IN SEARCH OF STABILITY – INVESTIGATING FLEXIBLE AND STABLE PRODUCTION STRATEGIES FOR AN OPTIMISED STEEL PLANT

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Abstract

It is crucial for a steel making production system to operate at the lowest possible production cost, while satisfying stability and reliability conditions. To plan future production strategies, it is therefore important to be able to model the system behaviour when internal and external parameters are changed. In this study the sensitivity and stability of an optimised solution, of an integrated steel plant, have been investigated. The solution’s sensitivity has been analysed taking both internal process changes and external price variations into account, through applying both simulation and optimisation. The analysis also includes both costs and environmental issues such as carbon dioxide and sulphur emissions. Based on the methodology suggested, it is possible to determine the stability of the system solution, including both economic and environmental performance.
Introduction

Due to industrial companies’ high degree of risk aversion it is important to have good decision support to aid decision making [1]. It is crucial for an industrial system to operate at the lowest possible production cost, while satisfying stability and reliability conditions. In addition, good performance with regard to environmental criteria such as carbon dioxide (CO$_2$) and sulphur emissions are of great importance for steel industries due to their high energy intensity and the national environmental directives. In order to plan future strategies, while taking changed conditions into account, it is therefore important to be able to model these criteria.

In an industry, several conditions are likely to change: regulations and the prices of material and energy, as well as variations in process flows due to natural fluctuations, or maintenance and repair. Hence, the production strategies should take these potential changes into account to reduce sensitivity to changes. The decrease in sensitivity to fluctuating conditions can be made either by finding a stable production strategy whose system cost only changes slightly if some conditions are changed, or by being flexible, i.e. adapting to the changed conditions.

Research studies often include some kind of sensitivity analysis, where one or several input data are changed, to determine the effect on the system solution. But it is seldom the case that process change effects are analysed; moreover it is also rare for more than one decision criterion to be included in the analysis. This study aims to include these two important aspects in order to investigate the sensitivity and stability of an optimised system solution when different conditions are changed. This study is an extension of an earlier study that analysed the choice of system boundary where a renovation of the coke oven plant was chosen as the case study. The stability of the suggested operation practice is analysed based on changed conditions for inner and outer conditions such as changes in process parameter and material/energy costs.

Method

The modelling of the studied system is performed in a developed process integration (PI) tool, which is based on the MIND method (Method for analysis of INDustrial energy systems) [2]. This analysis method is in turn based on mathematical programming, more precisely Mixed Integer Linear Programming (MILP), which in this study is solved using the commercial optimisation software CPLEX [3].

Stable production is of the utmost importance for a steel industry. Nevertheless, several external and internal conditions vary or are likely to do so. The system cost might change gradually or drastically in response to changed conditions. A stable solution is characterised by a slow, gradual change in system cost for operation practice outside the optimised solution. We will include both internal and external changes in order to make a thorough analysis of the optimised solution’s stability. The internal changes will be analysed through changes to the analysed parameter with fixed operation practice for the rest of the system, in order to see the effect of the different factors’. For the external changes, both simulation and optimisation will be applied in order to analyse the stability of the solution. The analysis will also include environmental issues such as carbon dioxide and sulphur emission in order to study their stability.
Model description of the studied system

The analysed steel plant, SSAB Tunnplåt AB, consists of a coke oven plant, a blast furnace (BF) with hot stoves, two basic oxygen furnaces (BOF converters), unit processes (CAS-OB and RH vacuum degassing unit) and two continuous casting units (CC) with an annual production of 2.3 Mtonne steel slabs. The different processes have been modelled separately and are connected together by each primary product and by-product interactions. The model’s level of sophistication varies between linear process models, empirically derived process relations based on engineering practice, and models based on mass and energy balances for the different processes. The primary driving force for the model is the required production of steel slabs. Each sub-process is linked to the next processing step by the primary product from each process, i.e. coke, hot metal (HM), and liquid steel (LS). The steel demand from the CC units will thus determine the production rate in the BOF, which in turn will determine the hot metal rate for the BF and so forth. The use of external material is based on the process requirements for each sub-process. The consumption and excess of by-products are also determined from each sub-process model. The problem is broken down into identified sub-processes, with delimitations and simplifications identified from the previous analysis [5].

