk of the heat energy is lost to the alloy and slag while a smaller portion of the energy is lost as furnace off-gases. Furthermore, Daavittila claimed that decreased plant availability and poor power utilization in the AF would lead to a further increase in power consumption<sup>2</sup>. This corresponds to the work done by Wilson *et al.*<sup>4</sup> on the production of steel with an SAF, which indicated that approximately 21 per cent of the heat lost within a SAF is due to the emission of flue gases, while 10 per cent is lost to cooling water and 2 per cent could be attributed to miscellaneous losses.

Chirattananon and Gao<sup>5</sup> generated a mass and thermal energy balance for the production of steel with a SAF from the expected inputs and outputs illustrated in Figure 2. Figure 3 depicts the heat losses typically expected during production with an arc furnace (AF), where miscellaneous heat losses included the heat lost during the charging of raw material, heat lost due to an open door, or from a furnace cover opening.

Given that the research done by Wilson *et al.*<sup>4</sup> and Chirattananon and Gao<sup>5</sup> was based on the production of steel

with an SAF, it is expected that the distribution of the heat losses would vary for ferrochrome production. However, since the research was done on a SAF, it is reasonable to assume that, as with the production of steel, the largest portion of heat would be lost to the FeCr alloy and slag, while a considerable portion would be lost to the off-gas, the cooling water, and miscellaneous factors.

### Financial modelling

#### Cost distribution

Modern-day ferrochrome production faces a number of challenges; as market prices continuously fluctuate and a shift in the global mind set has increased pressure to minimize waste production and improve working conditions. In order to adapt to these harsh economic conditions, the industry now places an even greater emphasis on minimizing operational and investment costs. The typical cost distribution of a ferrochrome smelter, as predicted by Daavittila *et al.*<sup>2</sup>, is illustrated in Figure 3.

The cost distribution for South African smelters varies slightly; typically chromite ore, reductants, and electricity each account for 30 per cent of the production costs, while factors such as maintenance, labour and waste disposal accounts for the remaining 10 per cent<sup>6</sup>.

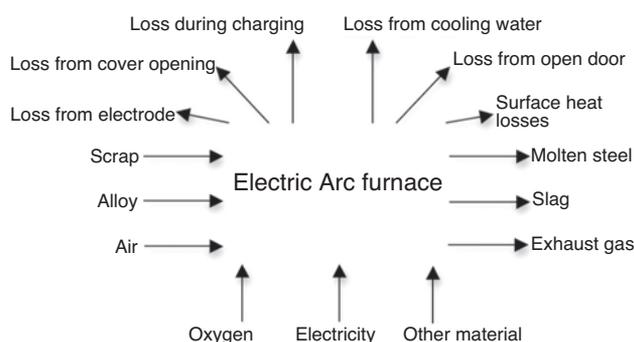


Figure 2 – An energy and material balance of an electric arc furnace (Chirattananon and Gao, 2004)

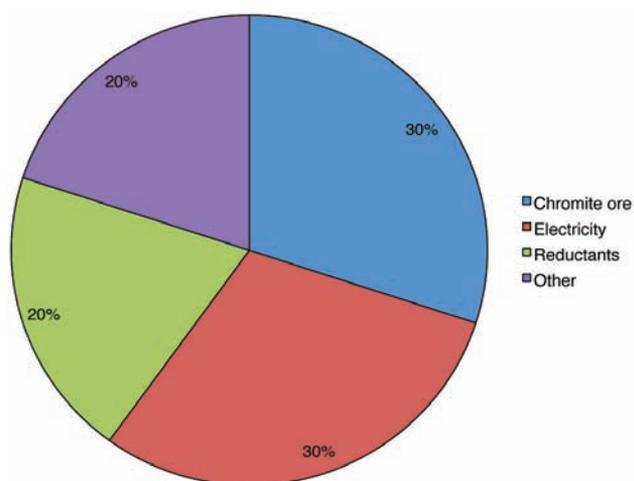


Figure 3 – Typical cost distribution expected for a ferrochrome smelter

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Although the cost distribution would differ slightly for various regions and different approaches to plant operation, it is clear that raw material and electrical costs account for the bulk of the process costs.

