DEVELOPING A BY-PRODUCT GAS SIMULATION MODEL TO ESTIMATE SYSTEM IMPROVEMENT INITIATIVES IN IRON AND STEEL MANUFACTURING

A. Ludick¹, J.H. Marais² & W.J.J. Breytenbach³

¹North-West University, CRCED-Pretoria, Pretoria, South Africa
aludick@researchtoolbox.com

²North-West University, CRCED-Pretoria, Pretoria, South Africa
jhm@researchtoolbox.com

³North-West University, CRCED-Pretoria, Pretoria, South Africa
wibreytenbach@researchtoolbox.com

ABSTRACT

High production costs and low steel demands recently placed the South African steelmaking industry under severe pressure. The industry is forced to evaluate and improve its current systems to improve profitability. The dated sector can relieve stress by implementing technologies of the present age. This paper proposes a simulation model that can be used to test system improvement initiatives on the gas network. The iron and steel making process produces combustible gases. These gases are recovered as by-products and used as fuel gas in combination with natural gas and Heavy Fuel Oil (HFO). By-product gases are used to generate heat typically for furnaces or to generate additional electricity through an on-site power generation plant. This gas distribution network is kept safe by flaring excess by-product gas. The proposed simulation model was verified on a case study highlighting the difficulties in predicting by-product gas behaviour as well as the benefit that a gas distribution simulation model can have.

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¹ Alexander Ludick holds a Masters in Mechanical Engineering from the North-West University.

² Dr Johan Marais is a registered professional engineer and holds a PhD in Electrical Engineering from the North-West University. He is currently a lecturer at the North-West University’s Centre for Research and Continued Engineering Development (CRCED) in Pretoria.

³ Dr Wynand Breytenbach holds a PhD in Engineering Development and Management from the North-West University. He is currently a post-doctoral student at the North-West University’s Centre for Research and Continued Engineering Development (CRCED) in Pretoria.
1. INTRODUCTION

High product cost and low demands have placed the South African iron and steel manufacturing industry under severe pressure [1]. The industry is forced to re-evaluate current production strategies [2]. A failure in reducing production costs may force the South African industry to close down. The South African government supports the iron and steel industry by safeguarding the local steel market from cheaper imports from countries like China [3]. Governmental support can only help to a limited extent. It is the sector’s responsibility to regain its position in the international market.

The steelmaking process starts with iron production in a blast furnace. Raw materials such as iron ore, coke and limestone are melted together with a constant supply of heated air within the blast furnace [4]. Ladle torpedoes transport liquid iron from the blast furnace to the steel plant after the tapping the blast furnace. Steel is produced from iron by either the Basic Oxygen Steelmaking (BOS) or Electric Arc Furnace (EAF) process [5]. In the BOS process, a Basic Oxygen Furnace (BOF) is used as opposed to an EAF [6]. The molten steel’s composition is modified to the desired grade by stirring, a ladle furnace or ladle injection [7] [9]. Finally, the steel is solidified in either slabs, blooms or billets by continues casters and rolled into different shapes at the mills [10].

The steelmaking process produces several off gases. Some of these gases are combustible and used as a by-product [11]. Throughout the steelmaking process, combusted by-product gas supplies heat where required. Three by-product gases are typically recovered and used in the industry. These gases include (1) Coke Oven Gas, (2) Blast Furnace Gas, and (3) Basic Oxygen Steelmaking Gas (BOSG). COG is a by-product from the coke making process, BFG from the iron making process and BOSG the steel making process [11] [13]. Not all iron and steel manufacturing facilities reclaim these gases. Each facility’s gas network is unique to the infrastructure. The cost of reclaiming and maintaining the by-product gas network needs to be less than then the potential profit.

