ENERGY COST REDUCTION IN SECONDARY STEEL MAKING THROUGH IMPROVED PRODUCTION PLANNING

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ABSTRACT

The international steel manufacturing industry is under financial pressure due to a surplus in production flooding the market. In a South African context, steel producers deal with additional challenges such as the increasing cost of raw materials, electricity tariffs, wages, and transportation. Steel manufacturing facilities consume approximately 18% of industrial energy worldwide. Further research indicates that between 20% and 40% of steel production costs originate from energy expenses.

In this paper, production scheduling is used in a novel way to reduce energy cost. The developed solution uses various energy awareness implementation techniques and supporting systems to assist production planners with scheduling tasks. Opportunities for energy cost reduction by improving production planning methods are evaluated, and suggestions are made for production planners to adapt schedules to reduce energy costs.

The solution is applied at a secondary steel making facility, and is used to manage electricity costs by utilising time-of-use tariffs. Electrical energy intensity of different steel qualities are evaluated, and production is scheduled accordingly. The practical implementation indicates an annual cost reduction of R 1.5-million. This solution makes provision for the addition and integration of other potential production scheduling solutions.

This work was sponsored by ETA Operations (Pty) Ltd

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1. BACKGROUND

1.1 The steel manufacturing industry

A surplus in international steel production has been reported to be flooding the market, placing the international industry under pressure [1, 2, 3, 4, 5]. Further reports indicate that the surplus most likely originates from China, where more steel is produced than consumed, with the remaining steel being exported to the rest of the world [6]. Of the 1 630 million tonnes of steel produced in 2016, China produced 49.6%, but only consumed 45.0% [7]. South Africa produced 0.4%, but only consumed 0.3% [7], indicating that they are a minority player in the international market, and easily affected by the actions of majority players.

Figure 1 (compiled from data obtained from the World steel association [7]) provides a summary of steel production versus consumption for major steel producing countries, and how they compare to South Africa. The comparison between production in Figure 1.a and consumption in Figure 1.b indicates the oversupply of 4.6% by China (approximately 75 million tonnes - more than 12 times the steel produced by South Africa). Due to subsidies provided to the steel manufacturing industry by the Chinese government, steel imported from China is often cheaper than countries can produce for themselves [8, 9].

![Figure 1: World steel production vs consumption for major countries and South Africa in 2016 [7]](image)

Additional factors constraining the South African steel manufacturing industry include the increasing cost of raw materials, electricity tariffs, wages, and transportation [9]. These irregular increases are reported to be a result of a weakening economy and exchange rate volatility [10]. Such challenges reportedly resulted in a steel production decrease in South Africa from 9.7 million tonnes in 2006 [11] to 6.1 million tonnes in 2016 [7].

1.2 Energy consumption in steel manufacturing

The iron and steel industry is one of the most energy intensive energy consumers in the industrial sector, consuming about 18% of the sector’s energy [12]. Research indicated that energy costs contributes 20% to 40% of steel manufacturers’ operational costs [13, 14]. It was also indicated that the energy consumption of an older plant can be reduced by up to 60% by using technological improvements [13]. It is thus expected that plants with resistance toward technological solutions would have the potential to reduce energy costs, highlighting it as a critical area of focus.

1.3 Steel manufacturing processes

Different approaches exist for steel making. The most popular methods are the electric arc furnace (EAF) - basic oxygen furnace (BOF) - blast furnace (BF) - BOF process [12, 13], as depicted in Figure 2 [13]. The EAF-BOF method is used for 25% of applications, and the BF-BOF process for the remaining 75% [13]. An open hearth furnace is a rarely used method for steel making (about 0.5% of production) [12].
This paper focuses on an application in the BF-BOF approach, which will be discussed in more detail. It is, however, of importance to note that the EAF-BOF process makes use of a batch production process, making it possible to induce buffers into the production process. Such buffers are useful for production planning initiatives.

The BF-BOF route typically consists of preparatory processes, such as a coke plant, sinter plant, and hot blast stove. These processes provide some of the elements used in the BF to produce liquid iron. A BF is charged with iron ore, fluxes, and fuel, which works together to establish combustion, and the melting of iron ore to produce liquid iron. This iron production process is continuous, and delays can therefore not be induced if required [15, 16, 17].