In a traditional integrated steel plant, the process gases are normally used internally as primary fuel for the coke ovens, the hot stoves and the pusher ovens in the rolling mill. But because the rolling mill for this steel plant is located at another company site, the structure of the steel plant has resulted in a surplus of energy-rich process gases, which are used by external gas consumers, such as a CHP plant. For the CHP plant model, the driving force is the demand for district heating. The major energy and material flows in the modelled system are shown in Figure 1. The main processes in the system are indicated in the figure as well as the steel plant and CHP plant system boundary.

All efficiencies and specific process-related data used are based on actual production data from the steel plant and the CHP plant. The development of the model used is further described in previous studies, where the possibilities for reducing specific energy use and the choice of system boundary during a coke oven renovation were analysed [4,5].

Figure 1. A schematic outline of the modelled system.
Objective function

The objective is to minimise the total cost for the system, which includes material and energy costs and revenues except the income from selling the steel slabs produced. All fixed costs and labour costs are also ignored. The costs included are based on the actual costs for material and energy at the steel plant. Costs and revenues are expressed in SEK/tonne for material flows, SEK/knm³ for gaseous flows, SEK/MWh for electricity and SEK/GJ for energy flows. Note that the CHP plant is co-owned by the steel plant and the municipal energy company. This is the main reason why it is included in the system boundary and why sold electricity and district heating are part of the objective function instead of described as gas sold to the CHP plant.

In addition to the minimisation of costs, two environmental goals are analysed, CO₂ and sulphur emissions, but not included in the optimisation. These are two environmental issues with high priority for the steel plant, primarily due to the Kyoto agreement [6] and the Swedish Parliament’s environmental quality objective [7] that regulates the permitted level of sulphur emissions. The calculation of CO₂ emissions is based on direct and indirect emissions, while the sulphur emission includes only direct emissions.

Main results for the renovation practice in the system boundary study

The renovation of the coke ovens results in a coke and coke oven gas deficit for the system. It was shown that the interactions between the different production units in the system were important to take into consideration in the analysis [5]. The total system cost could be reduced by widening the system boundary of the optimised system. It was also shown that the total system optimum was reached for case 3†, which has the widest system boundary. The gain was mainly in the coke oven plant for all cases. The effect of an widened system boundary on the system cost is shown in Table 1.

Table 1. The system costs for the different cases compared to the reference case

<table>
<thead>
<tr>
<th></th>
<th>Coke oven plant</th>
<th>Blast furnace</th>
<th>BOF</th>
<th>CHP plant</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share of costs (%)</td>
<td>34</td>
<td>63</td>
<td>16</td>
<td>(-12)</td>
<td>100</td>
</tr>
<tr>
<td>Case1 (coke oven plant)</td>
<td>-4.4</td>
<td>-0.1</td>
<td>0.9</td>
<td>(0.0)</td>
<td>-1.5</td>
</tr>
<tr>
<td>Case2 (steel plant)</td>
<td>-12.4</td>
<td>0.7</td>
<td>-3.0</td>
<td>(0.0)</td>
<td>-4.2</td>
</tr>
<tr>
<td>Case3 (steel and CHP plant)</td>
<td>-13.6</td>
<td>0.4</td>
<td>-3.0</td>
<td>(-7.2)</td>
<td>-5.7</td>
</tr>
</tbody>
</table>

The optimum solution for the widest system boundary resulted in a production practice where one sub-system (the BF system) had a higher cost than in the reference case. Although the renovation was made in the coke oven plant, its effects were seen in other parts of the system. One explanation for this is that when only the coke oven system is optimised, it is to meet the demand for coke and coke oven gas. Hence, no attention is paid to how the coke and gas are used. In the cases where the steel plant is included in the analysis, interactions between the different processes that would otherwise be overlooked are also included. The choice of

