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SHORT TECHNICAL NOTE

Development and Application of an Integrated Approach to Reduce Costs in Steel Production Planning

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Abstract

Steel manufacturing is critical for industrial development and contributes greatly to the world's energy consumption. A worldwide oversupply of steel has led to increased competition in the market, requiring developing countries to function on the same level as developed countries. Since energy use contributes between 20 and 40% of steel production costs, a reduction in energy consumption will result in decreased production costs, and increased competitiveness. This study therefore focuses on the development and application of an integrated approach to reduce energy costs in steel production planning. This is a new solution, as a review of existing research indicated that there is a lack of an integrated steel production planning model and application thereof on marginally profitable facilities. The key novelty lies in the integration aspect of the solution — both in terms of integrating different initiatives and different sections of such a facility. The proposed approach provides an opportunity to adapt outdated production planning methods without the use of capital, and simultaneously address resistance from personnel at these marginally profitable facilities in developing countries. The new cost model focuses on the identification, evaluation, comparison, prioritisation, implementation, and integration of steel production planning initiatives. The integration determines the effect that individual initiatives have on each other, and dynamically prioritises solutions by combining theoretically quantified benefits with practical constraints. Two initiatives were implemented on a South African facility, with an estimated cost benefit of US\$0.83 million per annum (approximately R13.3 million per annum).

Keywords Steel production planning · Integrated cost model · Energy cost efficiency · Prioritisation model · Benefit quantification

Background

The international steel manufacturing industry is experiencing challenges due to surplus production flooding the market (Breytenbach et al. 2017; Niekerk et al. 2017; Popescu et al. 2016; International Trade Administration Commission of South Africa 2016). In 2019, 1 870 million tonnes of steel was produced worldwide, of which only 1 545 million tonnes was used. In the same year, South Africa produced 5.7 million tonnes of the world's steel, which was about 0.3% of the global production (World Steel Association 2020). Figure 1 provides a comparison of South Africa's steel production and usage with that of the world's major steel-producing countries (World Steel Association 2020).

South Africa is a minor role player in the steel industry, making it vulnerable to the decisions made in other markets (Roberts and Zalk 2004). Apart from the challenges faced internationally due to an oversupplied market, South African steel producers also have to manage additional problematic factors. These factors include the increasing cost of raw materials, higher electricity tariffs, irregular wage inflations, and a hike in transportation costs (Roberts and Zalk 2004; Merchantec Research 2015). Such challenges are reported to have reduced the country's steel production capacity from 9.7 million tonnes in 2006 to 6.6 million tonnes in 2014 (Dondofema et al. 2017). The steel industry

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Exchange rate of R15.94 = US\$1, as on 3 January 2022

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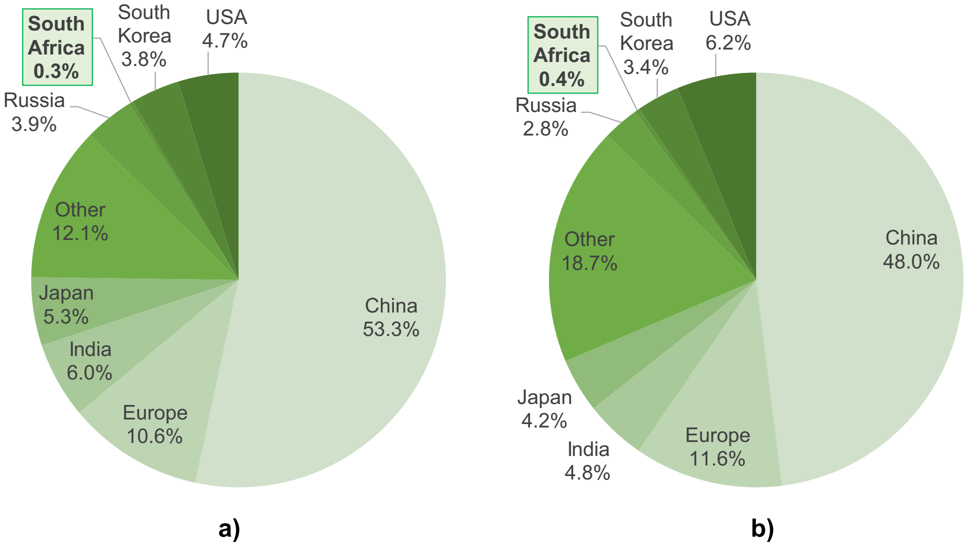

Fig. 1 Steel production (**a**) and usage (**b**) for major countries and South Africa (2019) (World Steel Association 2020)

is also experiencing the negative effects of COVID-19, with reports that the industry in South Africa might not be able to recover.[1]

Steel manufacturing facilities are reportedly responsible for 18% of industrial energy consumption in the world (He and Wang 2017). Further research indicates that between 20 and 40% of steel production costs originate from energy expenses (World Steel Association 2018; Asia Pacific Partnership for Clean Development and Climate 2010). It is also reported that, in some cases, energy efficiency improvements of up to 60% have been achieved, compared with plants' original states (World Steel Association 2018). Furthermore, a reduction in energy consumption could lead to decreased production costs and increased competitiveness.

A method for improved energy efficiency, that has obtained a great deal of attention in recent decades, is short-term production planning (Merkert et al. 2015; Biel and Glock 2016). The concept considers energy consumption as an input factor for production planning, making it possible to forecast and improve consumption trends.

Research by Dondofema, Matope and Akdogan (Dondofema et al. 2017) indicated that limited research on improved production processes has been published in South Africa (only five publications by the South African Institute of Industrial Engineering (Adams and Petrarolo 1993; Pretorius and Visser 2001; Mpanza et al. 2013; Mufamadi and Hatting 2013; Hartmann et al. 2014), which did not focus on addressing the same problem as identified in this research). This serves as an indication of the lack of focus on production optimisation in steel manufacturing facilities in the country, which could be a contributing factor to the declining performance of the industry.

There is a need to adapt outdated production planning methods without the use of capital, while simultaneously addressing the concerns of personnel at marginally profitable facilities in developing countries.

Production planning is commonly performed manually by experienced production planners (Merkert et al. 2015). The complexity of production planning is continuously increasing, making it vital for production planners to be receptive to new approaches and tools that can be used to assist in compiling production schedules. Resistance towards change and technological solutions further complicates the adaption towards the challenges in production planning processes (Deloitte 2012). To address this, behavioural changes (such as using an International Organisation for Standardization (ISO) 50,001-based approach) can be introduced, rather than introducing automated solutions.

