Model based evaluation of sustainability indicators in integrated steelmaking: A Swedish case study

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INTRODUCTION

SSAB Tunnplåt is one of Europe’s leading manufacturers of high-strength strip steels. The company has ore-based steel production in Luleå and strip steel manufacture in Borlänge. Slabs are transported by train between the two production sites, situated approximately 800 km from each other. This creates several challenges for the steelmaker:

- Due to the geographical situation it is necessary to extend the energy saving methodologies compared to the situation at a normal integrated plant,
- A holistic view is needed to economise the use of resources, and to evaluate and incorporate new technologies and methods, in terms of a sustainable development.

The integrated steel plant in Luleå includes coke ovens, an ironmaking plant with one Blast Furnace (BF), a steelmaking plant with two Basic Oxygen Furnaces (BOF), and a continuous casting plant with 100 % continuous casting (CC) of slabs. In 2005, the plant used 3 Mtonnes of ore and 1 Mtonne of coal and produced 2 Mtonnes of steel slabs. In addition, also 1.5 Mtonnes of by-products and residual products were produced, Figure 1. The ambition is to recover as much as possible of these by-products within or outside the plant.
There is a partial recirculation of dust and sludge. The dry dust from the blast furnace and the coarse fraction of the BOF sludge are recirculated as briquettes into the blast furnace. For the fine fraction of the BOF sludge and the BF sludge, there is no technique for recirculation, and those materials are presently being deposited as landfill. The hot BF slag is air-cooled and subsequently used for road building. The consumption of that slag varies from year to year, as it is dependent on ongoing road building projects in the area. An alternative could be to granulate the slag and then use it as a raw material for cement production. However, with the present structure of the concrete industry, the Swedish market for slag cement is not sufficient to motivate a slag granulation plant in Luleå.

![Figure 1 Gross material balance at SSAB Tunnplåt AB in Luleå (2005)](image1)

Approximately 2/3 of the BOF slag is re-circulated to the BF, the remainder is deposited as landfill. Limiting factors for re-circulation are the accumulation of Phosphorous and Vanadium in the system and, to some extent, the grain size of the slag.

The coal and coke are used as reactants to extract iron from iron ore, but it is also an energy carrier. Part of this energy remains as energy-rich byproduct gases after the processes. There are three types of gases: Coke Oven Gas (COG) with a heat value of approximately 17.5 MJ/Nm$^3$, BOF gas with a heat value of approximately 7 MJ/Nm$^3$ and BF gas with a heat value of approximately 3 MJ/Nm$^3$. In most integrated steel plants, the main part of this energy can be used in the subsequent rolling and finishing mills. In Luleå, this is not possible because of the distance of 800 km to those mills. Consequently, there is a surplus of process gases on site. A solution to this has been worked out in close cooperation with the local community, where the gas is used as primary fuel in a Combined Heat and Power plant (CHP) to produce a combination of electric power and hot water for district heating. The latter is an important commodity because of the location close to the Arctic Circle.

![Figure 2 Recovery and use of by-product energy gases (GWh)](image2)

The recovered energies and their use within and outside the plant are shown in Figure 2. The exported gas is used in the local CHP plant which covers the total consumption of electricity at SSAB Tunnplåt AB in Luleå, as well as the demand of heat for residential heating in Luleå. As a consequence of this cooperation, the price of district heating in Luleå is the lowest in Sweden\(^1\).
SCOPE OF PAPER

This paper exemplifies how optimisation models can be used for systematic analysis of steelmaking systems and for optimisation of sustainability indicators such as energy efficiency and greenhouse gas emissions, and by extension also material and cost efficiency.

STEEL & SUSTAINABILITY

Local environmental concerns

Sustainable development is development aimed at improving the quality of life for everyone, now and for generations to come. For all types of industry this pinpoints a further need to optimise the environmental, social, and economic aspects in all decision-making. The steel industry is no exception in this respect.

The production of steel in Sweden is putting a decreasing load on the environment. The steel producers continually improve their production methods - not least considering environment and energy. The high quality, the durability and the recyclability of the Swedish steel products also offer environmental advantages considering the entire life of the material.

At SSAB Tunnplåt AB, daily process improvements, modern processes and cleaning equipment, etc have gradually decreased the environmental impact on the surroundings. The effect is visible both from studies of the direct effect on the surroundings (moss sampling) and from measured emission and landfill data. Some examples are shown in Figure 3.