Indirect emissions: emissions from raw material preparation and credits for by-products, e.g. electricity generation in the CHP. The calculation principle used are further described in [8]. Electricity is allocated with CO₂ depending on production alternative, in this study 0.6 tonne/MWh has been used. A thorough discussion of electricity emission accounting is preformed in by Sjödin and Grönkvist [9]. The effect of different electricity emission accounting on the system is an issue that must be investigated further.

† Case 1 included a boundary where only the coke oven plant was optimised, case 2 included the whole steel plant, and case 3 the CHP plant as well.
system boundary should therefore include both primary and secondary process variables. Primary process variables are those that are directly affected by the proposed changes, in this case variables in the coke oven plant. Secondary process variables are those that are affected by the alteration indirectly, in this case, basically process variables that affect the operation practice in the BF, BOF, and the production rate.

Specific changes in primary and secondary variables were identified. During renovation, a reduction occurs in the supply of both coke and coke oven gas*. But the deficit can be reduced by making changes in addition to those made in the coke oven plant. In order to manage the material and energy balance for the system, both the coke oven, steel plant/CHP plant practice are changed. During renovation, the following practice was proposed:

- The coke oven should be operated with a slightly higher volatile mix (VM) than during normal operation, but lower than the reference case.
- The BF practice is changed to a higher blast temperature (BLT) and pulvèrisèd coal injection (PCI) rate resulting in a lower coke demand.
- The primary fuel for the CHP plant is changed to more BF gas and BOF gas.
- The slab production rate is decreased compared to the reference system.

**Identification and quantification of analysed parameters**

Based on these previous findings the different changes that will be analysed further in this study were identified. Changes to external input data, i.e. costs, are also included.

**Internal variations that affect the solution**

The internal parameters that were changed for the renovation period were the volatile matter in the coal mix for the coke oven, the blast temperature, pulvèrisèd coal injection rate for the BF and the hot metal /scrap rate for the BOF. The changes introduced are summarised in Table 2.

<table>
<thead>
<tr>
<th>Coke Oven</th>
<th>BF</th>
<th>BOF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal Blend wt% VM</td>
<td>PCI kg/tHM</td>
<td>BLT °C</td>
</tr>
<tr>
<td>Reference</td>
<td>24.8</td>
<td>135</td>
</tr>
<tr>
<td>Optimised</td>
<td>23.6</td>
<td>151</td>
</tr>
<tr>
<td>Difference</td>
<td>-4.8%</td>
<td>+11.9%</td>
</tr>
</tbody>
</table>

For the optimised system, the volatile matter in the coke oven system was decreased by 4.8%. The volatile matter in the coal mix is dependent on the different coal types available and is usually not temporarily changed. In this analysis, the solution is analysed in respect of a ± 5% [22.6, 25] change in the volatile matter. For the blast furnace, two main factors were changed in the optimisations: the PCI rate and the hot blast temperature. The PCI rate was increased by 11.9%. The solution is analysed in respect to a decrease of 11% in PCI rate, [130, 151] kg/tHM, where the upper limit is given by the optimised solution. For the BLT, the increase was 4.4%. The solution is analysed in respect to a decrease of 2% in BLT, [1130, 1151] °C, where the upper limit is given by the optimised solution.

* We present only suggested product practice during renovation. For more details about normal practices, please refer to the previous study [5].
The volatile content in the coal mix and the hot blast temperature and PCI injection in the BF were chosen for further analysis. The scrap/HM rate in the BOF was rather an effect of the internal HM price and thus the effect of an external parameter.