This solution will be addressed in this article by first evaluating the existing research to identify what possible solutions already exist that can be used, and to formulate the research objectives based on this review of literature. The development of the integrated cost model will then be demonstrated, followed by a discussion of the practical implementation thereof, and the results from this implementation.

Evaluation of Existing Research

New challenges due to the competitive market and changing needs of customers lead to increased complexity of production planning tasks. Production planners are expected to adapt to these challenges, which is difficult in the absence of assistive tools. Resistance towards change and technological solutions also restricts the adaption of these challenges.

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[1] https://www.engineeringnews.co.za/article/pandemic-dashes-hopes-for-a-domestic-steel-sector-turnaround-2020-06-12

The research conducted in this article therefore focuses on using an ISO 50,001-based implementation strategy. This is done with the purpose of addressing the resistance towards automated solutions, which is a challenge experienced by marginally profitable facilities.

Several studies focusing on energy efficiency and production planning were critically evaluated. Relevant studies were categorised as follows:

- General steel production energy management
- Steel production planning methods
- Production planning for energy cost reduction
- Production planning for production cost reduction
- Integration of solutions

General Steel Production Energy Management

Existing methods for steel production energy management were evaluated to serve as an indication of how such initiatives in this industry should be approached, as well as what has already been done. The evaluated existing research does not, however, focus extensively on developing a methodology to improve production planning for South African steelmaking facilities. Studies that are focused in South Africa mostly consider energy management strategies or they fall beyond the boundary identified for the research conducted in this article.

Steel Production Planning Methods

Several studies focusing on production planning in the steelmaking industry were evaluated. Most studies use automated solutions and complex mathematical models rather than the ISO 50,001-based implementation strategy used in the research conducted in this article (Pan et al. 2017; Jiang et al. 2016; Fazel Zarandi and Ahmadpour 2009; Karwat 2012). The models were not applied to South African facilities, and technological and capital constraints were not such major role players. The most relevant of these studies is the optimisation of production schedules in a steel production system developed by Karwat (Karwat 2012). Given the lack of capital availability and resistance from personnel to implement such solutions (resulting from a high unemployment rate), an automated solution is not practical in South Africa. The evaluation in Table 1 uses identified criteria to determine the relevance of the identified studies.

In general, the research for production planning on these facilities does not integrate different initiatives. The solutions mainly focus on production without integrating energy cost efficiency. The studies provide valuable guidelines for approaches towards steel production planning but contain important differences from the problem addressed by the research conducted in this article. Several of the methods are also conceptual and do not focus on the practical application thereof by implementing the solutions on a real-world scenario on an actual steelmaking facility.

The results are more idealistic than realistic and do not assess practical constraints. The facilities that these studies focus on are technologically advanced, and the studies do not deal with resistant personnel who oppose the implementation of automated solutions at marginally profitable facilities.

Production Planning for Energy Cost Reduction

Ample work has been done in various industries that use production planning to improve energy cost efficiency. These studies are evaluated in Table 2 to determine their relevance to addressing the identified problem.

These studies were used as an indication of which aspects can be of guidance for steel production planning to improve the focus on energy cost efficiency. From this survey, a few relevant studies considering the concept of energy efficiency as part of the focus when performing production planning were evaluated. It is seen that the concept is becoming more important due to various factors and that it is possible to achieve cost savings by considering energy consumption and cost as part of production planning.

A shortcoming of this research is the lack of applications in steelmaking. These solutions also only focus on improved energy efficiency within certain production requirements and do not simultaneously integrate the improvement of production efficiency.

Production Planning for Production Cost Reduction

A shortcoming of the previously discussed literature was the lack of integration between production efficiency and energy efficiency during production planning. Production efficiency in this study refers to methods used to improve the efficiency at which production outputs are achieved (include cost reduction and production rate improvements), while energy efficiency in this study refers to methods focused on the reduction of energy efficiency for a specific production output.

Existing work that focuses on production efficiency when performing production scheduling was considered in this evaluation. A significant amount of work in various industries has been done on this topic. The studies indicate the importance of proper production planning, and that it has a positive effect on production efficiency. The study by Lochmüller and Schembecker (Lochmüller and Schembecker 2016) considered the optimisation of batch production plants, and the importance of using available equipment capacities. This study, however, was not conducted in the steelmaking industry.

Table 1 Summary of literature related to steel plant production scheduling

Author	Criteria										
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility	Application on a South African case study
Chakravarty, Das and Singh (Chakravarty et al. 2013)	✓	✓	✓	✓			✓			✓	
Dao-fei, Zhong and Xiao-qiang (Dao-fei et al. 2010)	✓	✓		✓					✓		
Karwat (Karwat 2012)	✓	✓		✓						✓	
Lin et al. (Lin et al. 2016)	✓	✓		✓	✓					✓	
Mattik, Amorim and Gunther (Mattik et al. 2014)	✓	✓	✓		✓		✓				
Merkert et al. (Merkert et al. 2015)	✓	✓	✓	✓		✓			✓	✓	
NEDO (New Energy and Industrial Technology Development Organization (NEDO) 2008)	✓	✓	✓	✓							

Table 1 (continued)

Author	Criteria										
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility	Application on a South African case study
PSImetals Planning (Software and for Utilities and Industry, “Totally integrated planning at Isdemir: Hot savings with hot charging”, PSI Software for Utilities and Industry, xxxx)	✓	✓	✓	✓						✓	
Xu et al. (Xu et al. 2012)	✓	✓	✓		✓					✓	

Table 2 Summary of literature related to scheduling that focus on energy cost efficiency

Author	Criteria										
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility	Application on a South African case study
Gahm et al. (Gahm et al. 2015)		✓	✓								
Gong et al. (Gong et al. 2015)		✓	✓			✓				✓	
Hadera et al. (Hadera et al. 2015)	✓	✓	✓							✓	
Hamer (Hamer 2014)		✓	✓			✓				✓	✓
Lu et al. (Lu et al. 2017)	✓	✓	✓								
Maneschijn (Maneschijn 2012)		✓	✓			✓				✓	✓
Nolde and Morari (Nolde and Morari 2010)	✓	✓	✓								
Rager, Gahm and Denz (Rager et al. 2015)		✓	✓							✓	
Swanepoel et al. (Swanepoel et al. 2014)		✓	✓						✓	✓	✓
Yuan-yaun, Ying-lei and Shi-xin (Yuan-yuan et al. 2013)	✓	✓	✓								

The research discussed by Biondi et al. (Biondi et al. 2017) focused on improved coordination between production and maintenance scheduling with the purpose of increased equipment lifetimes. This study used aspects of energy awareness approaches, but was implemented on an electric-arc-furnace steelmaking facility. Another study that was considered was the business administration research done by Moshidi (Moshidi 2014) to determine the functions of maintenance planners at a South African steelmaking facility. This provides background to the steelmaking environment in the country, and suggested guidelines when approaching its planning functions. Table 3 evaluates the relevant studies.

