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System Optimization of an Electric Steel Making Plant with Sequenced Production and Dynamic Stock Level

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One third of the total steel production in the world today is produced by electrical steel making and is supposed to increase. It is a very energy intense process but for the production costs the scrap mix is nowadays clearly the most dominating cost factor. Because the ingoing raw material mix affects the energy consumption and the chemistry of the final product it is an important factor to control.
A system optimization model for a generalized electric steelmaking plant has been developed. The vision has been to include a planned production sequence and a dynamic scrap stock level along with a full material- and energy balance connected to the processes. This gives the opportunity to run optimizations with restrictions similar to real production conditions.
The generalized steelmaking plant produces hot rolled coils and five main processes are included in the model; a material pre-treatment process, an electric arc furnace, a ladle furnace, a continuous casting process and a hot rolling mill process. To estimate the chemical composition of the ingoing scrap grades, a regression model has been made based on process data from a Höganäs Sweden AB plant. Mixed Integer Linear Programming (MILP) has been used as the method for modeling the production system. Simulations and optimizations have been focused on changes in the chemical composition of certain scrap grades, restrictions of the availability of scrap grades and restrictions regarding the forecasted production sequence. The objectives used for the optimizations are production costs and total energy consumption. The model deliveries results in form of optimal raw-material mixes for the different steel grades defined in the model, optimal energy mix and optimal target temperatures for the sub-processes. Further it shows the effect on process parameters such as energy consumption, slag amount, off gas generation, injected carbon and oxygen etc.
The model makes it possible to simulate scenarios that are expected for the future regarding new steel grades, availability of raw-materials and changed amount of tramp elements in the raw material used today. It is a good tool to find an optimal solution not only for a single heat but for a sequence of heats with varying chemical specifications.

1. Introduction

Electrical steel making is producing approximately one third of the total steel production in the world today and it is supposed to increase. (worldsteel.org). It is a very energy intense process where both electricity and chemical energy are used. Nowadays the most dominating factor for the production cost is however the ingoing raw material mix and energy is the second dominating factor which can be seen in Figure 1.

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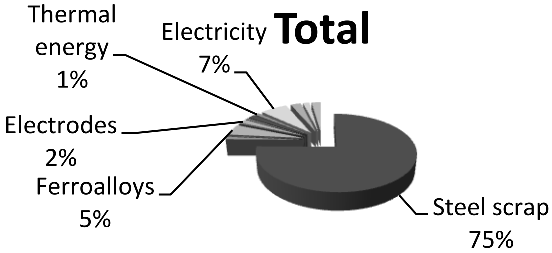

Figure 1: Cost for a general electric steel plant, not using DRI/HBI, per tonne of liquid EAF steel (steelonthenet.org)

In this perspective it is natural to work hard to decrease the cost for the raw material mix. However the ingoing raw material mix also affects the energy consumption of the production system and the chemistry of the final product. Possible new raw materials could also have effect on the settings of the individual processes in the system, alloys, waste material or environmental aspects. This altogether makes it important to include all aspects while trying to reduce raw material cost and energy usage to make sure that the chemistry of the final product is not compromised and that the calculated savings refers to the entire system. A system optimization model for a generalized electric steelmaking plant has been developed within Process Integration in Steelmaking (PRISMA) at Swerea MEFOS. The aim of this work has been to improve the model and to include the planned production sequence and the stock level along with a full material- and energy balance connected to the processes. This gives the opportunity to run optimizations with restrictions similar to real production conditions.

2. Methodology

2.1 Method

The strategy to describe the system has been to connect the individual processes in a system via flows of material and energy. The individual processes can be described by the occurring reactions of material- and energy input and the outgoing flows. When the outgoing flows are connected to other processes it is possible to see it from a system perspective. This means that energy consumption, material consumption, CO_2 emissions, production cost and time perspectives can be analyzed for the entire system. (Ryman, et al, 2008).

Mixed integer linear programming (MILP) has been used to develop this model. The Java based software ReMind have been used as an equation editor that generates standardized MPS-files (optimisation problem descriptions) which can be solved with an external solver. The external solver used in this work is CPLEX. A MILP problem includes continuous variables (material and energy flows) and floating variables that are used within the individual process nodes for creating mass and energy balances. Also integer variables are included to make the modelling more flexible, for example to approximate nonlinearities or discrete choices between process routes. The object function is dependent on the focus of the study and can differ from energy usage to total cost for material and energy. The MILP modelling is further described by Ryman, et al, (2008).