External variations that affect the solution

The external parameters investigated are energy related, i.e. the prices of electricity and coke. Coke and coal are essential as both raw material and energy carriers for the system. Only a change in the price of coke is analysed because the effect on the system is similar for a change in the price of coal. The recent change in the price of coke is also larger than for coking coal. Electricity is the second energy resource used in the system, and in addition is produced in the CHP plant.

The price of electricity in Sweden has historically been low due to the good availability of cheap production such as hydropower and nuclear power. Due to the European free trade directives for products such as electricity [10], the price can be expected to increase significantly. This is because European levels are up to double those in Sweden, Figure 2. The analysis is made for a change in the price of electricity from 80 to 150% compared to the actual price for the steel plant and the CHP plant today.

The coke prices were quite stable until recently when they accelerated. According to the “Coke Market Report” [12], the Chinese coke prices increased from 60 to nearly 300$/t fob (excluding transport) during the period from the middle of 2002 until the end of 2003. The price range in the analysis was set to 80-200% compared to the base optimised case.

Results

Three internal variations and two external variations were analysed. The effects of the internal variations were analysed by simulation. The optimised solution for the system boundary study [5] will from now on be referred to as the reference solution. The reference solution practice was used on all parameters other than the studied parameter. For the external variations, the effects are evaluated based on both simulation and optimisation.

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* District heating is also produced in the CHP plant, but quantities are dependent on customer demand.
† When the electricity price was changed, the oxygen price was changed by the same amount to get a fair comparison. This is because oxygen production is very electricity intensive and thereby highly dependent on the electricity price.
Internal variations

The impact on the cost objective of a change in volatile matter is shown in Figure 3. The effect on the cost objective differs between a higher volatile matter and a lower. In the case of lower volatile matter, the coke oven gas is in deficit, resulting in supplementary oil firing. The effect on the cost objective, however, is low. A decrease in volatile matter results in lower sulphur and CO$_2$ emissions. For an increased volatile mix, the cost is slightly increased. For the sulphur emission the increase is a result of the new coal mix, with higher sulphur content. The increase in CO$_2$ emissions are a result of the increased volatile mix.

The PCI rate influence on the cost objective is shown in Figure 4a. A lower injection rate increases the cost objective slightly. The sulphur objective is reduced while the CO$_2$ objective is nearly unchanged. The BLT influence on the cost objective is shown in Figure 4b. The effect on the cost objective is small. A lower blast temperature increases the cost and the CO$_2$ and sulphur emissions. The effects are small over the whole range.

External variations

The effect of the electricity price on the total system when simulating is small, mainly because the CHP plant produces almost as much electricity as the steel plant requires. A 10% change in the electricity price leads to a 0.22% change in the total system cost, which is a linear relation.

When optimising the system for changed electricity price, Figure 5, the only significant difference occurs for the sulphur emissions. With a lower price, the volatile matter in the coal mix is decreased to 22%. The decrease in sulphur emissions are mainly dependent on the choice of a coal mix with lower sulphur content.
For a change in the price of electricity of 20%, only minor changes in the operation practice occur. The volatile matter in the coal mix is increased somewhat, leading to a higher sulphur content. With a 40% increase in the electricity price, the hot blast temperature and PCI are decreased, which increases the amount of external coke. In addition, more blast furnace gas is used in the CHP plant to increase electricity production. These changes have only minor effects on the total system cost. The only significant change is the reduction in sulphur emissions.

External coke’s share of the total system cost was found to be 12.3% for the reference operation practice. A simulation of the coke price gives a linear relation, hence a 10% increase in the price of coke leads to an increase in total cost of 1.23%, with unchanged operation practice.

For the optimised system, significant effects occur for both CO$_2$ and sulphur emissions when the coke price is changed, Figure 6. When it is doubled, the potential for cost reduction is almost 2% compared to the simulated case. This is due to the increased use of scrap instead of external coke for metal production.