Figure 1 illustrates the gas network on a typical iron and steel manufacturing facility. By-product gases are produced and recovered at their respective processes. Each by-product gas is generally integrated with a gas holder and flare stack. Gas holders provide the ability to store gas while maintaining a constant pressure in the gas network. Flare stacks relieve the gas network of pressure in the case of excess gas. An intricate distribution network connects the by-product gas to several plants which require gas for production. Excess by-product gas generates additional steam for electricity [12]. Natural gas and Heavy Fuel Oil (HFO) substitute by-product gases in case of by-product gas shortages [14], [15].
2. **PROBLEM STATEMENT**

By-product gases, if utilised efficiently, can save a steelmaking facility significantly. By-product gas utilisation reduces natural gas and HFO consumption as well as electricity purchased from an external supplier such as Eskom. Improved utilisation results in less gas flaring thus a reduction in CO₂ emissions which will soon be taxed by the South African government. It is difficult to utilise by-product gas effectively. Imbalances between by-product gas production and demand exist daily. These imbalances exist due to manufacturing variations, equipment failures, shutdowns and control discontinuities.

As an example, a steelmaking facility which produces steel using the BOS process with the manufacturing capacity of a million tonnes of steel annually can provide by-product gas of R60 000/h. The high value of by-product gases has led to much research in cost-saving initiatives. Table 1 is a summary of research related to system improvements on the gas control. The gas network is integrated with most of the plants on a steelmaking facility. System improvements on the gas network can therefore be done on most of the plants.

<table>
<thead>
<tr>
<th>Section</th>
<th>Energy saving initiative</th>
<th>Study</th>
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<tr>
<td>Sinter and pelletizing</td>
<td>Use of waste fuels in the sinter plant, selective waste gas recycling and low emission and energy optimised</td>
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<td>Coke making process</td>
<td>Programmed heating, automation and process control system and COG recovery</td>
<td>[16], [19], [20]</td>
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Most of the work presented in Table 1 require highly specialised skills and CAPEX. Both of which are currently lacking in the South African industry. The South African iron and steel industry has recently lost specialised knowledge due to a combination of high personnel turnover rates and inadequate and partial handovers. Furthermore, the industry has not seen much changes in the last two decades which mean that the general South African steel manufacturer is running a dated facility. Dated machinery and equipment forces conservative operating conditions to avoid unnecessary strain.

The shortage of CAPEX, specialised skills and the deteriorated condition of overall plants place the industry in a difficult position to regain competitiveness. This paper focuses on a gas network simulation method which enables the steelmaking industry to simulate suggested system improvements on the gas network. The simulation method serves as a platform to test the effectiveness of system improvements and alterations without actual implementation. System upgrades can be reiterated, optimising the system upgrade before actual implemented to minimise implementation risk.

3. METHOD

There are many simulation software packages on the market as well as companies that specialises in plant simulations. It might be the preferred solution to contract the simulation model out to a specialised company. It is however, expensive and can be timely. Another disadvantage is that the plant personal does not gain a fundamental understanding and insight that comes with developing a simulation model. The simulation method in this paper will benefit the steelmaking facility optimally if the plant personal develops it. The model can be developed in Excel, VBA, Python, Matlab or any coding language with mathematical functions.

The simulation model consists of two sections. The first is gas production and consumptions predictions and the second is the distribution of by-product gas between these plants. The production and consumption prediction model provides insight on the by-product gas availability whereas the distribution model provides insight on utilisation. A production and consumption prediction model on its own can be used to predict by-product gas availability and schedule maintenance on the plants accordingly. A distribution model can be used to simulate isolated improvements or alterations on the distribution network.

These models were developed based on the current condition of the South African steelmaking industry. The industry currently functions on dated machinery which was modified over the years. Repairs, maintenance and modifications are typically done when plants are forced rather than preventive maintenance schedules. Machinery does not perform according to the commissioned specifications due to their dated and modified conditions.

The simulation model incorporates the dated condition of the machinery by using actual and historical plant data. This data provides an indication of the machinery’s condition at the time that the data was captured. It supplies the model with actual availability and production insights.
4. SIMULATION MODEL

4.1 By-product gas availability prediction

COG, BFG and BOSG production are proportional to either coke, iron and steel production. The proportion is dependent on the plant’s efficiency and the gas recovering system. By-product gases differ in quality which is dependent on how the relevant plants are producing their products. Gas quality is measured by energy density, Wobbe Index (WI), and how clean the gas is. Only the energy density is relevant for the prediction model. Wobbe analysers continually measure the WI of by-product gas. The by-product gas in energy is the product of the coke, iron or steel production, a scaling factor and the WI (Equation 1).

\[ Q_x = A_x M_x WI_x \]  

\( Q = \text{gas energy [J]} \)  
\( A = \text{scaling factor [m}^3/\text{tonne]} \)  
\( M = \text{production (tonne)} \)  
\( WI = \text{wobbe index (J/m}^3) \)  
\( x = \text{iron, coke, steel} \)  

Steel manufacturing facilities will typically have a planning schedule. Such a planning schedule will indicate the day to day production rates of each plant to reach the overall facility’s production targets. There is generally a deviation between planned and actual production values. The difference between planned and actual production is typically constant from day to day. The proposed prediction model incorporates a regression between the planned production and the actual production. The regression will provide a function to predict the daily production.