Sustainability Indicators

An indicator is something that helps you understand where you are, where you are going, and how far you are from your target, if you have one. For an indicator to be meaningful it must be derived from available data and have a global significance. Sustainability requires an integrated view of the world, thus requiring multidimensional indicators which link environmental issues with economy and social factors (society and health). The International Iron and Steel Society (IISI) have suggested eleven sustainability indicators to measure economic, environmental, and social performance¹;

1. Investment in New Processes and Products (economic)  
2. Operating Margin (economic)  
3. Return on Capital Employed (economic)  
4. Value Added (economic)  
5. Energy Intensity (environmental)  
6. Greenhouse Gas Emission (environmental)  
7. Material Efficiency (environmental)  
8. Steel Recycling (environmental)  
9. Environmental Management System (environmental)  
10. Employee Training (social)  
11. Lost Time Injury Frequency Rate (social)

Figure 3 Some environmental key values from SSAB Tunnplåt AB Luleå ²

a) Moss studies, Effect on surroundings  
b) Site emission values
From a process optimisations view the economic and environmental indicators are the most interesting to focus on. The following parts of the paper will cover energy intensity, GHG emissions (only CO\textsubscript{2}) and material efficiency, but some of the economic indicators can be treated by same methodology.

**OPTIMISATION METHOD**

**Process Integration**
The material and energy balances in and around a modern integrated steel plant are very complicated systems with interactions both within the plant and between the plant and the surrounding society. Global optimisation is then very practicable to avoid unfavourable operation. A separate research field, *process integration*, was formulated in the mid-'70s to study the problems of global energy optimisation of industrial systems. National programs have been formulated and carried out in all the Scandinavian countries. The Swedish national program was carried out as a cooperative effort with partners from the Swedish Energy Agency, process industry and academic research. The program was common for the entire Swedish process industry. The background is that the optimisation problem as such is similar between industry sectors, even if the processes are different. The program was financed by the Swedish Energy Agency with industrial co-financing. For the steel industry, SSAB Tunnplät AB constituted a major case study. Analysing the potential for improving energy use and environmental performance in steelmaking often involves complex interaction between several process sub systems. Improvements in a part of the system can propagate to other parts of the system and the total effect is not always a change for the better. A systematic approach can be of major help to avoid sub optimisation and to analyse the interaction effects of different operational measures in the iron- and steelmaking processes. The methodology to couple specific process models to an overall analysis model can be described as process integration and has proved to be especially valuable for analysis of energy minimisation problems and related issues e.g. CO\textsubscript{2} minimisation.

In contrast to the widespread application of optimisation in chemical and petroleum engineering, little work has been done on the optimisation of metallurgical operations. In fact, the accomplishments in this area are largely restricted to the routine application of linear programming to scheduling, inventory control, and similar problems. To handle a global multi-objective system, an optimisation technique based on mathematical programming, has been developed and applied on different energy optimisation problems for the system SSAB - CHP Plant - District heating\textsuperscript{2,3}. It was shown that this were powerful and relatively easy-to-use tools with practical application. The tools include a linear optimisation procedure. It was shown that the use of that these procedures gave better results than just a global simulation of predefined cases. During research on recirculation it could be established, that this technique could also be of value in bringing about a global minimisation of the environmental impact of metallurgical production systems. The existing steel-plant model was modified into a total model for optimisation of CO\textsubscript{2} emission, energy and landfill\textsuperscript{4,5}. The technique has proved to be a forceful and practical tool for global optimisation of total energy systems. So far it has been used for optimisation of energy, CO\textsubscript{2} emissions, environmental impact or economy.

**Optimisation with a MILP model**
The process integration tool developed is a mathematical programming tool based on mixed integer linear programming (MILP). The model core is an overall mass- and energy balance for the production chain and separate sub-balances for the main processes which makes it possible to perform a total analysis for the steel plant and to assess the effect of a change in the operation practice for the different processes. The material and energy use are based on the process requirements for each sub-process, which are determined from the individual process description relating the ingoing resources with the outgoing main product. The consumption and excess of by-products are also determined from each sub-process model, Figure 4.

![Figure 4 Modelling principle for each sub model](image)

In the site model the different main processes (i.e. coke oven, BF, BOF, and CC) are connected together by each primary product, by-product, and energy interaction. A desired production volume of the prime product drives the model. The sub-processes are linked to
the next processing step by the primary product from each process i.e. coke, hot metal (HM) and liquid crude steel (LS). The steel demand from the CC units will thus determine the production rate in the BOF, which in turn will determine the HM rate for the BF and so forth. The different processes included and the main process flows in the model are shown in Figure 5. The standard way of operation for the steel plant can be changed by integrating new process equipment or materials, and by establishing the interaction with the total system.