### Triple bottom line accounting

As previously mentioned, the global economic climate has changed from the 1900s to the 21st century, with the private sector becoming more aware of corporate responsibility. According to Hamson<sup>7</sup> this awareness has led to the expansion of the traditional frame of reference for financial performance to include both social and ecological aspects, giving rise to the term 'triple bottom line accounting'. Triple bottom line accounting has also been defined in terms of the three pillars; namely people, planet, and profit.

The first pillar pertains to human capital, with the focus on beneficial corporate policies toward labour practices and the health and safety of the surrounding community.

The second pillar could also be referred to as natural capital. This pertains to minimizing the ecological footprint of an enterprise through careful management of resource consumption, as well as waste production and disposal.

This concept of accounting is similar to that of eco-capitalism, where the profit is not considered just as the turnover after deduction of the input costs, but includes the economic benefit enjoyed by society. Using this integrated approach, small expenditures on social and ecological aspects may ultimately lead to increased profit<sup>7</sup>.

### Waste disposal and environmental considerations

Applying the integrated approach of triple bottom line accounting to ferrochrome smelting operations, it becomes clear that environmental considerations such as the disposal of ferrochrome slag and off gas emissions need to be accounted for.

### Ferrochrome slag

The molten products obtained from the ferrochrome smelter operation are alloy and slag. According to Beukes *et al.*<sup>8</sup>, South African producers generate slag- to- metal ratios of between 1.1–1.9 t slag per t FeCr. These ratios are worrying, considering the current production volumes and the SA Minimum Requirements for Waste Act, which indicates that the maximum disposal rate permitted for FeCr slag is 585 t/ha/month. Furthermore, weathered and current arising slag heaps have mostly been classified as hazardous waste material due to the presence of Mn, Fe and Cr(VI).

However, treatment of the slag could allow for its use in building aggregate and cement brick production, as well as road construction. The use of FeCr slag as saleable product would not only generate revenue, but could reduce the cost of waste disposal and the use of natural resources.

### Off-gas emission

According to Niemelä *et al.*<sup>9</sup>, ferrochrome production generates large amounts of CO gas the composition and volume of which depend on the combination of the raw materials used, feed pre-treatment, furnace type, and operating conditions. These operating conditions include changes in temperature, electrical input, material flow, segregation, and electrode position, as well as the time to tap.

Within open and semi-closed furnace setups the gas generated would be burned off as it leaves the furnace, while a closed furnace setup allows the gas to be extracted by fans, scrubbed, and utilized as fuel. Furthermore, the volume of off-gas generated within a closed furnace setup is much lower than that of any other furnace setup. Off-gas volumes range between 650–850 Nm<sup>3</sup>/t FeCr, whereas semi-closed and open furnaces generate off-gas volumes of up to 10 000–15 000 Nm<sup>3</sup>/t FeCr.

The off-gas typically consists<sup>8</sup> of 75–90 per cent CO, 2–15 per cent H<sub>2</sub>, 2–10 per cent CO<sub>2</sub>, and 2–7 per cent N<sub>2</sub> and depending on the composition of the off-gas, the energy of combustion would vary between 2.0–2.3 MWh/t FeCr or 7200–8280 MJ/t FeCr<sup>9</sup>.

### Possible uses for off-gas in plant operation

Off-gas formed within a closed furnace setup is a source of energy that could be utilized as fuel in a variety of different processes on the plant. According to Niemelä *et al.*<sup>9</sup>, the heating value of the gas is close to 60 per cent of the energy supplied by the reductant and could account for approximately 70 per cent of the electrical energy required for smelting.

Daavittila<sup>2</sup> suggested that instead of losing the latent heat of the CO gas formed during smelting, it could be utilized for pre-heating or pre-reduction processes in order to reduce the plant's overall power consumption. Furthermore, considering furnace off-gas as a saleable product would not only reduce waste disposal costs, but could also compensate for the increase in operational costs due energy losses.