The standard error of the sampling distribution of the regression model should be used as an indicator of the model’s prediction reliability. The number of data points can adjust the fit of the regression model. A linear regression model should in most cases be sufficient. Alternatively, a combination of regression models can be used as a compounded result.

Predictions are based on the regression models in combination with the correlation between by-product gas and plant production. This model predicts how much by-product gas will be produced on a daily period. It is not useful if the by-product gas requirement of the plant is still unknown. The requirement can be calculated similarly. For example, by-product gas consumed by the reheat furnaces is proportional to the steel rolled at the mills. Similar to the by-product gas consumed at any other plant. Thus, the required by-product gas can be calculated using regression models between the plants’ forecasts and actual production.

4.2 By-product gas distribution network

The by-product gas distribution network can be simplified to gas production, gas consumption, gas holders utilisation, gas flared and steam and electricity generation. By-product gas which is not consumed is stored in the gas holders. The gas is flared if the gas holder reaches the specified maximum limits. The interaction between by-product gas availability, gas holder utilisation, flaring and electricity generation is simulated in the distribution network simulation model.

Surplus by-product gas is stored in the gas holders. Once the gas holder reaches its specified maximum limit, it will automatically start to flare excess gas. The specified maximum gas holder level is ±85% to ensure safe operation. The gas holder level indicates by-product gas availability at any instance. If the gas holder level increases, then there is a surplus of by-product gas being produced and if the gas holder level decreases there is a shortage of by-product gas. These imbalances are the challenges that the operators face daily.

Figure 2 illustrates each component of the gas distribution simulation model. The simulation model starts by initialising the required variables. These variables include the system operating limits, gas energy density, gas rates, boilers and steam turbine and electricity generation efficiencies. The operating limits ensure that the system is operated in an appropriate and safe manner, for example, the gas holders’ capacity and limits, electricity generation limits, steam turbine and generation ramp up and ramp down rates. Any parameter which ensures that the systems are operated in a safe condition.
The gas energy density measured by a Wobbe analyser should be as recent as possible due to the gas quality deviations which can have a significant influence on the electricity generation per volume gas. The gas rates provide the ability to measure the simulated impact on the facility relevant to the way the plant is controlled or different iteration of the gas control philosophy. The boilers’ efficiency is used to determine steam generation from gas which is used to convert to electricity generation with the steam turbine and generator efficiency.

The initiated variables are fed with the actual gas availability data into the simulated control philosophy. Figure 3 illustrates a flow chart of the simulated time steps within the control philosophy component. For the first time step the initial conditions are used. The actual gas availability data of the following time step is added to the initial conditions. This data includes gas holder levels, gas flared, and electricity generated which are converted back to thermal energy.
generation. The thermal energy is then distributed according to the control philosophy and the initial energy distribution. Once the energy is distributed then it is converted to either the gas holder level, gas flared or electricity generated.

An energy balance ensuring the conservation of energy is done within each simulated time step. This concludes the initial simulated time step. For the rest of the time steps the same process is repeated however the previous time step’s distribution is used rather than the initial conditions. The control philosophy logic is the system improvement’s impact simulated for. Different iterations and versions can be compared with one another using classes for version comparisons.

The time increments of the simulation model should be small enough to accurately capture the physics of the system. Thus, the driving factor for the time increments is the tempo by which by-product gas can be produced. This tempo is generally high and requires a time step of 30 seconds or less. Another gas balance needs to be completed after all the time steps are simulated. It is critical that no energy is lost, or additional energy gained within the simulated time. The sum of the energy flared, stored in the gas holder and electricity generated should be equal to energy into the system over the entire period.