Liquid iron is then moved to the BOF where it is refined to liquid steel by blowing oxygen into it. The oxygen removes impurities, and adjusts the carbon content as required for the steel quality [16]. Liquid steel is further refined to the steel quality requirements at the secondary metallurgy (SecMet) section [16]. During the refining at SecMet, the liquid steel temperature decreases due to the addition of material at ambient temperature.

Ladle furnaces are used to increase the temperature of steel to a specific set point before it can be casted [18, 19]. A ladle furnace uses a three-electrode system, and is thus a large consumer of electrical energy. The main focus of the case study discussed in this paper is on the energy cost reduction of the ladle furnaces by means of improved production planning.

Liquid steel is sent to the continuous casters (ConCast) after it has reached its required specifications at SecMet. It is then casted through a tundish, continuously solidifying it into slabs at the bottom of the caster. More than one consecutive cast of the same steel quality is called a sequence. The interruption of such a sequence has critical cost and production delay implications [19].

This is a very important constraint to be considered when performing production planning on a steel plant. Other factors to be considered during production planning at such a facility have been reported to be production delivery dates, limitations of the casters, the requirements of the rolling mills, etc. [19].

1.4 Problem statement

Research by Dondofema et al. indicates that limited research on improved production processes have been published in South Africa (five publications by the South African Institute of Industrial Engineering) [11]. Dondofema et al. also referred to the review of South African industrial engineering by Van Dyk, indicating that few industrial engineers are employed by the iron and steel industry in South Africa [11, 20].

A problem exists in the South African steel making industry to remain profitable amid challenging international and local conditions. The high contribution of energy towards the operational cost of steel manufacturing.

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Figure 2: Different routes for steel production [13]

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highlights it as a key area of focus. Production planning has been identified as a possible tool that can be utilised to reduce energy costs without negatively affecting production.

2. EXISTING RESEARCH FOR PRODUCTION PLANNING TO REDUCE ENERGY COST

Production planning is most commonly performed manually by experienced production planners [21]. The problem is, the complexity of production planning is continuously increasing due to higher production requirements, a wider variety of products, unstable orders from customers, and increased pressure to reduce production and energy cost [21]. Short-term production planning is gaining attention as a method to reduce energy cost. This has been described as an “enabler” for improved energy consumption [21].

The concept consists of taking energy consumption into consideration when performing general production planning – something that has not been done at the case study plant in the past. This makes it possible to predict and improve consumption trends, thereby managing energy consumption with the result of reducing energy costs [21].

As part of the review of previous work relevant to this study, the following fields were critically evaluated:
- Production scheduling with the focus on energy cost efficiency [22, 23, 24]
- Production scheduling with the focus on production efficiency [25, 26, 27]
- General iron and steel making energy initiatives [1, 11, 12, 28, 29, 30]
- Steel plant production scheduling research [31, 32, 33, 34, 35]

The most relevant of this research is the concept of electrical load shifting by utilising varying electricity prices. This is a well-known technique in various industries to reduce energy costs without affecting production [21]. It is typically done by making use of available buffers in a process to shift electrical energy intensive processes to less expensive time periods.

A study by Merkert et al. discusses the correlation between energy and scheduling, and highlights the value of electrical load shifting [21]. The study discusses the possibility of using the energy intensiveness of different batches in a process to shift electrical load, rather than inducing buffers in the process [21]. Existing research on performing electrical load shifts on ladle furnaces made use of the EAF-BOF production process [19, 36].

As discussed in section 1.3, buffers can be induced in the EAF-BOF process, making it possible to schedule delays during more expensive electricity time periods. This paper, however, uses a new approach of combining these concepts to perform an electrical load shift on the ladle furnaces in a BF-BOF production process, where the continuous production of liquid iron restricts the induction of delays in the process.

The concept of using the energy intensity of batches, as suggested by Merkert et al., will thus be used to reduce peak time electricity consumption by evaluating the energy intensities of different steel qualities [21]. Even though the BF-BOF process is not considered as a batch process, this novel approach suggests viewing a sequence of steel qualities as a “batch”, and using the energy intensity of different batches to reduce energy costs.