A MILP problem can be written as:

$$\min f(x,y) = \sum c_i x_i + b_i y_i \ , i = 1, \dots n \qquad \text{subject to} \quad \begin{bmatrix} A_1 & 0 \\ A_2 & B \end{bmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \le \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} \qquad (1)$$

$x \in R^n$, $y \in \{0,1, \dots n\}$

Where, f (x,y) is the object function for the minimization problem;

x are the studied variables, (x_i means the i^{th} variable);

y represents integer variables;

c is the coefficients for the object function. It can represent prices for materials or energy equivalents.

2.2 General electric steel making model

The general electric steelmaking system model including scrap pre-treatment, electric arc furnace, ladle furnace, continuous casting and a hot rolling mill process has been further developed from previous work described by Riesbeck. et al, (2011). Process data from Höganäs Sweden AB production site has been used for the electric arc furnace and ladle furnace. The principal plan of the model was that it should give a full overview of the system and cover aspects that will be affected by future and alternative strategies. It is important that that the model delivers results that are realistic and reliable. Therefore the model has been calibrated based on known process data. The calculated results have been compared to average chemical analysis and other measured process data for a couple of steel grades, both for the model calibration and a validation period. Total energy consumption and production cost has been included as alternative objectives. An overview of the model can be seen in Figure 2.

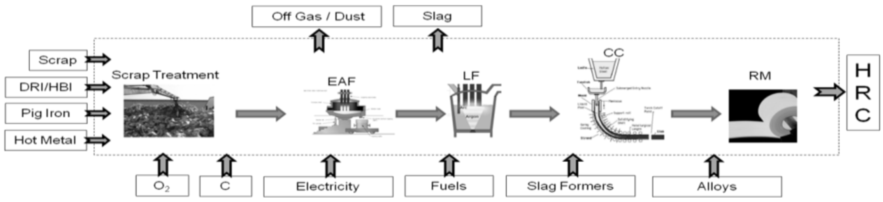

Figure 2: An overview of the modelled production system

2.3 Scrap pre-treatment

The purpose of the scrap pre-treatment node is to split up the charge material flows into flows of elements and oxides to the EAF according to equation 2, where W_X is weight element/oxide X (Me or MeO), W_n is weight of charge material n and $w\%_{X,n}$ is the weight percentage of element/oxide X in charge material n.

$$W_X = \sum_{n=1}^{N} W_n * w\%_{X,n} \tag{2}$$

There is a high uncertainty about the chemical composition of the different scrap grades ($w\%_{X,n}$). Therefore a multivariable regression model based on process data from 1400 heats from Höganäs Sweden AB was made to estimate the content of elements and oxides in each scrap grade. The objective of the regression model was minimisation of the total sum of squares for error in calculated concentration (w%) of selected elements (Fe, C, Mn, P, S, Cu, Ni, Cr, Mo, etc) in the steel tapped from the EAF by adjusting the chemical composition of the charge materials (w%) and the distribution factors for each element and oxide to steel and slag.

2.4 Electric arc furnace

The purpose of the EAF process is to melt the charge materials and heat the molten steel to a target temperature. The main energy source is electricity (graphite electrodes) but about 1/3 of the energy is chemical heat from oxidation of metallic elements and combustion of fossil fuels in oxy-fuel burners. A general mass and energy balance have been used to model the EAF node. When the ingoing elements and oxides enter the EAF they will end up in either the steel, slag, dust or the off gas. To model this, distribution factors for elements and oxides to these phases have been set up. These distribution factors have been statistically determined by analysis of average chemical composition and weight of the phases. Other ingoing materials are hot briquetted iron (HBI), direct reduced iron DRI, slag formers, nitrogen for stirring, burner fuel and carbon- and oxygen injection via lances. Distribution factors for these materials have also been set up For the energy calculations two formulas has been used, an empirical formula that calculates the electrical energy demand (Köhle., 2002, Pfeifer et al, 2005) for the furnace and a theoretical formula which calculates the sum of the total energy consumption (Adams et al, 2002). When the electrical energy is calculated a number of furnace parameters and ingoing material are considered such as tapping weight, charge weight, tapping temperature, tap to tap time, weight of HBI/DRI, shredded scrap, hot metal, flux materials, lance and post combustion oxygen. This formula has been further adapted with additional charge materials and energy sources to improve the calculation of electricity consumption more precise. For the calculation of the total energy input to the process the theoretical chemical energy content for example the fuels are added to the electrical energy.