### Cost of carbon emissions

Carbon emission tax may be implemented in the South African industry, at an estimated R150 to R200 per ton CO<sub>2</sub>, according to research by Deloitte<sup>10</sup>. Through determining the cost of the carbon emissions from an estimated price of R165 per ton CO<sub>2</sub>, it could be seen that, approximately R207 would be charged per ton CO.

### Model development and operation

The objective during modelling was to incorporate all the specified process variables while maintaining ease of operation and allowing for the possibility of expansion.

The optimization model consists of a financial balance of the process input and output costs in order to achieve maximum profitability, while minimizing the social and environmental costs. The variables focussed on during the investigation are illustrated in Figure 4.

For the purposes of this project, the model generated was based on the production of ferrochrome with a submerged arc furnace. However, the aim was to develop the model in such a way that by changing the input variables it could be applicable to a variety of electric arc furnace types and ferrochrome alloys of different grades and carbon contents.

The model was developed in Microsoft Excel as various worksheets for the different sections of interest. Initially, the operational variables had to be specified according to the plant conditions being simulated. The operational variables pertained to the product requirements, the furnace type and

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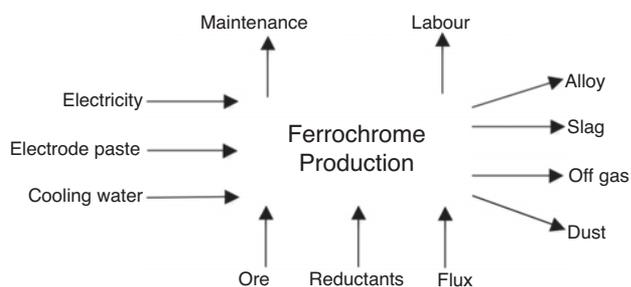


Figure 4—Input and output variables used for economic modelling

operating conditions, the routine maintenance done on the furnace, as well as the type and composition of the charge material.

Once the operational variables had been specified, the model iterates within the stipulated ranges and empirical relationships developed for the mass and energy balances, to predict the quantity and composition of the products generated, as well as the energy lost during production. The cost of the inputs and outputs from the various worksheets is accounted for as the direct operating cost or OPEX, in the worksheet labeled 'Financial balance'.

### Product requirements

In order to analyse the influence of numerous raw material combinations on the cost of production, a minimum and maximum value had to be specified for each element of a specific alloy grade, the desired Cr and Fe recovery to the metal, as well as the minimum and maximum allowable values for the slag basicity.

As can be seen from Table I, the model allows the user to track the values predicted for the current combination of raw material inputs and product requirements. The values calculated by the model were colour-coded in varying shades of green, yellow- and red; where green indicates that the predicted values are safely within the lower region of the specified range, and shades of orange through red indicate that the predicted values are moving towards the maximum specified limit. This increases the ease with which the user

can keep track of changes within the model and take corrective action if required.

### Furnace setup and operating conditions

The furnace setup and operating conditions were specified through numerous drop-down lists, which allows the user to choose the furnace type (AC or DC), the rooftop configuration (open, semi-closed, or closed), the furnace shape (circular or rectangular), the number and configuration of tapholes, as well as the electrode configuration. Furthermore, by allowing the user to specify the minimum and maximum furnace capacity, the model can simulate the cost of operating at lowered furnace capacities, as well as furnace shut-down and start-up procedures.

### Routine maintenance

Due to the difficulties in predicting the effect of plant operation on the equipment and refractory life, the routine maintenance cost of plant operation was divided into sub-categories of short-term, long-term- and 'true' long-term costs.