3. A COST MODEL FOR PRODUCTION PLANNING IN SECONDARY STEEL MAKING

3.1 Overview of the cost model for production planning

The cost model developed for this study forms part of a larger integrated production planning model, as presented in Figure 3. This paper only focuses on the development of a single initiative, and the implementation thereof. The integration between initiatives in the methodology of Figure 3 will not form part of the discussion or the implementation on the case study plant. The steps in the methodology that will be discussed are the identification, evaluation, implementation, and revision of a production planning initiative.
The output of the model is a set of “tools” for production planning to adapt the latest production schedule to reduce energy costs. It is important that other implicated costs be considered when implementing a solution. The steps in the methodology are discussed in more detail in this section. Before the steps are configured, a proper understanding of the production planning process of the specific facility is required. This includes continuously gathering the latest production planning information.

3.2 Identify production planning initiative

After obtaining the required production planning information, the first step in realising energy cost reduction is to identify an energy cost saving initiative. This can be done by means of various methods, such as investigating literature for existing solutions in other industries, or at other steel plants. In this case, the literature reviewed in section 2 led to the identification of an electrical load shift on the ladle furnaces by using the variation in electrical energy intensity of steel qualities. After an initiative has been identified, it has to be determined what the status of the initiative is on the facility.

It could be possible that the implementation of such an initiative has been attempted in the past, but is no longer in effect. This will serve as an indication of what the major risks are for implementing the solution. Alternatively, it has to be established why such an initiative has not been attempted before. This will include the identification of the risks and limitations of the initiative in a facility’s unique conditions. Once the limiting factors have been identified, historic data should be collected to confirm the information obtained from discussions with the facility personnel.

Previous implementations of similar initiatives, and the risks and limitations that were identified, will serve as an indication of what data is required. The historic data that is collected should be representative of different conditions on the facility in order to be representative of the potential that exists for the initiative.

3.3 Evaluate production planning initiative

Once the initiative and its risks and limitations have been identified, it is important to evaluate the energy cost saving potential at the specific facility. The first part of this step is to evaluate the historic data that was collected. Different data analysis techniques can be used, depending on the conditions of the facility and the requirements for the initiative. From the evaluation of the data it should be possible to determine to what extent the initiative is already implemented on the plant. It can also be determined which conditions are favourable for optimal performance. This will serve as an indication of the theoretical potential benefit.

In this case, the electrical power profile will serve as an indication of the variation in electrical energy consumption throughout a typical day. Correlating this data with the steel qualities that were being processed at that instance will serve as an indication of the energy intensity of the steel quality. It has to be evaluated as to whether the energy intensity of a steel quality is the same on a recurring basis by identifying and evaluating several such instances.
After determining the theoretical potential benefit, the practical constraints that could prevent the implementation of the initiative need to be evaluated. In this case, energy intensity of steel qualities have never been considered as an input factor when performing production planning. Personnel was thus resistant towards such a solution, and the concept first had to be proven to them theoretically. This also led to the use of an awareness-based approach, rather than the development of an automated system.

The next factor that has to be considered is to determine the theoretical potential benefit. It is, however, important to make use of methods that can be used for real-time benefit quantification, as this will be required when the integration between initiatives is done. This quantification method also includes compiling a baseline for the evaluation of the initiative after implementation.

### 3.4 Implement production planning initiative

After it was determined whether scope exists for the implementation of the initiative on the facility, and the risks and limitations are known, the implementation step can be initiated. This consists of developing a solution and implementing it. The limitations and practical constraints that were identified for the initiative and the specific facility, will serve as a guide for the type of implementation approach that should be followed.

For most production planning initiatives, it is preferred by plant personnel to not make use of automated solutions. This is due to the complexity of scheduling and the human decision-making that is required. As part of the awareness-based approach production planners should be provided with assistive tools to use when performing production planning. The tools can be used to compare different scenarios, and flag opportunities for cost savings.