The main effect on CO$_2$ occurs with a 170% increase in the price of coke or a reduction to 80%. The effect of increased CO$_2$ emissions when lowering the price to 80%, is mainly due to the increased use of external coke and decreased use of scrap. The effect, however, is reduced somewhat by an increase in electricity production. In the case where the price of coke is increased by 170% or more, there is a CO$_2$ reduction, in this case related to the use of less external coke and instead more scrap.

For the sulphur emissions, reducing the coke price to 80% results in lower emissions. This occurs although more coke is used because less PCI is used and more sulphur is bonded in slag. When the price is increased by 170%, the sulphur emissions also decrease, now mainly due to the smaller amount of external coke used even though the smaller quantity bonded in slag reduces the effect.

**Discussion**

This study has investigated the sensitivity and stability of an optimised solution. The solution’s sensitivity has been analysed taking both internal process changes and external price variations into account. The analysis also includes both costs and environmental issues such as carbon dioxide and sulphur emissions. The inclusion of both internal and external changes makes it possible to make a thorough analysis of the optimised solution’s stability. As regards the internal changes, we changed the analysed factor with fixed operation practice for the rest of the system in order to see the effect of the different factors on the system.

Two methods were applied to analyse the stability when external changes were made: simulation and optimisation. Simulation was used to investigate the effect of the changed parameters on the existing system cost. With the optimisation made when the external
conditions were changed, it is possible to analyse both when a change in operation practice occurs and what effect it has on the system cost and CO$_2$ and sulphur emissions. Based on these results, it is also possible to analyse the stability of the system solution, including both economic and environmental issues.

**Stability of the studied system**

The effects of changes in internal parameters are small. The different objectives are affected in different ways. The increase in the cost objective, when the volatile matter is decreased, is due to a shortage in coke oven gas. Decreasing the amount of volatile matter results in a smaller demand for coking coal, which in turn results in lower CO$_2$ and sulphur emissions. When the amount of volatile matter is increased, the effect on the cost objective is small. For the PCI rate in the BF, the effect is slightly different. The cost objective is only slightly increased, while the CO$_2$ emissions are almost unaffected. However, the sulphur emissions decrease with a lower injection rate, suggesting that the BF operation practice with low injection rates will result in a global decrease in sulphur emissions for the system. With a lower hot blast temperature, the different objectives are somewhat increased. Hence, a change in the important internal parameters will not drastically change the objective value.

The effect on the system cost of changes in external parameters was largest for the change in the price of coke. The change in the price of electricity has only a small effect on the system cost due to internal production of electricity that is almost as large as the quantity used (when electricity use for O$_2$ production is included). With a change in the price of coke, the environmental effects are mainly due to the amount of scrap used in the process, i.e. the more scrap that is used, the better the environmental performance. However, note that scrap has originally been produced with certain emissions, though it certainly indicates the importance of recycling. For a change in the electricity price, it is only sulphur that has a significant reduction, mainly due to changes in the coal mix and use of PCI in the blast furnace.

The system solution is a combination of the different parameters, which were suggested to lessen the effects of renovation of the coke oven. The solution suggested in the coke oven analysis has been shown to be characterised as slow and gradually increasing for an operation practice slightly outside the suggested operation practice. Hence, an endeavour to achieve an operation practice in the direction of the optimised solution will result in a better system solution, even if some parameters cannot be changed to the same extent as suggested here, e.g. the volatile matter in the coal mix.

**Conclusions**

Through using both simulation and optimisation it is possible to analyse the stability of both economic and environmental performance. In this case the stability of a optimised system solution for a integrated steel plant with an connected CHP plant has been analysed. The analysis suggests that the system solution is stable for the studied internal changes. For changes of external parameters, i.e. electricity and coke price, the solution also showed to be stable because it required a large change of price before the solution changed. The variations also affect environmental criteria for the system, e.g. CO$_2$ and sulphur emissions from the system. For the analysed system it was concluded that the use of scrap had the most significant effect on the environmental performance. Further analysis is needed of how different objectives are influenced by each other.
Acknowledgement

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References