2.5 Ladle furnace

When it comes to the basics of the mass balance of the ladle furnace it is treated in the same way as the EAF process with statistically determined factors that distributes the incoming elements and oxides between steel, slag, dust and off gas. The chemical composition of the added alloys have however not been determined by statistical analysis. A fixed energy consumption for raising the temperature of the liquid steel (kWh/ton*˚C) was determined from process data. Further there are a number of temperature drops of the liquid steel that the model needs to consider and that contributes to the energy consumption. The considered temperature drops are tapping of EAF, transport from EAF to LF, alloy and slag former additions and argon stirring.

2.6 Continuous casting

The continuous casting unit is treated as a yield loss in the model. For the material flow, a material loss in percentage based on the total liquid steel amount from the LF unit is assumed when casting. A specific oxygen consumption based on the final product is assumed to calculate the total oxygen consumption. The oxygen is needed when cutting the slabs.

2.7 Hot rolling mill

The slabs from the continuous casting node are heated with three alternative fuels; natural gas, oil or LPG. Both the consumption of fuel for heating and the consumption of electrical energy are set as a constant per ton of steel. The off gas generated from the burners is calculated according to several assumptions.

2.8 Multiple grade optimization with dynamic scrap stock level

The model has been divided into a number of time steps with equal length. For this application the time steps does not represent differences over time. It has been made to enable optimization of several steel grades connected to each other at the same time. This means that each time step has been used to symbolize one specific steel grade that is being produced at the steel plant. It enables different process settings and chemical specifications to be set up for each specific grade. Also planned production volume for each grade during a chosen period can be specified. This makes it possible for the model also to consider the relationship between the volumes of the steel grades. Connected to this, a dynamic scrap stock level has been modeled. The stock level available for the production period for each scrap grade can be specified. While optimizing, the stock amount will be distributed between the different steel grades while satisfying the most optimal solution regarding to the chosen objective. The model with the extended functions can be seen in picture 2. Not only restrictions according to the stock levels are programmed, there are also a number of restrictions according to scrap density and process requirements.

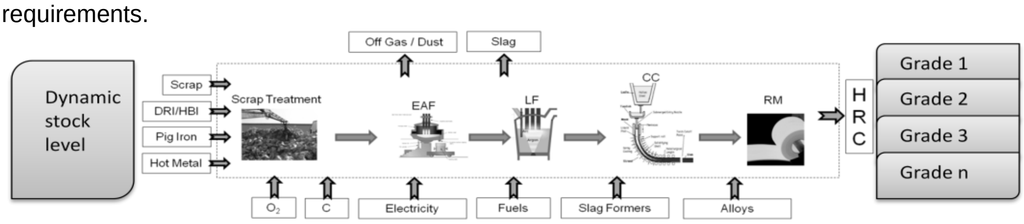

Figure 3: An overview of the modelled production system with dynamic scrap stock level and multiple steel grades

3. Results

The model has been used to analyse three cases, the reference case with single optimization, multiple grade optimization with infinite scrap stock level and multiple grade optimization with restricted scrap stock level. An analysis regarding the effect of the price relation between critical scrap grades have been made.

3.1 Multi grade optimization compared to single grade optimization

If the stock levels for the different scrap grades are set to infinite amounts the model gives the same results as for the single grade optimization except for the fact that the user only have to perform one optimization to receive results for all steel grades. The model optimization delivers results in form of specified raw material recipes, tapping temperatures, carbon and oxygen injection, post combustion oxygen, slag formers, slag composition, off gas volume, off gas composition, steel chemistry, alloying materials etc. The result shows that scrap grades which requires low energy consumption for melting such as shredded scrap is maximized. Sculls and other internal scrap that contains slag formers are preferred because it can replace slag former additions that in other case will require high energy consumption for melting (Köhle., 2002), (Pfeifer. et al, 2005). Also HBI/DRI is minimized due to high energy consumption for melting regarding to the energy calculation formulas. The refining function (oxidation of C, Fe, Mn, Cr, and P) connected to the injected oxygen enables the model to choose more scrap that requires less melting energy and still deliver steel within the chemical specification. This results in the fact that the model maximizes the amount of injected oxygen for low quality steel grades to obtain lowered total energy consumption despite that it contribute to a higher chemical energy consumption. The model chooses to heat the steel as much as allowed in the electric arc furnace because of the higher efficiency than in the ladle furnace.

3.2 Multi grade optimization with restricted scrap stock levels

When optimizing, the system model prioritizes high volume steel grades compared to the low volume steel grades. In this way the average optimization result for the total volume are kept optimum.