Some processes are especially complex to model. Under these circumstances it can be justified to define a feasible operating range by use of off-line simulation models and to use the simulation results as input in the optimisation model. An example where stand alone simulation models can be helpful is the blast furnace process.

A consequence of a general modelling approach (based on mass and energy balances) is that it is possible to use the same model to analyse several different objectives, such as economic analysis, energy conservation or environmental impacts (climate change, landfill, material efficiency), by changing the objective function.

**Objective function / objectives**

An efficient industrial system should be operated in a way that maximises the profit, and minimises the energy use and environmental impacts. The minimisation goal, the objective, for the MILP model is described by the objective function that is independent of the model. Hence, several objectives can be used for the same model but only one objective function at a time. The objective functions defined in the analysis are minimisation of conversion cost, energy use and CO₂ emission and residues to landfill.

Generally, the objective function imbedded within the optimisation model, in mathematical terms can be written as follows

\[
\min z = \sum_{i=1}^{n} c_i x_i, \quad x_i \in R
\]  

... (1)

where,  
- \( z \) is the objective function for the minimisation problem. In this case it is the CO₂ emission which is set for the purpose of the optimisation;  
- \( x \) is the studied variables (\( x_i \) means the \( i^\text{th} \) variable);  
- \( c \) is the coefficients for the objective function, and it depends on the objective function. For example, it could be emission factors for the variables.

The coefficients for the objective functions used in the following case calculations are given in Table I.

Emission factors for direct emissions are based on carbon contents of the raw materials and the material factor considered is the Fe-content of the materials. Emission and material deductions are also made for the deliveries of prime slabs from the system and for some carbon rich by-products. Description of by-product recovery within the model have been included to some extent, but is not fully covered in this version. The credit coefficients for products leaving the system are given in Table II.
Table I, Coefficients for the objective function.

<table>
<thead>
<tr>
<th>Unit</th>
<th>CO₂ direct (metric ton)</th>
<th>Energy (GJ)</th>
<th>Material (t Fe/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coking coal</td>
<td>2.948</td>
<td>30.0</td>
<td>0.004</td>
</tr>
<tr>
<td>PCI coal</td>
<td>2.822</td>
<td>28.2</td>
<td>0.003</td>
</tr>
<tr>
<td>Iron ore pellets</td>
<td></td>
<td></td>
<td>0.667</td>
</tr>
<tr>
<td>Scrap</td>
<td>0.015</td>
<td>-</td>
<td>0.97</td>
</tr>
<tr>
<td>Ferrosilicon</td>
<td>0.002</td>
<td>-</td>
<td>0.24</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.440</td>
<td>-</td>
<td>0.002</td>
</tr>
<tr>
<td>Dolomite</td>
<td>0.477</td>
<td>-</td>
<td>0.002</td>
</tr>
<tr>
<td>Burnt dolomite</td>
<td>-</td>
<td>-</td>
<td>0.003</td>
</tr>
<tr>
<td>Other fluxes</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>Alloys *</td>
<td>0.220</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Oxygen</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Power</td>
<td>-</td>
<td>3.6</td>
<td>-</td>
</tr>
</tbody>
</table>

*) Calculated as a mean C-value for composition adjustment.

Table II, Credit coefficients for the objective function.

<table>
<thead>
<tr>
<th>Unit</th>
<th>CO₂ direct (metric ton)</th>
<th>Energy (GJ)</th>
<th>Material (t Fe/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel slabs</td>
<td>-0.015</td>
<td>-</td>
<td>-0.975</td>
</tr>
<tr>
<td>By-product tar</td>
<td>-3.387</td>
<td>-41.95</td>
<td>-</td>
</tr>
<tr>
<td>By-product benzole</td>
<td>-3.368</td>
<td>-48.67</td>
<td>-</td>
</tr>
<tr>
<td>By-product sulphur</td>
<td>-</td>
<td>-2.213</td>
<td>-</td>
</tr>
<tr>
<td>Power</td>
<td>-</td>
<td>-3.6</td>
<td>-</td>
</tr>
</tbody>
</table>

After the objective function is established, some necessary boundary conditions are defined to govern the process in order to make sure the results are reasonable and may be identified in the current model. The boundary conditions can be expressed by Equation 2 which is used to describe variations in the system.

\[ x_i \leq b_i, i = 1, ..., n \]  \hspace{1cm} \text{...}(2)

where, \( b_i \) describes the boundary for the \( i \)th variable \( x \). The \( x_i \) variables could be the corresponding flow variables, and the boundaries, \( b_i \), are the corresponding restrictions. The constraints for the most important system nodes are summarised in Table III.