The base infrastructure was taken as 30 per cent of the total capital cost (CAPEX), while the major and minor infrastructure costs were taken as 60 per cent and 10 per cent of the base infrastructure costs respectively. The routine maintenance costs in the first 12 months were specified as 5 per cent of the minor infrastructure cost. Minor infrastructure generally refers to small pumps, fans, hoses, certain instruments, lights etc. In 12–60 months the maintenance costs were calculated as 3 per cent of the major infrastructure cost, which refers to the furnace shell, refractories, as well as sections of the copper water cooling system. Once exceeding the 120 month period, the maintenance costs were calculated as 1 per cent of the base infrastructure cost<sup>6</sup>.

### Raw material feed

Once the above specifications have been entered by the user, various ore combinations can be examined in the worksheet labelled 'Raw material inputs'. In this worksheet, the user had the ability to vary the raw material inputs in order to determine the most cost-effective combination, while

Table I

### Illustration of the 'Product requirements' input sheet

Product Specifications							
Type	Chemical Composition						
P110: F2 Metal	Cr	Fe	Si	C	P	S	
Average	49.84066788	37.422374	3.59392228	6.87870674	0.017132969	0.049746205	
Stdev	0.608458136	0.55533687	0.91706458	0.358133023	0.000527425	0.013703196	
Min	46.8	35.05	3.5	5.87	0.016	0	
Max	50	40	4.6	7	0.02	0.06	

Slag Specifications			
	Min	Max	
Slag/Metal ratio	1.1	1.9	1.1
Basicity	0.98	0.99	0.958773234
Cr recovery	80.00%	90.00%	85.06%
Fe recovery	80.00%	90.00%	90.00%

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monitoring furnace stability and product quality. The furnace capacity for the instance illustrated in Table II was expressed as the maximum amount of raw material that could be fed into the furnace per day.

### Mass balance inputs

The raw material inputs were linked to a mass and energy balance that involved a complete elemental analysis of all the inputs and outputs. This was done through using the reconstituted values of the given raw material compositions, in order to account for the presence of trace elements as well as plant spillage. The influence of raw material pre-treatments was taken into account by allowing the user to specify the temperature (°C) at which the raw material was treated.

### Mass balance outputs

The elemental analysis for the desired combination of raw material inputs was related to the required product specifications, as stated by the user. This was done for a single batch, which was restricted to the maximum specified furnace capacity.

All the calculations were iterated within the specified product compositional ranges. The slag composition was calculated from the excess constituents that did not report to the alloy. The Cr and Fe distribution ratio was chosen by the user in the worksheet labelled 'Product requirements', as the

percentage recovery to the alloy. This was done according to what would generally be expected for the specific plant's operation.

The total amount of CaO, MgO, and Al<sub>2</sub>O<sub>3</sub> present in the feed was assumed to report to the slag and the basicity was calculated accordingly. Furthermore, the slag- to- metal ratios were allowed to iterate within a specified range.

The excess carbon and sulphur that did not report to the metal would report to the off-gas as CO<sub>x</sub> and SO<sub>2</sub> respectively. Furthermore, any moisture present in the raw materials would also report to the off-gas, along with all the nitrogen present in the system.

According to literature, the off-gas typically consists of 85–90 per cent CO and only 2–5 per cent CO<sub>2</sub>. It was therefore decided that the excess carbon in the system would be combusted as CO, while the CO<sub>2</sub> present in the off-gas would originate from the CO<sub>2</sub> introduced into the system through the dolomite and lime.

### Energy balance

For the thermal balance, the enthalpy values of the different raw material inputs and products were calculated at the specified temperatures, for the specific molar mass of each of the constituents. The total energy required for the smelting operation was then calculated as the difference between the chemical energy of the products and the total chemical energy of the raw material inputs.