Additionally, the use of energy awareness is a useful tool to ensure that all parties are on-board with the implementation of the initiative. The awareness-based approach was also used to inform different parties of the benefits of the initiative, and to provide feedback on the progress and performance. Once all of the tools and assistive systems have been developed, it has to be implemented.

### 3.5 Revise production planning initiative

It is critical to regularly evaluate the performance of the initiative and to provide feedback to plant personnel. Discussions with the involved parties should also be used as inputs to adapt the system and the approach. The evaluation will make it possible to identify and adapt to practical limitations. Feedback on the progress and performance will also serve as a further awareness tool. The same evaluation techniques used in section 3.3 should be applicable when monitoring the performance of initiatives in this step.

### 4. CASE STUDY RESULTS

#### 4.1 Facility description

The methodology was applied to a steel making facility. A simplified layout of the facility is presented in Figure 4. The facility makes use of the BF-BOF production process. The steel plant consists of three BOFs, a SecMet section with a vacuum degasser and two ladle furnaces, and ConCast with two casters. Depending on the steel quality requirements, liquid steel is either sent to the vacuum degasser from the BOF (referred to as “route 3”), or directly to the ladle furnaces (“route 2”).
The facility makes use of time-of-use electricity tariffs, which vary depending on the time of day and the season. This makes it possible to perform an electrical load shift by reducing electrical energy consumption during more expensive peak times, and increasing it during the less expensive off-peak and standard times. The facility also consumes various other energy sources and utilities during this process such as steam, natural gas, compressed air, nitrogen, argon, and oxygen.

On this facility, a production planner is responsible for compiling a priority list three days in advance for the required steel qualities and its quantities. This is then provided to the scheduler, who is situated at ConCast. The scheduler is responsible for scheduling steel production throughout the day, ensuring that the steel is provided to ConCast on time, and that it is of the correct quality and temperature. The scheduler is in regular contact with the production planner and the operators in the different sections of the plant.

4.2 Practically identify production planning initiative

The first step of the methodology is the identification of an energy cost saving initiative. This was done from the literature review in section 2 of this paper. An electrical load shift on the ladle furnaces using the energy intensity of different steel qualities was identified. This focus is further justified by the analysis of the cost distribution of energy sources on the plant, as presented in Figure 5.

Figure 4: Basic layout for the case study plant

Figure 5: Steel plant energy cost distribution for case study facility
Figure 5.a presents the energy / utility cost distribution for 2016, from which it is seen that the largest cost contributor is oxygen (42%), followed by electricity (37%). In Figure 5.b, however, the winter months in 2016 are isolated, and it is seen that the higher electricity cost during these months increased the contribution of electricity to 43%, making it the largest cost consumer on the plant.

As per the methodology, the possibility of implementing the identified initiative was discussed with plant personnel. It was found that there has been some analysis done on the differences in electrical energy consumption for steel qualities, but it has not led to the implementation of any initiatives. There has also been several evaluations and initiatives to improve the efficiency of the ladle furnace electrodes. No attempts have, however, been made to reduce peak time electricity consumption.

Since no restricting factors could be identified from past projects, it was necessary to obtain sufficient data to properly assess the potential of the initiative. The data listed in Table 1 was collected for a period of 1 year. It is important to obtain a wide variety of available data to properly assess the potential of the initiative.

<table>
<thead>
<tr>
<th>Data collected</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>Half-hourly power consumption of each ladle furnace</td>
</tr>
<tr>
<td>Steel quality description</td>
<td>Coded description of the steel qualities</td>
</tr>
<tr>
<td>Time spent at ladle furnace</td>
<td>Duration of heats at the ladle furnace</td>
</tr>
<tr>
<td>Ladle furnace used</td>
<td>Which ladle furnace was used</td>
</tr>
<tr>
<td>Date and time of heats</td>
<td>When the heat took place</td>
</tr>
<tr>
<td>Production route followed</td>
<td>Whether route 2 or route 3 production was used</td>
</tr>
<tr>
<td>Start temperature</td>
<td>Temperature at which steel was received at SecMet</td>
</tr>
<tr>
<td>End temperature</td>
<td>Temperature at which steel was required at ConCast</td>
</tr>
</tbody>
</table>

As part of the investigation of the process, it was found that a unique code is used for the identification of different steel qualities. The digits in the code represents specific requirements of the steel. The exact meaning of the different codes are withheld due to confidentiality reasons. Differences in steel quality requirements are expected to result in the variation of energy intensity for different qualities.