Even though a specific solution was not developed, the provided guideline based on the relevant research is of high value for the development of a solution in the research conducted in this article. In general, the research lacked applications for a BF–BOF steelmaking facility, and no focus was placed on energy efficiency.

Integration of Solutions

The last major focus area for the evaluation of existing studies is the integration of solutions. Various studies using integration techniques were evaluated. These studies indicate the benefits of using an integrated approach as part of the solution. Integrating existing solutions ensures that the benefit obtained from the implementation is optimal while integrating different sections ensures that the interactive effects of sections are accounted for. Additionally, integrating production and energy cost benefits ensures that one aspect is not neglected to compensate for another. Various studies using integration techniques were evaluated, as summarised in Table 4.

These studies were, however, not applicable to steel production planning using the BF–BOF production method and had limited practical applications. Most studies were also not focused on South African case studies, and resultantly neglected some of the unique challenges addressed by the research conducted in this article.

Research Objectives

The main objective of the research conducted in this article is developing an integrated cost model for steel production planning, and applying it to a marginally profitable facility as a case study. This model will reduce cost by identifying, evaluating, comparing, prioritising, implementing, and integrating production planning initiatives. The research objectives to achieve this are indicated in Fig. 2, along with how it contributes to the shortcomings identified in the research field.

These research objectives were identified by comparing the need for the study with the shortcomings identified from the existing literature, and stipulating which aspects will need to be included in order to address this need sufficiently.

The research process used to develop each step in the methodology is not discussed in detail in this article. The focus is rather placed on the developed methodology and practical application thereof. The methodology utilises several aspects of existing literature. These aspects were critically evaluated and adapted to be applicable to the methodology. These aspects were integrated in a novel way, focusing on addressing the problem identified in steel production planning.

Development of an Integrated Cost Model

Based on the identified problem and resulting research objectives, the development of an integrated cost model for steel production planning was conducted. The development of the integrated cost model makes use of several existing solutions obtained from literature and integrates these solutions to develop a new model (Pelser 2019). The existing solutions that were investigated are linked to the developed methodology in Fig. 3.

The newly developed methodology consists of five steps. Steps 2 and 4 occur for each identified initiative individually, while the other steps take place for all initiatives simultaneously. The steps are discussed on a high level in the following sections to keep the discussion short and concise. The practical application of the case study will provide the reader with more information on how to incorporate these steps on a facility, and address some of the aspects of the steps that might come across vague in this initial discussion.

The following assumptions were made with regard to the type of facility where the methodology will be implemented:

- That the initiatives identified in the methodology are viable at the relevant facility;
- That the facility is marginally profitable, and experiencing similar issues as the case study facility (such as resistance from personnel to implement automated solutions and issues with integration between sections);
- That the facility has opportunities for energy and waste reduction, but the necessary capital to make large improvements is not available;
- That the facility plans production in advance based on certain inputs; and
- That the facility has variable electricity tariffs throughout the day, which can be utilised to achieve cost savings.

Step 1: Gather Production Planning Information and Identify Production Planning Initiatives

The first step in the methodology is to gather production planning information and to identify viable initiatives for

Table 3 Summary of literature related to scheduling that focus on production efficiency

Author	Criteria										
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility	Application on a South African case study
Biondi, Sand and Harjunkoski (Biondi et al. 2017)	✓	✓		✓						✓	
Liu et al. (Liu et al. 2011)	✓	✓		✓							
Lochmüller and Schembecker (Lochmüller and Schembecker 2016)		✓		✓						✓	
Long et al. (Long et al. 2014)	✓	✓		✓	✓						
Moshidi (Moshidi 2014)		✓		✓							✓
Tu, Luo and Chai (Tu et al. 2011)	✓	✓		✓							

Table 4 Summary of the literature related to the integration of initiatives

Author	Criteria										
	Focused on steel industry	Focused on production planning	Focused on energy cost efficiency	Focused on production cost efficiency	Integration of different sections	Integration of existing solutions	Integration of production and energy	Prioritisation of initiative implementation	Prioritisation of implemented initiatives	Practical implementation on a facility	Application on a South African case study
David, Goldblatt and Zhang (David et al. 2015)	✓			✓	✓	✓				✓	
Dias and Marianthi (Dias and Marianthi 2016)		✓		✓		✓					
Gajic et al. (Gajic et al. 2017)	✓	✓	✓		✓	✓	✓			✓	
Ghanbari, Saxén and Grossmann (Ghanbari et al. 2013)	✓		✓			✓	✓				
Li and Ierapetritou (Li and Ierapetritou 2009)		✓		✓	✓						
Marais (Marais 2012)			✓		✓	✓		✓		✓	✓
Shah and Ierapetritou (Shah and Ierapetritou 2012)		✓		✓	✓						
Ubando et al. (Ubando et al. 2019)	✓		✓		✓	✓	✓				
Zhao, Grossmann and Tang (Zhao et al. 2018)	✓	✓	✓			✓	✓				