Table II

Illustration of a section of the 'Raw material input' sheet

Raw Material					
	Supplier	Tonnage	Cost/t	Total cost	
Reductants	Coal	Coal_Graspan_ave	R 800.00	-	
		Coal_Umcebo_Peas	R 800.00	-	
		Coal_Umcebo_L_Nut	R 800.00	-	
		Coal_1	58.666 t	R 900.00	52,799.40
		Coal_2	R -	-	
		Coal_3	R -	-	
		<b>Coal T total:</b>			52,799.40
	Coke	Coke_Mital_SmNts	R 3,600.00	-	
		Coke_Mital_Peas	R 3,600.00	-	
		Coke_Mittal Cobbles	R 3,600.00	-	
		Coke_GMR_grade_4_Anth	R 4,000.00	-	
		Coke_GMR_toll_coke	R 4,000.00	-	
		HG_Coke	49.778 t	R 4,000.00	199,112.00
		<b>Coke Total:</b>			199,112.00
	Char	Char_ACM_Nuts	R 800.00	-	
		Char_AFC_Nuts	R 800.00	-	
		Char_tech_Nuts	R 900.00	-	
		Char_1	R -	-	
		Char_2	R -	-	
		Char_3	R -	-	
<b>Char T total:</b>			-		
Anthracite	Anthracite_Maloma	R -	-		
	Anthracite_Tendele_Duff	R -	-		
	Anthracite_Tendele_Snuts	R -	-		
	Anthracite_Ave	R -	-		
	Anthracite_1	13.819 t	R 1,100.00	15,200.90	
	Anthracite_2	31.922 t	R 1,000.00	31,922.00	
Anthracite_3	R -	-			
<b>Anthracite Total:</b>			47,122.90		
<b>Total mass of inputs</b>		<b>788.316</b>			

Metal composition	
C	7.9
Cr	51.96
Fe	42.01
S	0.222
Si	6.86

Slag composition	
Al <sub>2</sub> O <sub>3</sub>	29.4104
CaO	9.81666
Cr <sub>2</sub> O <sub>3</sub>	7.3285
FeO	6.54723
MgO	18.235
SiO <sub>2</sub>	28.6528
P	0.00933

<b>Slag/Metal ratio</b>	1.10
<b>Basicity</b>	0.95877
<b>Cr recovery</b>	85.06%
<b>Fe recovery</b>	90.00%

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The chemical energy was converted to MWh/t FeCr and incorporated into the overall energy balance. For the overall energy balance, the total required electrical input can be calculated from the energy required for smelting, as well as the typical heat losses expected for a furnace of the specified size. On the other hand, the typical heat losses can be determined by deducting the energy required for smelting from the total electrical input as specified by the user.

The cost of the electrical inputs was calculated according to Eskom's Mega flex peak, off-peak, and standard tariffs for 2011. Within this worksheet, the user has to specify the month from the drop-down list illustrated in Table III, in order to account for the price increase from the low to high demand season. The electricity cost in Table III was calculated on a monthly basis assuming that the furnace was operated continuously without interruption. For the financial balance, the monthly cost was converted to the cost per ton FeCr.

### Carbon footprint

The worksheet 'Carbon footprint' was developed with the aim of analysing the effect of the CO off-gas on the productivity and profitability of the process. This was done by examining the effect of carbon taxes on the profit margin, as well as investigating the possibility of reducing the energy requirements by recycling the off-gas generated during the smelting operation.

The worksheet was linked to the 'Material and Energy balance' sheet, in order to obtain the amount of off-gas generated for the given set of raw material inputs. From this the amount of off-gas generated was converted from ton to Nm<sup>3</sup>, assuming a density of 1.19–1.26 kg/Nm<sup>3</sup>.

The worksheet was developed in such a way that the recycling of the off gas could be simulated only for a closed furnaces setup. If this was the case, the user had to specify the percentage of off-gas that could successfully be recycled back into the system.

Since CO and H<sub>2</sub> are the only flammable components in the off-gas, the energy of the off-gas was assumed to be between 10.1 and 11.5 MJ/Nm<sup>3</sup>. The reduction in the energy requirements (MWh) due to the recycled off-gas was then calculated from the heat generated (MJ/Nm<sup>3</sup>) multiplied by the amount of off-gas recycled (Nm<sup>3</sup>).

Once the amount of recycled off-gas has been calculated, the tax levied on the amount of CO and CO<sub>2</sub> emitted is

calculated according to the carbon emissions cost estimates of Deloitte.