Thus, the idea is to use this to shift electrical load into off-peak periods by scheduling lower electrical energy intensive steel qualities in peak times. This had to be verified by an analysis of the available data in the next step of the methodology.

4.3 Practically evaluate production planning initiative

The collected historic data was analysed to determine whether enough variance existed between the electrical energy intensity of different steel qualities to verify the concept. An example of such an analysis is presented in Figure 6 in the form of frequency curves. The energy consumption of two random steel qualities is compared, from which it is seen that there is a correlation between steel quality and electrical energy consumption. This is typically due to differences in the additives (aluminium, silicon, etc.) and casting temperature requirements of different steel qualities. It is further seen that the difference in energy consumption for the two steel qualities is about 1.3 MWh per heat, providing sufficient variation to implement a load shift initiative.
The average electrical energy consumption at the ladle furnaces was determined for each steel quality that was produced in the past year, from which a database of electrical energy intensities for steel qualities was compiled. This database was used to plot the expected power profile and related energy cost for a planned schedule on a given day. An example is presented in Figure 7 for a randomly selected day.

By considering the energy consumption of steel qualities, the planned schedule was adapted manually. The purpose was to attempt to reduce peak time energy consumption by switching around steel qualities throughout the day without affecting the day’s production outputs. The main practical constraints that were identified and had to be taken into consideration were the level of liquid iron available, and that a sequence of a steel quality could not be interrupted at ConCast.

The power profile and related cost for the manually adapted schedule is presented in Figure 8. By using the winter electricity tariffs for the specific plant, the maximum theoretical potential cost reduction for the specific day was calculated as about R 35 000. This verified that the reduction of energy cost by scheduling steel qualities based on their energy intensities, is theoretically possible.

In order to quantifying the benefit of the initiative practically, it was decided to make use of average daily power profiles for weekdays, Saturdays, and Sundays, as presented in Figure 9. Average power profiles for a 6 month period were used due to the lack of a repetitive power profile in the past. This is due to the energy intensity of steel qualities historically not forming part of production planning inputs.
4.4 Practically implement production planning initiative

As previously discussed, the initiative was implemented using an awareness-based approach. The focus was on providing schedulers with the required tools to adapt production schedules to take the electrical energy intensity of steel qualities into account. The first step was thus to inform all of the involved parties of the initiative, and to provide production planners and schedulers with the necessary information to make informed decisions.

The database of calculated energy intensities for different steel qualities was used to classify the qualities into preferred time-of-use periods. Colour coding was used as a quick reference to determine which steel qualities to schedule in which period. A steel quality indicated in red was considered to be safe to produce in peak ("red") time. The sheet provides an alphabetical list to easily find steel qualities, as well as categorised lists to indicate the order of preference.

Regularly produced steel qualities were split from less-regularly produced qualities to simplify the reference process. This dataset sheet enable schedulers to easily determine what steel qualities are preferred during specific times of the day. An example of the summary for route 2 steel qualities is presented in Figure 10. A similar summary page was provided for route 3 steel qualities.

Figure 9: Average daily power profiles used for baseline

It is recommended that the baseline methodology make use of an adjustment method to account for differences in production during the baseline and assessment periods. This is, however, out of the field of study for this paper, and is not discussed in detail.
Additionally, an online interface was developed for schedulers to use as a tool to estimate the effect of changes that can be made in advance. The interface used the blast furnace production rate, current liquid iron level, and current production schedule as inputs. A second production schedule could then be compared to the original schedule to evaluate what the effect of changes would be. Figure 11 provides an example of the inputs required by the system.