Fig. 2 Research objectives linked to the contributions of the research field

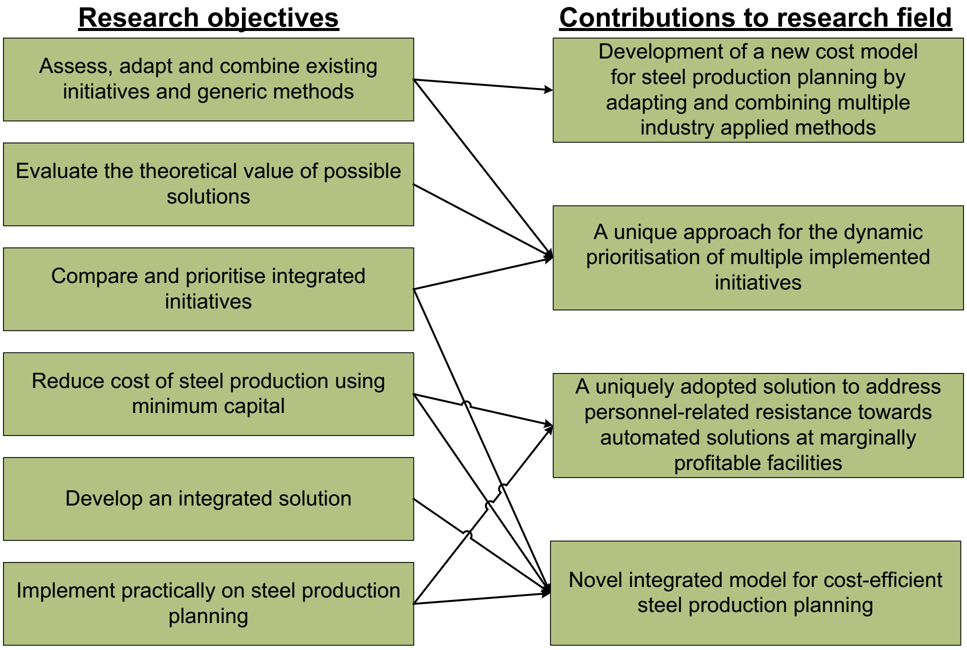
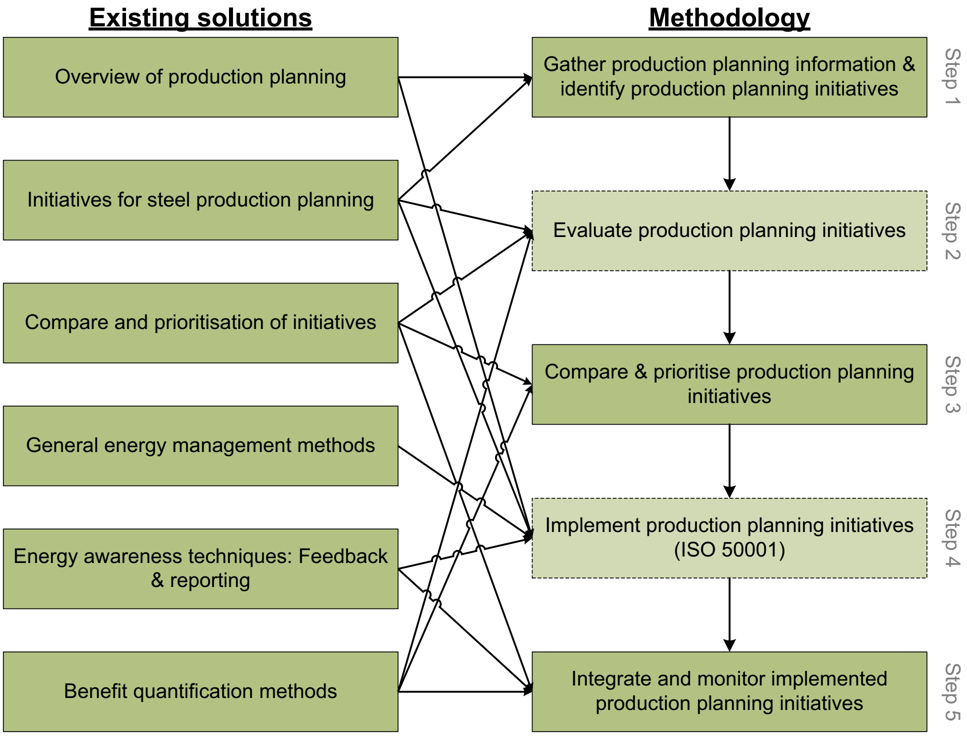


Fig. 3 The use of existing solutions to develop the new methodology



the specific facility. This provides the required platform to understand the operation of the specific facility and its production planning functions. To better understand these factors, the following should be familiarised for the specific facility:

- Forecasts for production;
- Maintenance procedures and intervals;
- Equipment reliability and capabilities;
- Energy consumption of sections and equipment; and
- The availability of buffers in the system.

By familiarising the above aspects for the specific facility, a more practical approach can be taken when assessing the most viable options for application to the facility. This is not described in detail in this section but will be

Table 5 Description of identified initiatives

Initiative	Description
Hot charging of the primary rolling mill furnace	Hot charging casted steel into the primary rolling mill furnace when possible. If this is already done, it can be attempted to improve/increase the amount of hot charging that takes place
Ladle furnace load shifting	Reducing the power consumption of ladle furnaces during peak tariff times by processing less energy intensive steel qualities during such periods
Ladle and crane time loss reduction	Reducing time losses between the continuous caster (ConCast) and preceding processes by the improved scheduling of cranes to be used for transport, and ladles to be used for heating
Primary rolling mill apportionment model	Arranging of blooms with similar specifications and thermal performance together in the furnace to improve heating quality
Primary rolling mill load shifting	Reducing power consumption of the motors of the primary rolling mill during peak tariff times by rolling less energy intensive steel or delaying operations during such periods

demonstrated at the hand of a case study. There are several variables that affect production planning. These factors also need to be considered when adapting production planning procedures and therefore form part of the information that needs to be gathered and understood for the facility. Examples of typical information that need to be collected for the facility to better understand and manage the production planning process include the following:

- Delivery dates for orders received from clients;
- Steel qualities to be casted;
- Required profiles to be rolled by the primary rolling mill; and
- The stock level at the time.

The use of such information in the methodology will be demonstrated at the hand of a case study. As part of the first step, viable production planning initiatives must be identified for the specific facilities. This can be done by considering the layout of the facility and its components, along with the factors mentioned above. By considering non-capital intensive and non-automated solutions from literature, the initiatives listed in Table 5 have been identified as viable options for the cost model developed in this article. The initiatives can be adapted (or eliminated) as needed for the specific facility.

