Adaptation of process integration models for minimisation of energy use, CO_2-emissions and raw material costs for integrated steelmaking

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The structure of the energy and mass flows in steelmaking is rather complex with a lot of connections between the unit processes. A further developed optimisation model for integrated steelmaking based on mixed integer linear programming (MILP) is described. The system includes today's dominating steel production route, basic oxygen steelmaking, based on iron ore, steel scrap, and carbonaceous reducing agents. Multi or single objective minimisation problems in steelmaking are represented by energy use, CO_2 emissions and raw material cost to produce steel slabs. Finally the paper briefly discusses the effects of process and product related constraints on the modelling results.

1. Introduction

1.1 Background

Analysing the potential for improving energy use and environmental performance in steelmaking often involves multifaceted interaction between several process sub systems. Improvements in a part of the system can propagate to other parts and the total effect is not always a change for the better. A systematic approach can be of major help to avoid non-optimised solutions 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.

1.2 Steelmaking

Steel is basically an alloy of iron and carbon. It can be produced from iron oxide (iron ore) in a multi stage process were blast furnace (BF) ironmaking and basic oxygen steelmaking (BOS) are the two most important process steps. In the BF process iron ore is converted to liquid (1400-1500 °C) iron, or hot metal, by reduction and smelting with additions of coke/coal and fluxes e.g. limestone. In the following BOS step, the carbon-rich hot metal is converted to low carbon liquid steel in the basic oxygen furnace (BOF) by blowing oxygen onto the metal bath, causing the temperature to rise to about 1700 °C.

Depending on local conditions, e.g the availability of scrap, blast furnace hot metal and the extent of hot metal pre-treatment, 70-95% of the metallic charge is hot metal and the remainder steel scrap. Scrap is recycled iron or steel. In some BOS practices, also limestone, dolomite and/or iron ore are used as coolant when needed, to prevent the melt and furnace from overheating. Carbon and silicon, transferred from the BF to the BOF, are very important elements for the heat balance in the BOF converter. The silicon content directly influences the possibility to charge scrap in the heat as it provide reaction heat to the process. The hot metal composition also influences the lime consumption in the converter, hence the resulting slag volume and metallic yield. The total steelmaking system also consists of a coking plant and casting machine, and supporting processes, see Figure 1.

2. Method

2.1 Optimisation with a MILP model

In a survey on mathematical programming applications, Dutta and Fourer (2001) states that mathematical programming were used in the steel industry as early as 1958. In contrast to the broader application of optimisation in chemical and petroleum engineering, reports from the metallurgical industry has mainly been restricted to application of linear programming for inventory control, blending, scheduling and similar purposes. Deo et al. (1998) describes the possibility to use either mathematical programming or genetic algorithms to find the optimum operating conditions in integrated steelmaking. Up till now, there are unexpectedly few reports on how to solve this type of complex steel plant optimisation problems by process integration tools. The method described in this paper is a mathematical programming tool based on mixed integer linear programming (MILP). Earlier developments of this type of model have been described by Larsson and Dahl (2003), Ryman et al. (2004) and Larsson et al. (2004).

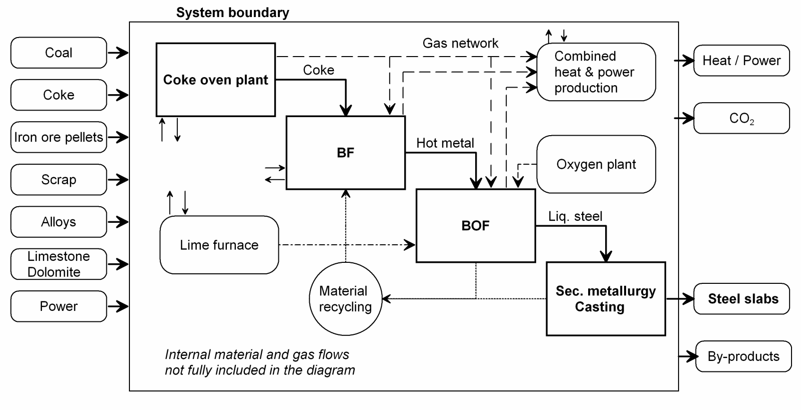

Figure 1, Schematic definition of the steelmaking system.

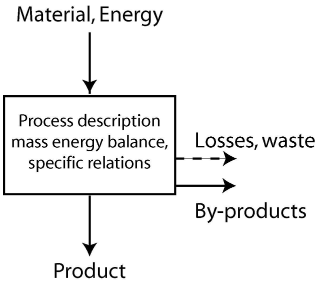

Figure 2, Modelling principle for each sub model.

The model core is an overall mass- and energy balance for the main product and separate sub-balances for the main processes which make 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 full system. 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 2. In the site model the different main processes (i.e. coke oven, BF, BOF, and casting) 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 and liquid crude steel. The steel demand from the casting machines will thus determine the production rate in the BOF, which in turn will determine the production rate for the BF and so forth. In earlier modelling the intermediate products had fixed properties, but in this further developed model, some critical product parameters have been defined as variables, thus allowing improved analysis of the process interaction in the total system.

2.2 Objective function / objectives

An efficient industrial system should be operated in a way that secures 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. Generally, the objective function imbedded within the optimisation model, in mathematical terms can be written as follows

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

where, z is the objective function for the minimisation problem, x is the studied variables (x_i means the ith variable), and c is the coefficient for the objective function. The coefficients for the objective functions used in the following case calculations are given in Table I.