An example of the output provided by the system is presented in Figure 12. The output compares aspects of the original and revised schedules. These aspects include the predicted liquid iron level, expected energy cost distribution over the time-of-use periods for the next three days, and the total estimated energy cost. The scheduler can thus estimate the effect of changes in the schedule in advance, and pro-actively adapt the schedule to reduce the cost of steel making.
The project was implemented for a three month period, from 1 July 2017 to 30 September 2017 (two winter months and one summer month). The effect was evaluated on a weekly basis by using the discussed baseline approach. An example of the weekday profile for one week of the implementation is presented in Figure 13. This figure provides the weekday baseline profile, the actual profile, and the adjusted (scaled) baseline profile.

It is seen from this result that the actual power consumption reduced during the morning peak time, leading to a successful energy cost reduction by means of a load shift. This method was applied to every week in the assessment period, calculating the weekly energy cost savings. During this time a total cost saving of about R 500 000 was achieved, as indicated in Table 2 for each month.

<table>
<thead>
<tr>
<th>Month</th>
<th>Energy cost saving</th>
</tr>
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<tbody>
<tr>
<td>July 2017</td>
<td>R 240 000</td>
</tr>
<tr>
<td>August 2017</td>
<td>R 155 000</td>
</tr>
<tr>
<td>September 2017</td>
<td>R 105 000</td>
</tr>
<tr>
<td>Total</td>
<td>R 500 000</td>
</tr>
</tbody>
</table>

From the monthly energy cost savings in Table 2, it is seen that the achieved benefit during September 2017 was significantly less than during the two preceding months. This is due to the reduced summer billing tariffs for this month having a smaller difference between off-peak and peak time cost. It is estimated that the annual effect...
of this initiative is about R 1.5-million, by considering the results for the different seasonal tariffs in the implementation.

4.5 Practically revise production planning initiative

The final step of the methodology is to revise the implemented system and assistive tools. During this step, the performance of the initiative was evaluated and discussions with plant personnel were used to adapt the system accordingly. Revision of the implementation strategy took place continually throughout the process in order to take the experiences and feedback of plant personnel into account.

Feedback to plant personnel was provided in the form of weekly performance reports, indicating the effect that the initiative had had over the past week. The main indication in this report was the resulting power profile presented in Figure 13. Production schedulers also received daily feedback reports to evaluate the performance for the previous day and week-to-date.

From the revisions, limitations were identified and the approach was adapted accordingly. The most notable adaptions to the approach included:

- the separation of route 2 and route 3 steel qualities in the database sheets;
- the inclusion of the blast furnace production rate and liquid iron level in the online interface; and
- the addition of daily feedback reports for schedulers.

These changes were made at various times during the implementation, and were made possible by properly monitoring performance on a continual basis.

5. DISCUSSION OF RESULTS

The results indicate that it is possible to make use of production planning to reduce the cost of energy on a steel plant. A sequence of steel qualities was considered as a “batch”, and the suggested approach by Merkert et al. in section 2 was used in a novel way to schedule batches according to their energy intensity [21]. This resulted in an electrical energy cost reduction of about R 500 000 (over three months). This unique approach makes it possible to perform a load shift on a ladle furnace in a steel plant using the BF-BOF production process.

The methodology is designed to integrate various production scheduling initiatives, while this paper only focusses on the implementation of one such an initiative. The result is used to validate the use of the individual solution per initiative before integrating multiple initiatives. It was found that production scheduling takes various factors into account, such as production rates, the available liquid iron levels, steel orders, etc., which have to be considered as part of the solution. The focus of this study was to include energy consumption as one of these factors.

6. CONCLUSION

This paper presents the development and implementation of an initiative for reducing energy cost in steel making by means of production planning. The discussed methodology forms part of an integrated cost model. The model is practically implemented on the ladle furnaces of the SecMet section of a steel plant in the BF-BOF production process, with the purpose of managing the power profile around time-of-use electricity tariffs. This makes it possible to reduce the energy costs without affecting production.

An awareness-based approach is used for the implementation, resulting in a cost reduction of R 500 000 over a three month period, and an estimated annual effect of R 1.5-million. The main focus is on scheduling steel qualities based on their electrical energy intensity. This unique implementation validates the novel method used for implementing a cost saving initiative by adapting production planning.

REFERENCES