Step 2: Evaluate Production Planning Initiatives

After it has been determined which production planning initiatives can be applied on the facility, the different initiatives need to be evaluated. This evaluation is simplified by using five categories and providing four criteria options for each category. The following categories are used for the evaluation (the criteria for each category are provided in “Step 3: Compare and Prioritise Production Planning Initiatives” section):

- Category A: Determine the status of the initiative on the facility;
- Category B: Collect the required historical data;
- Category C: Evaluate the performance from historical data;
- Category D: Evaluate any practical constraints for the initiative; and
- Category E: Determine the theoretical potential benefit.

These categories have been carefully selected based on the identified problem and the desired output of the methodology. The categories have been sourced from literature and were adapted and integrated as part of the development of the methodology. The practical evaluation of the initiatives will be demonstrated at the hand of a case study and is therefore not discussed in detail in this section.

Step 3: Compare and Prioritise Production Planning Initiatives

After the individual evaluation of each identified initiative, the findings for the different initiatives need to be compared. Values are allocated to each category, as indicated in Table 6, based on the selected criteria for the specific category. An initiative ranking value is resultantly calculated for each initiative by classifying each category of the evaluation in one of the criteria. Negative values are allocated to the least favourable criteria and a higher value to the most favourable criteria.

The values in Table 6 (i.e. $-2, -1$, 0, and 2) were carefully selected based on the effect that it will have on the methodology. This was done based on a combination of the practical understanding of steel production planning facilities and literature.

After allocating an initiative to the relevant criteria, the initiative ranking value is calculated using Eq. 1. In this equation, all values are added together, but the ratings for category D (practical constraints) and category E (potential

Table 6 Value allocation of evaluation categories for initiative ranking

Category	Description	− 2	− 1	0	2
A	Status	Successfully implemented	Previous unsuccessful attempt	Implemented, but ineffective	Not previously considered
B	Data availability	No data available	Selective data available	All data unsustainably available	All data sustainably available
C	Historical performance	No variation	Limited variation	Possible variation	Sufficient variation
D	Practical constraints	Cannot be mitigated	Capital required	Resistance exists	Few constraints exist
E	Potential benefit	No potential	Limited potential	Achieved if conditions allow it	Potential benefits exist

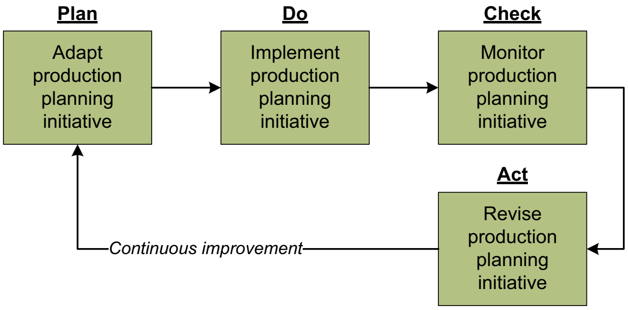


Fig. 4 Implementation of the initiatives based on ISO 50,001

benefit) are doubled. This is due to the critical role that these aspects play in the successful implementation of the initiative. A higher ranking indicates the highest prioritised initiative. The scoring criteria were critically developed based on an understanding of the steel production planning process, and the viability of implementing initiatives based on the identified criteria.

$$Initiative\ ranking = A + B + C + [D + E] \times 2 \qquad (1)$$

The rating of initiatives based on the criteria should be conducted by plant personnel in the different sections of the facility. It is recommended that a group of individuals involved in different sections and roles at the facility are included such as production planning personnel, upper management, and plant operators. This will ensure that the management level and practical challenges and advantages are considered when performing these steps.

Step 4: Implement Production Planning Initiatives (ISO 50,001)

After prioritising the implementation order of initiatives, the initiatives are considered separately again. As part of the methodology, the *plan-do-check-act* cycle of ISO 50,001 is applied to the identified initiatives as an *adapt-implement-monitor-revise* cycle. The purpose of these steps is to adapt the initiatives, which were identified from literature to be applicable to the specific conditions of the facility, and to implement the initiatives practically. The relevance of the steps in the methodology to ISO 50,001 is presented in Fig. 4.

This step will vary significantly based on the identified initiatives and characteristics of the facility. This application will be demonstrated in more detail at the hand of a case study.

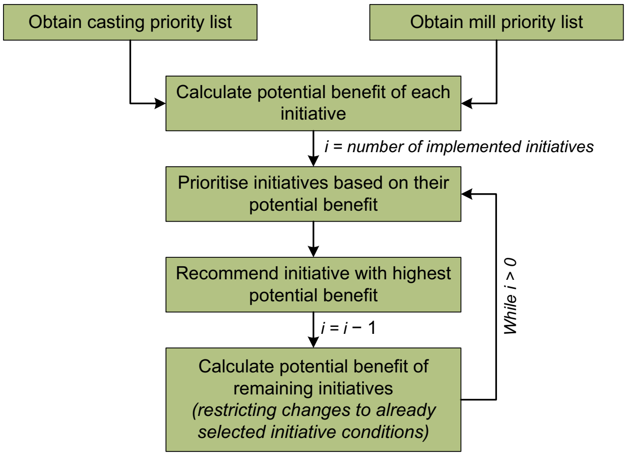


Fig. 5 Integration of multiple production planning initiatives

Step 5: Integrate and Monitor Implemented Production Planning Initiatives

As soon as multiple initiatives have been implemented, these initiatives must be integrated to ensure that the optimal benefit is obtained by dynamically prioritising initiatives according to their predicted benefits. The basic concept of integrating several initiatives is based on Fig. 5. As per Fig. 5, the latest priority lists for the steelmaking and primary rolling sections are compared, and the potential benefits of each initiative are calculated. Thereafter, the initiatives are prioritised based on their theoretical potential (with *i* being the number of implemented initiatives). The highest prioritised initiative is recommended to the relevant parties for implementation, and the theoretical benefits of

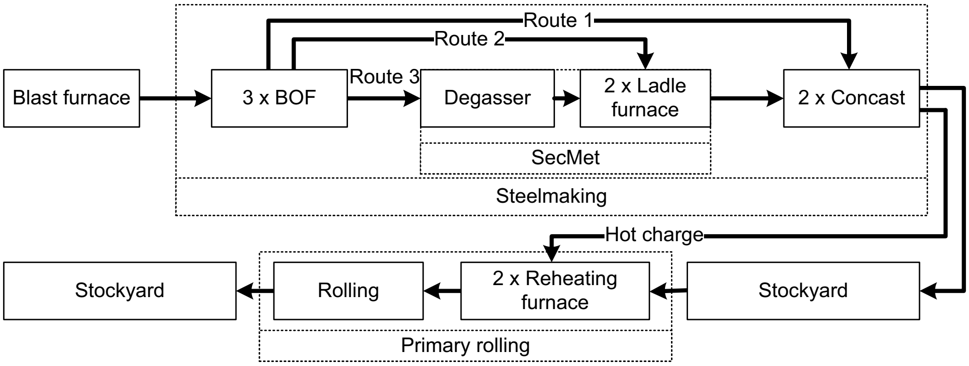


Fig. 6 Simplified overview of the case study facility

the remaining initiatives are calculated. The calculation of the theoretical benefits of the remaining initiatives must consider the restrictions that the already prioritised initiative(s) enact on the system. Initiatives are then prioritised again, and the process is repeated until no more initiatives remain.