The main target with this case calculation is to demonstrate the methodology. Reasonable upper boundaries for the level of scrap use in the BF and BOF has been set to approximately 20 and 30 percent of the ferrous burden charged to each process. This means that the operation of this system is within established metallurgical borders but yet a very high accumulated scrap utilisation is conceivable. It should be noted, however, that the following model work is inspired by the model created for SSAB Tunnplåt AB but that it does not take into account all practical limitations and boundary conditions, why the results at this stage of the development does not fully reflect the actual situation at the site.

Energy intensity
In this calculation defined as the total energy consumed to produce prime slabs normalised by the amount of slabs produced. In the model plant the energy intensity is influenced by the possibility to produce electricity within the system.

CO₂ emissions
The CO₂ emission per tonne of slabs is based on the difference between ingoing carbon and the carbon content of products.

Material efficiency
Material efficiency measures the amount of material used for steel production compared to the material which is disposed of, either in secondary products, landfill or incineration. In the following calculations the material efficiency has been defined as the difference between ingoing iron and iron content in produced slabs, in other words a yield factor for Fe within the system. This is a definition which diverges from the IISI definition of material efficiency which instead focuses on the difference between steel produced and waste produced. With further model development it will be possible to optimise the material efficiency also by the IISI definition.
Table III, Main constraints for the principal nodes of the model.

<table>
<thead>
<tr>
<th></th>
<th>BF</th>
<th>BOF</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prod. [t/h]</td>
<td>-</td>
<td>-</td>
<td>250</td>
</tr>
<tr>
<td>Scrap use [%]</td>
<td>Limited to 20</td>
<td>Limited to 30</td>
<td></td>
</tr>
<tr>
<td>FeSi use [%]</td>
<td>0</td>
<td>Unlimited</td>
<td></td>
</tr>
<tr>
<td>% C in product [%]</td>
<td>4.5-4.7</td>
<td>0.05</td>
<td>0.2</td>
</tr>
<tr>
<td>% Si in product [%]</td>
<td>0.2-1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Coal injection [kg/t]</td>
<td>0-200</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Slag volume [kg/t]</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Slag CaO/SiO₂</td>
<td>-</td>
<td>1.05</td>
<td>4</td>
</tr>
<tr>
<td>Tap temperature [°C]</td>
<td>1468</td>
<td>1680</td>
<td></td>
</tr>
</tbody>
</table>

RESULT AND DISCUSSION

Optimisation of different objectives

The results of optimisation of the system are given in Table IV. Typical (reference) operational data are given for comparison. The different objectives have been optimised one at a time and the solution for minimisation (in the case of material efficiency maximisation) of each objective function can therefore be different.

Table IV, Optimisation results for the defined case.

<table>
<thead>
<tr>
<th>Objective value</th>
<th>Typical (reference)</th>
<th>Min CO₂</th>
<th>Min Energy</th>
<th>Material efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emission [t/t slabs]</td>
<td>1.593</td>
<td>1.297</td>
<td>1.313</td>
<td>1.821</td>
</tr>
<tr>
<td>Material efficiency [%]</td>
<td>98</td>
<td>95</td>
<td>95</td>
<td>98</td>
</tr>
<tr>
<td>HM ratio BOF [%]</td>
<td>82</td>
<td>72</td>
<td>72</td>
<td>97</td>
</tr>
<tr>
<td>Scrap (ext) [%]</td>
<td>15</td>
<td>40</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Coke prod. [t/h]</td>
<td>71</td>
<td>54</td>
<td>54</td>
<td>81</td>
</tr>
<tr>
<td>BF Pellets [t/t HM]</td>
<td>1.371</td>
<td>1.098</td>
<td>1.093</td>
<td>1.371</td>
</tr>
<tr>
<td>Scrap [t/t HM]</td>
<td>0.000</td>
<td>0.188</td>
<td>0.188</td>
<td>0.000</td>
</tr>
<tr>
<td>Coke+Coal [t/t HM]</td>
<td>0.424</td>
<td>0.418</td>
<td>0.424</td>
<td>0.473</td>
</tr>
<tr>
<td>Slag volume [kg/t HM]</td>
<td>129</td>
<td>145</td>
<td>129</td>
<td>174</td>
</tr>
<tr>
<td>Hot metal (HM) [t/h]</td>
<td>227</td>
<td>207</td>
<td>205</td>
<td>260</td>
</tr>
<tr>
<td>BOF HM [t/t LS]</td>
<td>0.868</td>
<td>0.780</td>
<td>0.783</td>
<td>0.992</td>
</tr>
<tr>
<td>Pellets [t/t LS]</td>
<td>0.010</td>
<td>0.000</td>
<td>0.000</td>
<td>0.060</td>
</tr>
<tr>
<td>Scrap [t/t LS]</td>
<td>0.184</td>
<td>0.300</td>
<td>0.300</td>
<td>0.031</td>
</tr>
<tr>
<td>FeSi [t/t LS]</td>
<td>0.000</td>
<td>0.014</td>
<td>0.009</td>
<td>0.000</td>
</tr>
<tr>
<td>Slag volume [kg/t LS]</td>
<td>48</td>
<td>238</td>
<td>229</td>
<td>64</td>
</tr>
<tr>
<td>Liquid steel (LS) [t/h]</td>
<td>262</td>
<td>262</td>
<td>262</td>
<td>262</td>
</tr>
<tr>
<td>CC Prime slabs [t/h]</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
</tbody>
</table>