Because of the fluctuation of the price of both raw materials and electricity the model is a god tool to easy keep track of the optimum settings of the processes and the raw material mix into the system. Analyze of the results shows that critical scrap grades to maintain the quality restrictions are high quality new scrap and HBI/DRI. An interesting scenario to illustrate this is the synergy between high quality new scrap such as thinplate and bundled thinplate, sheared scrap, structural scrap and HBI/DRI. When there is no price difference between high quality new scrap and HBI/DRI the model suggests the high quality new scrap because of the higher energy consumption for the HBI/DRI. In figure 4 it can be seen that when the price difference is moderate (12.5%) the production cost decrease until a breakeven point where the extra energy consumption increase the production cost again. When price for the HBI/DRI decrease even more relatively to the high quality new scrap (30%) the production cost will decrease for all of the relations and no breakeven point can be seen. When HBI/DRI is used it can be diluted with low quality sheared or structural scrap depending of the steel specification. The HBI/DRI often requires more lime, to maintain the basicity of the slag, which also contributes to higher energy consumption. The model shows that the increased levels of slag and off gas also have to be considered while using HBI/DRI. Since the price of electricity also fluctuates this is also an important factor to the final solution.

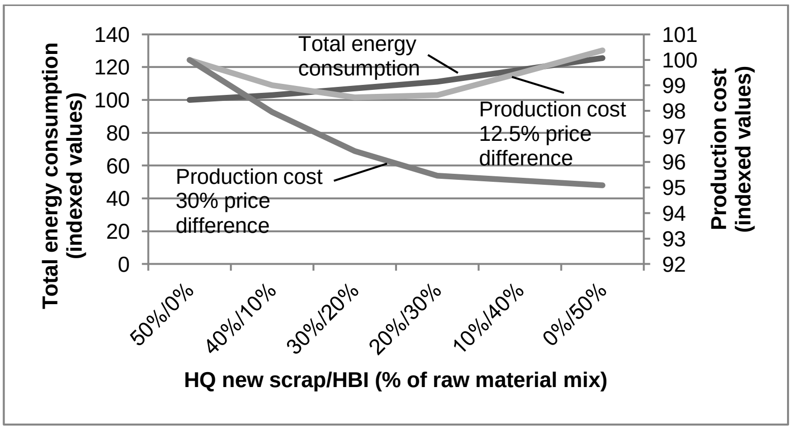

Figure 4: Total energy consumption and production cost connected to the relation between HQ new scrap and HBI

3.3 Energy and cost effects

Because of the two different objectives that can be chosen for the model optimization it is interesting to investigate what happens to the other objective when optimizing according to one objective. For the reduction of electricity it can be seen in table 1 that from the average specific electrical consumption the potential electricity savings are 8 respectively 4.5 percentage when using energy objective and cost objective.

Table 1: Potential savings of electrical energy for total energy and cost optimization objective

Optimization case	Electricity reduction (%)
Average process data	0
Energy objective	8
Cost objective	4.5

Since electricity also is a major cost the model wants to keep this as low as possible. It can also be said that the low cost materials often have low specific energy consumption according to the electrical energy demand formula.

4. Discussion

The purpose for this work has been to develop a model for electric steel making that can handle multiple grade sequenced optimization with a dynamic scrap stock level connected. The model works in agreement with these conditions.

It is especially for short term optimizations where the dynamic scrap stock level could be applied. The planned sequence for a steel plant often changes with relative short notice and scrap deliveries come frequently. Therefore the model with this function is preferably applied to a production sequence of a number of days or a week. The model could be applied for optimizations for production of the most profitable sequence of steel grades related to what is available at the scrap yard at that time. Market conditions where the price can differ dependent on purchased amount of material can also be applied.

Additionally it would be satisfying to use the model at a frequent basis to update the recipes for each steel grade. This would be done in agreement with the latest market conditions such as prices for steel scrap, iron ore based metallics, alloys, energy prices etc. In this way it could be decided which materials that should be prioritized during certain market conditions. This could be an important guidance also in an earlier stage while planning purchasing of material for a suitable period of time. It could also give an early guidance for future scenarios regarding increased levels of tramp elements in scrap grades, forecasted price changes over time for energy or materials, a quick way of evaluation for investments, production of new steel grades or the possibility to use new types of raw materials.

The importance of doing cost and energy optimizations regarding to the entire production system has been shown. If a cost optimization would have been done independently for each process it is not sure that the result would have been entirely positive. Also, without consideration and limitations of important process factors in the individual process nodes, the results may have been non-realistic.

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