The integration of initiatives ensures that the most beneficial aspects of all implemented initiatives are utilised. The proposal for the most beneficial scenario should be included in the flagging system, which is used to inform production planners of how to utilise initiative benefits. As with the monitoring and evaluation of individual initiatives, it is also important to evaluate the success of the integration thereof. This step is a variation of the *check* step of ISO 50,001. It is important to monitor counteractive initiatives and their performance and to revise the approach accordingly.

This step will also vary significantly based on the identified initiatives and characteristics of the facility. This practical application thereof in the next section will demonstrate this in more detail at the hand of a case study.

Results and Discussion

Facility Background

The integrated cost model was applied to a case study facility. A basic overview of the facility production process is presented in Fig. 6. From this representation, it is seen that a blast furnace is used to produce liquid iron, which is then sent to the steelmaking section for further processing. The steelmaking section consists of three basic oxygen furnaces (BOFs), secondary metallurgy (SecMet), which includes a degasser and two ladle furnaces, and two ConCasts. Three different production routes can be followed at the steelmaking section (as indicated in Fig. 6) to process the liquid steel, depending on the specification of the steel qualities. Casted steel blooms are then either sent to a stockyard or hot charged directly into the reheating furnace of the primary rolling mill.

The production planning department is responsible for the coordination of this section of the facility, based on the orders received from clients. The basic operation of this department is that there are two production planners who are responsible for the coordination of production. Production planner 1 is responsible for coordinating the orders received from clients with the blast furnace and steelmaking facility, and providing the required information to the other production planner. Production planner 2 then makes use of this information and the orders received from clients to coordinate the production of the primary rolling mill (and additional processing mills where relevant).

Application of the Model on the Case Study

The integrated cost model methodology presented in Fig. 3 was applied to the case study facility. Once an understanding of the facility was obtained (step 1), the production planning initiatives identified in Table 5 were evaluated individually (step 2). The initiatives in Table 5 were evaluated, compared, and prioritised using the categories in Table 6 and the initiative ranking calculation provided in Eq. 1 (step 3). The resulting evaluation is presented for each of the identified initiatives in Table 7, indicating the prioritised order of initiatives.

The implementation (step 4) and integration (step 5) of initiatives were first conducted theoretically, and thereafter practically. These respective applications are discussed hereafter.

Theoretical Application of the Integrated Cost Model

The theoretical application was conducted by using data for a full year (2016) and calculating the theoretical benefits of each of the initiatives. From this evaluation, it was found that one of the initiatives (primary rolling mill apportionment model) was not viable for application on the case study facility, and it was omitted from the remainder of the application. The “Crane scheduling” initiative was included in the

Table 7 Comparison of evaluated initiatives

Category	Description	Hot charging of the primary rolling mill furnace	Ladle furnace load shifting	Ladle and crane time loss reduction	Primary rolling mill apportionment model	Primary rolling mill load shifting
A	Status	0	2	2	2	−1
B	Data availability	2	2	−1	−1	2
C	Historical performance	2	2	−1	−2	0
D	Practical constraints	2	0	0	−2	0
E	Potential benefit	0	2	−1	−2	2
Initiative ranking		**8**	**10**	**−2**	**−9**	**5**

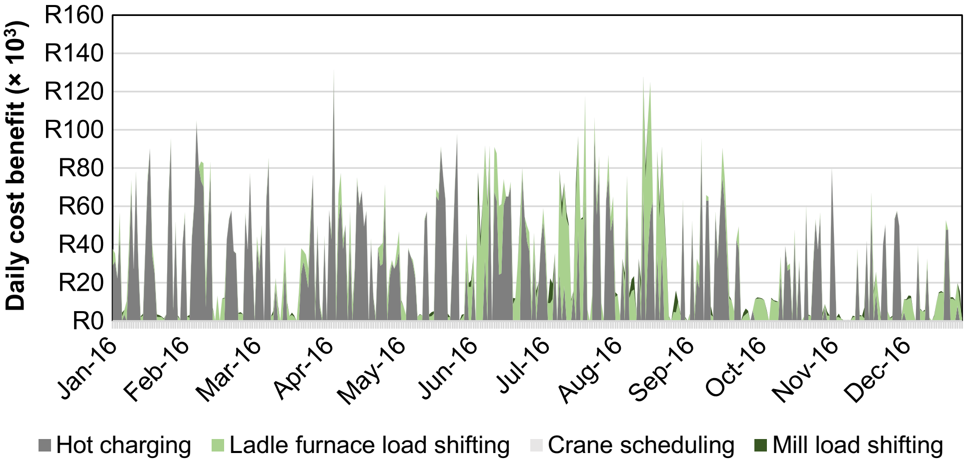


Fig. 7 Daily theoretical cost benefit of the initiatives after integration

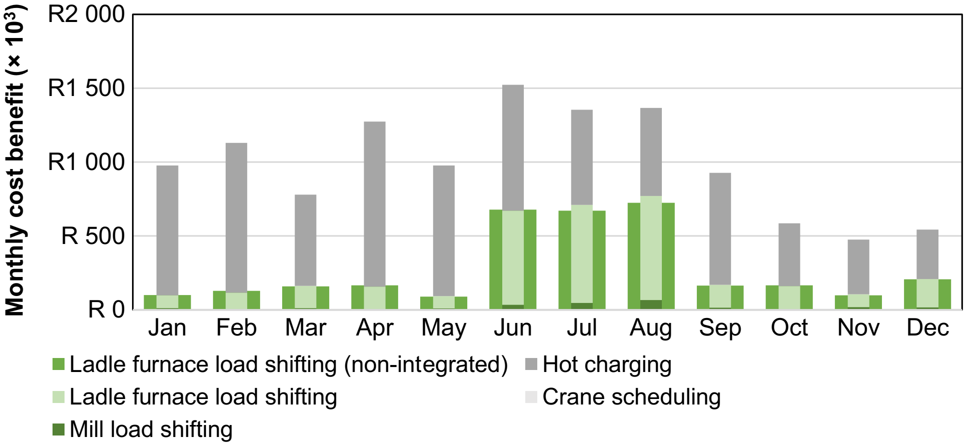


Fig. 8 Monthly theoretical cost benefit comparison between the integrated and non-integrated approach