### Financial analysis

The values obtained from the worksheets mentioned above, were related back to a 'Financial Sheet'; where the costs were expressed per ton ferrochrome produced. This was done for the labour, maintenance, overhead, raw material, utility, pollution, and laboratory costs; according to the direct operation cost (OPEX) calculations suggested by Vatavuk<sup>11</sup>.

The utility costs were calculated for the amount of electricity, water, and electrode paste consumed. It was assumed that the amount of water consumed by the cooling system, would vary between 2–3 t per ton ferrochrome, at a cost of R3–R5 per ton water. Furthermore, it was assumed that approximately 10 kg electrode paste would be required per ton ferrochrome, at a cost of R5750–6250 per ton paste<sup>6</sup>.

The pollution cost calculations were based solely on the cost of carbon emissions and did not include the cost of slag disposal. The literature indicated that numerous ways exist to reduce the cost of slag disposal and possibly generate another avenue for revenue; therefore it would be advisable to expand future versions to include these costs.

### Results and discussion

Once the model had been completed, the validity and level of accuracy of the results generated had to be determined. This was done by running numerous simulations with plant data obtained for the raw material and electrical inputs, the chemical composition of the alloy and slag, as well as the cost distribution expected for general plant operation.

When feeding the plant data into the model, it was found that the weight per cent calculated for the various alloy constituents remained within the specified range as illustrated for the data simulated in Table I. The calculated values, however, had a propensity to deviate towards the upper limit of the range. Furthermore, the calculated slag compositions and basicities correlated well with those indicated by the literature, as well as with actual plant data.

In order to validate the results obtained for the product and slag compositions, the actual weight per cent chromite in the slag was compared to the calculated values. The decision to compare the weight per cent of chrome oxide in the slag, rather than the weight per cent chromium in the alloy, was

Table III

### Illustration of the worksheet pertaining to the calculation of the electrical costs

Electricity use for September					
Time period	No Hours	Rate	Hours of production per month	Power usage	Total cost
<b>Weekdays</b>					
Off Peak	22:00-6:00	8	0.2417 R/kWh	176	15047.32 R
	6:00-7:00	1	0.3446 R/kWh	22	15047.32 R
Standard	10:00-18:00	8		176	15047.32 R
	20:00-22:00	2		44	15047.32 R
Peak	7:00-10:00	3	0.561 R/kWh	66	15047.32 R
	18:00-20:00	2		44	15047.32 R
<b>Saturday</b>					
Off Peak	20:00-07:00	11	0.2417 R/kWh	44	15047.32 R
	12:00-18:00	6		24	15047.32 R
Standard	07:00-12:00	5	0.3446 R/kWh	20	15047.32 R
	18:00-20:00	2		8	15047.32 R
<b>Sunday</b>					
Off Peak	0:00-24:00	24	0.3446 R/kWh	96	15047.32 R
					<b>R 627,214.78</b>

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based on the fact that the alloy composition was limited to a specified range; whereas the slag composition could vary according to the empirical relationships developed during modelling.

The percentage error due to the variations in the calculated and actual slag mass was determined to be  $\pm 0.2$  per cent. From Figure 5 a linear correlation can be seen between the calculated and actual weight per cent chrome oxide, obtained from plant data. This indicated that changes in the predicted values remained fairly close to the changes in the actual values, under normal operating conditions. However, the model fared poorly in predicting the alloy and slag composition for data obtained during periods of instability, where instability refers to any deviation from normal operation.

From the thermal energy balance it was found that, the energy required for smelting would vary between 2.3 and 2.8 MWh/t FeCr. Deducting the energy required for the smelting operation from the actual electrical inputs obtained from plant data, the theoretical heat losses were determined to be between 1.1 and 1.17 MWh/t FeCr. This corresponds to the plant data, where the heat losses were indicated to be between 12–15 kWh/m<sup>2</sup>.