In general terms the most energy and emission efficient solutions are to produce HM and LS with maximised amounts of scrap load. This lowers the coke needs within the system but will also cause some iron losses due to extended slag volumes. To optimise the material efficiency the model prescribes a high hot metal ratio and limited slag losses. The results points at solutions which deviate from what is considered “normal” practice and are therefore not fully validated against actual production data or facilities. When working closer to industrial practice, the systems usually have less adjustment means than described here. It is the common to define minimum and/or maximum limits for some of the variables depending on factors such as supply, cost, contamination risk, or that materials are difficult to handle because of equipment limitations etc. Another important factor is that the effects on productivity has not yet been included in the model.
Multi objective analysis

The steel production system is subject to several different criteria regarding energy and environmental effects, making the decision-making more complex. Different objectives might be in conflict to each other, e.g. a decreased energy use or CO₂ emission might result in an increased production cost or decreased material efficiencies. By including the different objectives directly in the objective function, new analysing possibilities arise. An elementary type of analysis is to graphically or numerically estimate any interplays or contradictions between different objectives. Such analysis, as given in Figure 6, discloses an almost linear covariance between CO₂ emission and energy use. This is normal for integrated steelmaking since it is heavily dependant on carbonaceous reducing agents such as coal and coke.

![Figure 6, Correlation between objectives for a number of calculated operational modes for the steelmaking system](image)

For conflicting objectives there are different methods for performing multi-objective analysis. Some of these are the weighted sum, ε-constraint and goal programming. In the ε-constraint method, one objective is optimised while the other objectives are bounded through global constraints. This approach makes it possible to define pareto optimal fronts which defines the optimised boundary of the feasible solution range for a for bi-objective optimisation problem. The pareto front curve represents all the solutions from minimising one objective with upper level constraints bounded by the other objective, and vice versa. This makes it possible for the decision maker to grasp an acceptable trade-off between the two goals by considering the different solutions along the pareto front.

![Figure 7, Principal pareto front curve between CO₂ emissions and material losses (dashed line), circular dots indicates calculated example operational modes](image)
Figure 7 illustrates the practical meaning of the pareto front which connects the solutions for the two optimisation problems *minimum CO₂ emission* and *maximum material efficiency*. The example operational points are all located on, above, or to the right of the dotted line. This type of analysis can be forceful to conduct when the objectives are conflicting or appear to be incompatible.

**Summary**
The complex structure of the energy and mass flows in steelmaking has resulted in many attempts to describe the process dynamics by models. Swedish steelmaker SSAB Tunnplåt has long practical experience on how to use optimisation models for planning and decision-making related to energy and material utilisation. Sustainable development is development aimed at improving the quality of life for everyone, and is a factor of increasing importance in the industry. This paper exemplifies how optimisation models can be used for systematic analysis, design and balancing of steelmaking systems, and how it can be used for optimisation of sustainability indicators such as energy efficiency, greenhouse gas emissions and material utilisation with a limited effort and time. The methodology can also be extended to include cost optimisation.

**Further work**
The model description in this work is from an ongoing project and more detailed models and result are to be expected. Further work will include improved descriptions of alternate energies, by product loops, and element balances.

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