evaluation, but it did not indicate any potential savings during this period. The concept presented in Fig. 5 was used for the theoretical integration of initiatives, using the practical constraints of a prioritised initiative to adapt the theoretical benefits of the others. The theoretical daily cost benefit is presented in Fig. 7.

From Table 7, it was determined that the ladle furnace load shifting initiative should be implemented first (highest prioritised initiative). It is therefore assumed that a non-integrated approach would have consisted of only this one initiative being implemented. The monthly cost benefit of this non-integrated approach is compared with the cost benefit of the integrated approach in Fig. 8. From the theoretical evaluation, the non-integrated approach would have resulted in a yearly cost benefit of US$0.21 million

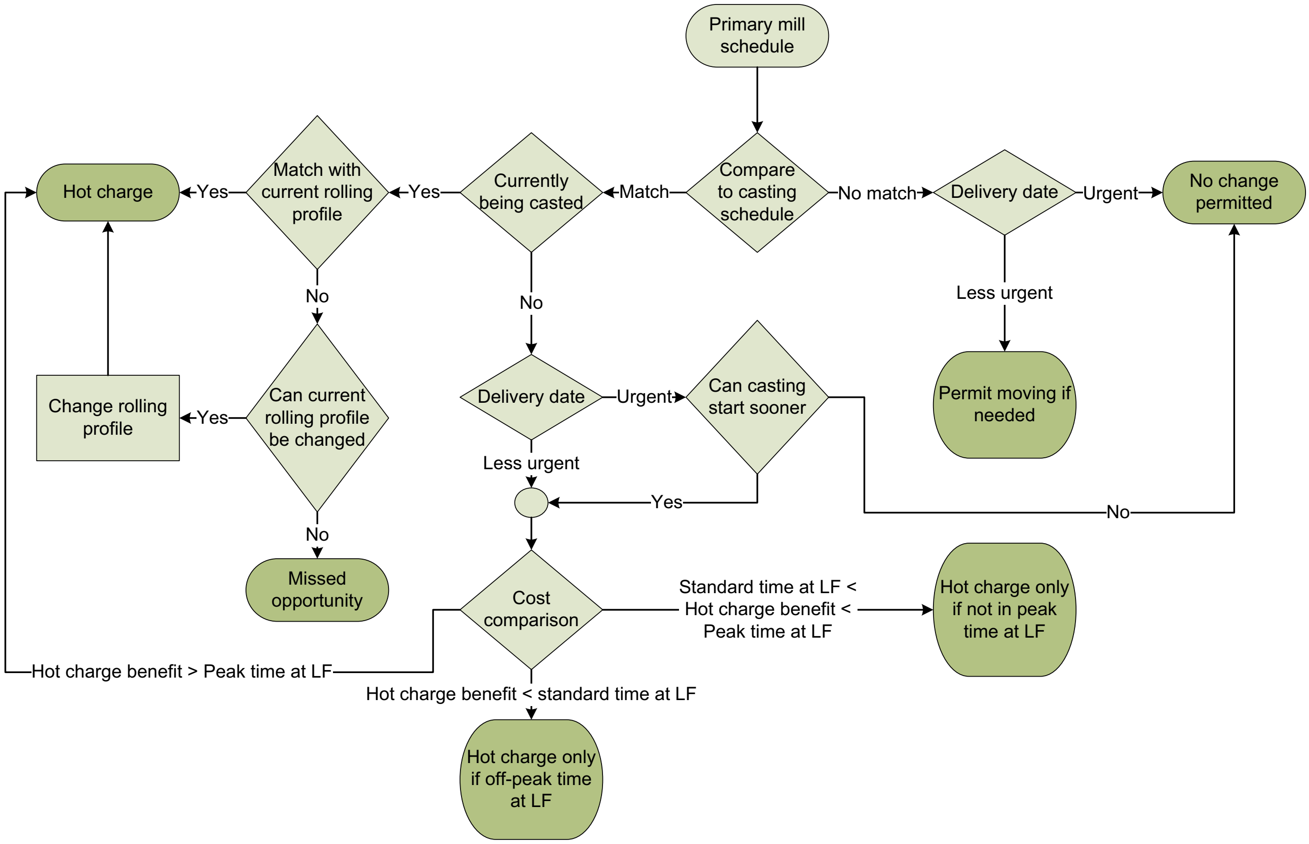


Fig. 9 Practical decision-making flow diagram for the integration of initiatives

(R3.4 million[2]), which is only 29% of the US\$0.75 million (R11.9 million[3]) cost benefit of the integrated approach.

Practical Application of the Integrated Cost Model

The practical application of the integrated cost model on the case study facility resulted in two of the identified initiatives being practically implemented. The *Ladle furnace load shifting* was implemented on 1 July 2017, and the *Hot charging of the primary rolling mill furnace* was implemented on 1 March 2018. The delay in implementation between the initiatives provides sufficient information to evaluate the effect of the non-integrated versus integrated approach. The practical implementation was achieved by making use of an ISO 50,001-based implementation strategy, rather than using automated solutions. This was done to address several of the practical implementation constraints of such a marginally profitable facility.

Upon the implementation of the second initiative, it was required to practically integrate the initiatives based on the concept presented in Fig. 5. This was practically achieved by using the decision-making flow diagram in Fig. 9.