### Carbon footprint

#### Recycling of the off-gas

By running simulations with plant data it was calculated that, the amount of off-gas produced varied from 850–950 Nm<sup>3</sup>/t FeCr, assuming that the density of the off-gas ranged from 1.19–1.26 kg/Nm<sup>3</sup>. This is slightly higher than the 650–850 Nm<sup>3</sup>/t FeCr reported by Niemelä *et al.*<sup>9</sup>

Assuming that CO and H<sub>2</sub> are the only burning components of the off-gas, the heat generated by the off-gas was calculated to be 2.72 kWh/Nm<sup>3</sup> off-gas or 2.05 MWh/t<sup>-1</sup> FeCr, for the simulation. This varied only slightly for the rest of the data sets and corresponds well to the 2.8–3.2 kWh/Nm<sup>3</sup> off-gas or 2.02.3 MWh/t FeCr predicted by Niemelä *et al.*

Furthermore, it was found that recycling the off-gas could lead to a 50–60 per cent reduction in the energy requirements, assuming that 85–90 per cent of the off gas could be recycled effectively.

### Carbon taxes

Assuming that the tax levied on the CO and CO<sub>2</sub> was R260.00 and R165.00 respectively, it was calculated that the cost of carbon tax on average would be R290.00 per ton FeCr. However, through recycling approximately 85 per cent of the off gas to pre-treatment processes, the cost could be reduced dramatically, to an estimated R45.00 per ton FeCr.

### Financial analysis

The cost distribution remained fairly constant, with the raw materials accounting on average for 50 per cent of the cost, the electricity for 40 per cent, and labour, maintenance and carbon taxes for the remaining 10 per cent.

Should the off-gas be recycled, a decrease of up to 25 per cent in the production costs could be obtained; with the raw materials now accounting for approximately 70 per cent of the costs, electricity for 20 per cent, and labour, maintenance, and pollution costs for the remaining 10 per cent.

### Sensitivity analysis

As can be seen from the cost distribution calculated above, the electrical costs account for approximately 40 per cent of the overall production cost, which is 10 per cent more than what was expected from data in the literature. It was therefore decided to analyse the sensitivity of the production cost to changes in the electrical inputs to the furnace.

From the sensitivity analysis in Figure 6 it can be seen that a 5 per cent increase in the electrical inputs corresponds to a 1 per cent increase in the overall production cost. The production cost therefore shows a 2 per cent sensitivity to variations in the electrical inputs, which could account for the discrepancy in the predicted cost distribution.

### Conclusion

Through the use of material and energy balances, a robust model was developed to predict the influence of numerous process variables on the profitability of a ferrochrome smelting operation. It was found that the model remained fairly accurate when applied to stable furnace conditions, but was met with a numerous limitations when applied to more complex situations. These limitations could, however, be

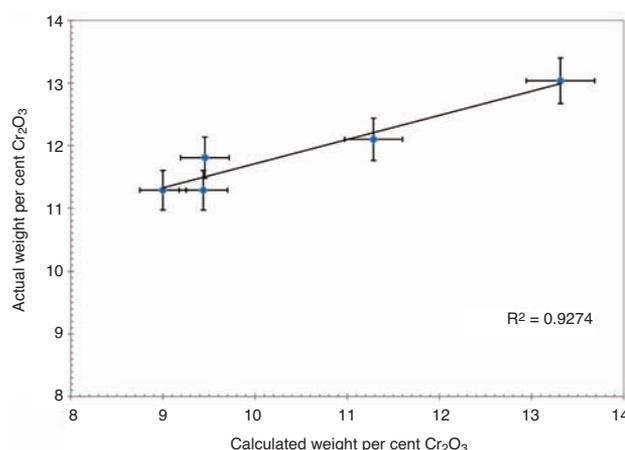


Figure 5—Comparison of the calculated weight per cent chrome oxide to the actual weight per cent chrome oxide in the slag