The final step is to include a method to measure the impact of the simulated gas philosophy. This model can include the actual monetary impact using the gas rates. As long as a definite comparison can be made between the simulated control philosophy and either the actual data or a previous iteration of the gas control. This part allows for proving safe operation and a method to find the ideal control before actual implementation.

![Control philosophy flow chart](image)

**Figure 4: Control philosophy flow chart**
5. CASE STUDY

5.1 Production and consumption prediction correlations

A case study was performed to illustrate the effectiveness of the proposed simulation model on a South African steelmaking facility. Both the production and consumption prediction models and by-product gas distribution model were implemented. The facility produces iron and steel with a blast furnace and BOF. On the facility, only COG and BFG is reclaimed and distributed to various consumers as by-product gas. The facility is extensively trying to reduce production costs to regain a competitive position in the market.

The model was constructed using rolling yearly, month and weekly linear regression models. A daily correlation model was also used. The model calculated a COG and BFG production prediction based on the planned iron and coke production. Similarly, the model estimated COG and BFG consumption prediction based on the expected production of the plants which consumes the gases for production. The surplus is the difference between the gas produced and consumed. Beneficial provisions can be made by knowing the surplus gas availability.

The COG and BFG surplus predictions are illustrated in Figure 5 and Figure 6. A forecast for one month was made based on the yearly, monthly, weekly and daily models. The actual surplus by-product gas was superimposed alongside the predictions for comparisons. The yearly prediction performed the best in both the COG and BFG cases. Similarly, the daily prediction model had the poorest performance in both cases. The prediction models struggled to predict the variances found in the actual data.

![Figure 5: Yearly, monthly, weekly and daily surplus COG prediction vs actual](image-url)
Figure 6: Yearly, monthly, weekly and daily surplus BFG prediction vs actual

The prediction models average daily error vs average daily Std Dev. are illustrated in Figure 7. The error was calculated as the percentage difference between the actual surplus gas and the prediction. A reasonable prediction would result in a low error and Std Dev. A high error indicates that the model is generally inaccurate whereas a high Std Dev suggests that the prediction model struggles to predict day to day variances.

The yearly COG prediction model had the lowest error and Std Dev. combination. The rest of the COG prediction models performed in the same regions with relatively high errors and Std Dev. In the BFG prediction models, the daily and weekly models performed the best. However, the other prediction models did not differ much regarding the error.

The Std Dev. were much more scattered than the COG. For example, the yearly BFG model’s daily error was slightly lower than the daily and weekly’s but had a scientifically higher Std Dev. The COG prediction varied more than the BFG predictions. However, the actual day to day variances was much more than both prediction models. This is highlighted in Std Dev. of the models.

Figure 7: By-product gas prediction models’ error vs Std Dev
5.2 By-product gas distribution system improvements

The gas distribution simulation model was implemented on the same steelmaking facility. The facility has two gas holders, one for the BFG and the other for COG. An improved BFG surplus gas control philosophy was developed in correspondence with the plant personnel. This control philosophy was designed with operation parameters and safety constraints. The plant did not have an automatic controller regulating the surplus by-product gas. Instead, excess by-product gas was controlled manually. The goal of the new control philosophy was to improve the facility’s actual electricity generation by reducing the by-product gas flaring. A shift from passive to active control would allow for increased electricity generation.

The simulation was developed to test and possibly refine the controller on the actual system, without the danger of damaging any infrastructure. Actual system characteristics were incorporated into the simulation. The simulation consisted of four steps namely, variables initiation, gas control philosophy, gas balance and impact comparisons. The impact comparisons compared different iterations of the control to provide the safest control philosophy with the best improvement impact.

Figure 8, Figure 9 and Figure 10 illustrates how the simulated control philosophy performed against the manual control. In manual operation, the constant variances in the BFG availability caused the operator to generate electricity conservatively. This is to ensure that the gas holder remains at safe operating levels preventing the holder to drop too low too fast. The operators testified that they have too much to focus on to actively distribute surplus gas. They would instead generate less additional electricity which provides them with a buffer should the gas production unpredictably drop or consumption increase.

The simulated controller does control actively and not passively. Active control has the advantage of acting instantaneously providing safe control at a less conservative level. Any increase in the BFG availability is utilised by generating more steam for additional electricity. Similarly, the electricity generation would instantaneously decrease should the surplus gas decrease.