The initiatives were implemented for a limited period, and the practically achieved results were extrapolated to a 1-year period by using the theoretical results. The extrapolated practical monthly cost benefit of the non-integrated approach is compared with the cost benefit of the integrated approach in Fig. 10. This evaluation indicates that the non-integrated approach would have only resulted in a yearly cost benefit of US\$0.11 million (R1.7 million[3]), while the integrated approach would result in a yearly cost benefit of US\$0.83 million (R13.3 million[4]). This evaluation shows that if a non-integrated approach was used instead of an integrated approach, only 13% of the annual cost benefit would have been achieved.

Overview of Results

The extrapolation of the practical results to a 1-year period provides a valuable platform to compare the theoretical and practical application of the integrated cost model. The theoretical application was adapted to also only consider the two initiatives that were practically implemented. This monthly cost benefit comparison is presented in Fig. 11.

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[2] Exchange rate of R15.94 = US\$1, as on 3 January 2022.

[3] Exchange rate of R15.94 = US\$1, as on 3 January 2022.

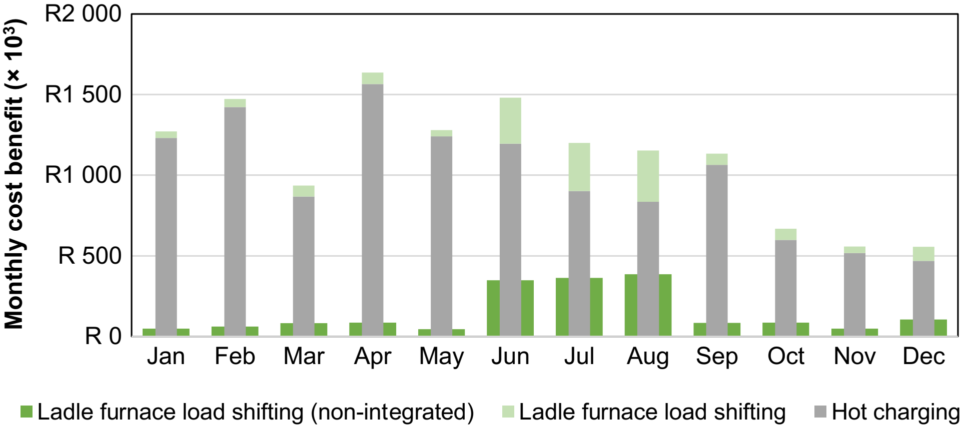

Fig. 10 Extrapolated monthly practical cost benefit comparison between the integrated and non-integrated approach

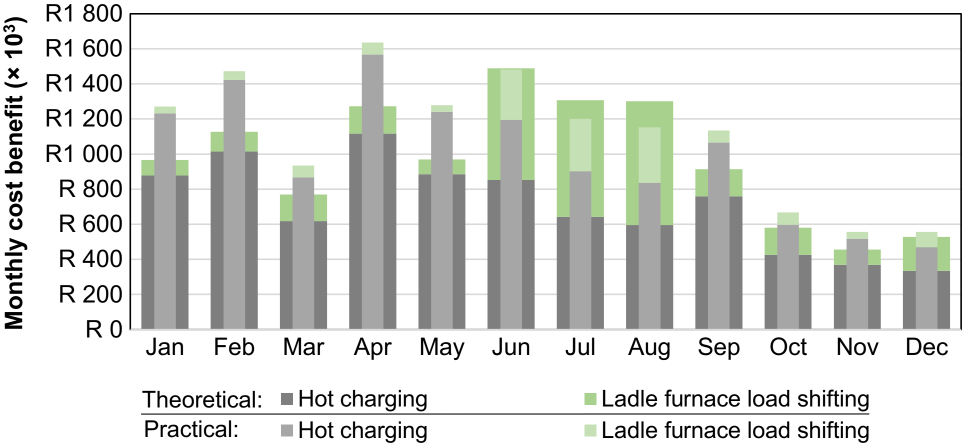

Fig. 11 Monthly comparison between the theoretical and practical cost benefits of the integrated approach

This comparison shows that the cost benefit of the extrapolated practical application (US$0.83 million/R13.3 million[4]) is slightly higher than that of the theoretical application (US$0.75 million/R11.9 million[4]). The practical application validates the results achieved from the theoretical application, concluding that the methodology reduced the cost of steel production successfully.

The practical result can be further extrapolated to determine the possible effect on the South African steel industry. The case study facility produced about 22% of the steel in the South Africa steel market during 2016. Using this, the potential effect on this industry in South Africa is calculated to be US$3.76 million (R60 million[4]) per annum.

Conclusion

The South African steel industry, along with the rest of the world's steel producers, is facing financial challenges. A need was identified to reduce the cost of steel production, and energy cost was identified as a large contributor to the production cost.

A review of existing research indicated a lack of an integrated production planning model, and applications thereof on marginally profitable steel manufacturing facilities. Such an integrated model was developed using an ISO 50,001-based implementation strategy, and the method was described in this article. The integration determines the effect that individual initiatives have on each other, and dynamically prioritises solutions by combining theoretically quantified benefits with practical constraints. The model was then practically applied to a case study facility to determine the actual effect thereof on a real-world scenario.

The theoretical potential benefit of implementing the integrated cost model for a year was US$0.75 million (R11.9 million[5]). The use of a non-integrated approach would have only resulted in 29% of the potential cost benefit. The practical application of the integrated cost model was extrapolated over a year, indicating that the integrated cost model would result in practical cost benefits

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[4] Exchange rate of R15.94 = US$1, as on 3 January 2022.

of US\$0.83 million (R13.3 million[5]). A non-integrated approach would have only resulted in 13% of the cost benefit.

By applying the integrated cost model on the remainder of the steel manufacturing facilities in South Africa, an estimated US\$3.76 million (R60 million[6]) per annum benefit is possible. This also indicated the potential for implementation on marginally profitable steel manufacturing facilities in other countries.

The unique conditions of marginally profitable facilities placed several restrictions on the development of the new cost model developed in this paper. Adaptation of the integrated cost model will allow integration of automated solutions for facilities or even other industries using similar production planning functions.

It is recommended that this research be taken further by applying the integrated cost model on additional steel manufacturing facilities in South Africa (and also marginally profitable facilities in other countries). There is also potential for the methodology to be modified for use in other industries that face similar challenges, and additional research to achieve this will be of high value.

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Code Availability Not applicable.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The authors declare no competing interests.

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[5] Exchange rate of R15.94 = US\$1, as on 3 January 2022.

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