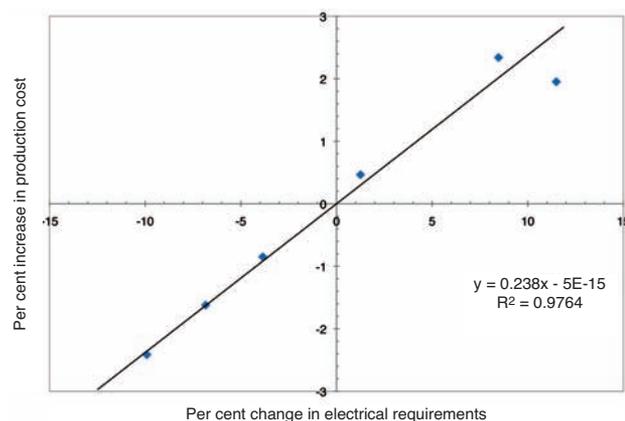


Figure 6—Sensitivity analysis to changes in the electrical input requirements of a Submerged arc furnace

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overcome through further development of the existing model with more plant-specific data and expansion to include a larger number of process variables.

### Advantages

The model setup was chosen due to its simplicity and the fact that it allows the user to specify the product composition range while monitoring the slag composition and properties in order to optimize the raw material inputs. The advantage to this type of setup is that it gives the user the freedom to evaluate the furnace performance and profitability using particular ores, reductants and electrical inputs at a specified costs. Furthermore, the utilization of worksheet-based programs makes models such as these easily expandable, and the model could with time be developed to include almost any process variable that can be predicted or quantified.

### Limitations

Although the model has been developed to take numerous operational parameters into account, it cannot accurately account for certain process phenomena, such as the electrode penetration operation, the reactivity of the various types of raw material inputs, or material retention. Furthermore, to correctly quantify the transient furnace conditions such as those experienced during plant start-up and shut-down procedures, one would have to account for the sensitivity of the electrodes to cyclical loading, the possibility of the refractories experiencing thermal shock due to the gross temperature fluctuations, and finally the cost of material losses. Therefore in order to maintain a high degree of accuracy, the current model can ultimately be applied only to stable furnace conditions.

### Applications

The model could also be extended to applications such as determining the future selection and profitability of new ore materials, feasibility studies on production at various furnace capacities, and the competitiveness of the plant compared to other producers.

### Possible areas for expansion

As has been mentioned, the limitations of the model could be overcome through the development or expansion of certain sections.

One of the limitations is that the model does not account for the reactivity of the different raw material types. When considering the large influence the pre-treatment of raw materials has on the furnace's productivity, it would be advisable to look into this matter.

Another limitation is that the model does not account for the cost of refractory wear for various operating conditions and raw material inputs. Since unforeseen refractory failures could result in extended periods of downtime, during which production ceases and maintenance costs skyrocket, it could be worthwhile to include the influence of different raw materials and operating temperatures on the refractory wear and maintenance of the furnace.

Furthermore, for the purposes of this model, the surface heat losses were calculated as the electrical input energy that was not utilized during the smelting process. However, to

obtain a more accurate account of the amount of energy lost during production, the miscellaneous heat losses, as well as the surface heat losses, need to be taken into account. During the development of the model provisions were made to calculate the surface heat losses as a function of the furnace size. If the electrical input is known, and the surface heat losses were calculated according to the furnace size, the miscellaneous heat losses could be examined. This would allow the user to benchmark the heat lost during operating procedures such as charging of raw materials.

For the purposes of this model, the focus was mostly on the optimization of the furnace inputs, rather than the furnace outputs. It was previously indicated that the energy requirements and production cost could be reduced significantly by recycling the off-gas; however, one needs to examine the cost of erecting and maintaining the off-gas recycling plant as well. Furthermore, it was suggested by Beukes *et al.*<sup>8</sup> that processed slag could be sold as a secondary product to civil engineering and construction companies, providing that the slag meets the required specifications. Therefore it can be concluded that, in order to effectively optimize an operation, any means of minimizing waste and generating revenue also needs to be evaluated.

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