The simulation model displays the same dynamics of the actual system. Both the actual and simulation models start on the same instance, gas holder level, electricity generation and gas being flared. In the cases where the gas holder level increased so does the simulated electricity generation resulting in the simulated gas holder level increasing slower than the actual. In the cases where the actual gas holder reaches the flaring set point, the simulated gas holder generally reaches it later. It is due to the simulated control that generates more electricity causing the holder level to be operated on a lower average level.
The simulation model proves that the proposed control can control the electricity generation, boilers and gas holders within safe operating parameters. The gas holder did not drop below 20% or go above 85%. Any additional gas was flared keeping the gas holder below 85%. A minimum of 5 MW electricity was generated at all times which is the facility’s emergency load. No more than the electricity generator’s maximum capacity were reached. An energy balance between the actual and simulated model was done to prove that no energy was added or removed by the simulation model.

The steelmaking facility was satisfied with the simulated control philosophy. Forecasting proved possible flaring reductions of ± 400 GJ per day. Permission was granted to implement the control into SCADA system. The implementation period was relatively fast due to the control being simulated which required only a syntax change to the SCADA. Additionally, the new insights gained by the simulation model allowed the plant personal more insight in the gas holder utilisation and electricity generation dynamics.

6. RESULTS

The consumption and production prediction models proved that at best a crude prediction was made of the surplus by-product gas availability. Both the generally high average daily error and Std Dev. of the models indicated that there is room for improvements. Variations in the actual surplus gas that was missed in the
prediction model can be the result of unreliable machinery. This is due to the model using planned production, the variations in the actual data mean that the planned production could not consistently be achieved.

The system of by-product gases in the steelmaking process is complicated. Both the enormity and deteriorated condition of the system are among the factors that make prediction models challenging to construct. The daily and weekly models will perhaps be more suitable for short-term predictions as it provides the most recent system condition. The model can be used as is for crude indications of surplus gas availability. For example to plan maintenance stops depending on gas availability potentially reducing natural gas consumption. Future work could entail combining the different prediction models for a more comprehensive forecast.

It was proved that the by-product gas distribution simulation model can be used to test system improvements before actual implementation. The dynamic behaviour of the actual system was accurately reproduced. Which allowed the facility to implement a system improvement knowing that it is safe and what the actual impact would be before implementation. The simulation proved that the system improvement has the potential to save in the order of 400 GJ of thermal energy per day. This translates to 25 MWh electricity which is approximately R20 000 cost reduction at a South African steelmaking facility.

Actual plant data was analysed to prove the effectiveness after the by-product gas distribution model was implemented. The model was challenging to measure due to many different systems influencing the plant gas consumption. These systems caused noise making it difficult to calculate the actual result that the by-product gas distribution model had. Thus, 5 different baseline models were constructed, 4 of the 5 models were in a band of R400 000 with two of the models, 1 and 4, in the middle of the band. Baseline model 1 and 4 proves a saving of R800 000 over 60 days which is R13 500 per day. Figure 11 illustrated the accumulated monetary benefit of each baseline model and the actual utilisation of the gas holder over 60 consecutive days.

![Figure 11: Accumulated monetary by-product gas distribution model benefit](image)

A comprehensive simulation model can be developed by coupling the prediction and distribution model. The coupling would provide a predicted gas availability input for the distribution model. This type of model would be beneficial for forecasting monthly gas utilisation. Therefore, allowing predictive gas distribution modifications for optimal energy utilisation. The prediction model needs to be more reliable and have a higher prediction resolution.

7. CONCLUSION

Simulating by-product gas behaviour in the South African steelmaking industry is complicated due to the enormity of the systems and the dated condition of the equipment. A gas network simulation model can provide steelmaking facilities with a platform to develop, test and expand system improvements without putting fragile and dated machinery at risk. The proposed model proved that predicting by-product gas surplus availabilities are difficult and complicated. Results from the case study demonstrated that system improvements on the gas distribution network could save the facility around R20 000 a day. Actual results proved a saving of R13 500 per
day thus justifying the need for an accurate and reliable simulation platform to test, promote and validate similar system improvements.

8. REFERENCES