Table 1, Debit and credit coefficients for the objective functions.

	Unit	Energy (GJ)	CO_2 (ton)	Cost* (USD)
Coking coal	(ton)	30.0	2.948	100
PCI coal	(ton)	28.2	2.822	80
Purchased coke	(ton)	28.0	3.035	350
Iron ore pellets	(ton)	-	-	85
Scrap	(ton)	-	0.015	250
Limestone	(ton)	-	0.440	20
Dolomite	(ton)	-	0.477	40
Burnt dolomite	(ton)	-	-	120
Other fluxes	(ton)	-	-	40
Alloys **	(ton)	-	0.220	1000
Power	(MWh)	3.6	-	50
Steel slabs	(ton)	-	-0.015	-
Tar	(ton)	-41.95	-3.387	-200
Benzene	(ton)	-48.67	-3.368	-600
Sulphur	(ton)	-2.213	-	-20
Power	(MWh)	-3.6	-	-50

*) Estimated in 2006 price level in Europe, from different www-sources.

**) Estimated as a mean values for composition adjustment.

2.3 Problem constraints

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.

$$x_i \le b_i, i = 1,\ldots,n \qquad (2)$$

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 main emphasis of this paper is to describe some of the dynamics in the steelmaking system. To do this, some base constraints for the main processes have been set, see Table 2. These constraints are relatively free, in the sense that the BF and BOF can be operated with different scrap content, that the coke/coal ratio can vary, and that the hot metal silicon content and hot metal temperature are product variables connected to the hot metal flow from the BF to the BOF. Later on, other constraints, and their consequence, will be discussed.

Table 2, Base model constraints for the BF and BOF.

		BF	**BOF**
Prod.	[t/h]	free	250
Pellet use	[%]	80-100% of Fe	Free
Scrap use	[%]	0-20% of Fe	Free
% C in product	[%]	4.7	0.04
% Si in product	[%]	0.2-1.0	0
Coal injection	[kg/t]	100-200	0
Slag volume	[kg/t]	Free	Free
Slag CaO/SiO_2	-	1.05	4
Tap temperature	[°C]	1448-1488	1675

3. Result and discussion

3.1 Single objective optimisation

With the given coefficients and base constraints it is possible to optimise the system for minimum energy use, minimum CO_2 emissions, and minimum raw material+energy cost. The main variables for each solution are given in Table 3. Notice that the solutions for energy and CO_2 minimisation are alike, but the solution for cost minimisation is different.

Table 3, Summarised consumption rates at single objective optimisation.

		Min Energy	Min CO_2	Min Cost
Objective value				
Energy use	**[GJ/t slabs]**	**12.45**	12.45	17.78
CO_2 emission	**[t/t slabs]**	1.259	**1.259**	1.793
Cost	**[USD/t slabs]**	254.9	254.9	**212.5**
Coke production	[t/h]	54	54	81
Coke purchase	[t/h]	29	29	72
Coke+Coal to BF	[t/h]	82	82	119
Pellets to BF	[t/h]	248	248	358
Pellets to BOF	[t/h]	0	0	13
Scrap to BF	[t/h]	47	47	0
Scrap to BOF	[t/h]	60	60	20
Hot metal prod.	[t/h]	207	207	240
Liquid steel prod.	[t/h]	262	262	262
Prime slab prod.	[t/h]	250	250	250
Power	[MWh/t]	18	18	5

3.2 Bi- and multi-objective optimisation

The steelmaking system is subject to several different criteria regarding energy, emission and cost effects, which makes the decision-making complex. For conflicting objectives there are different methods for performing multi-objective analysis. If one objective is optimised while the other objectives are bounded, it is possible to identify a Pareto front curve which defines the boundary of the feasible solution range for a bi-objective optimisation problem. In Figure 3a, this has been done for the energy and cost objectives.

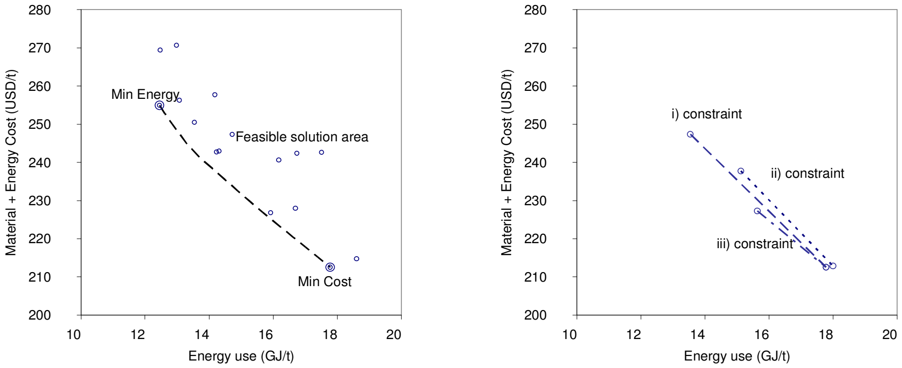

Figure 3, a) Pareto front and operability range, b) Pareto fronts influenced by constraints.

The example operational points in Figure 3a, are all located on, above, or to the right of the Pareto front curve. It is conceivable to handle three or more objectives accordingly, however with greater challenges to illustrate the results graphically.

3.3 Constrained system optimisation

When working with specific industrial systems, it is necessary to consider more restrictions and to work with less adjustment means than described so far. In practice, at least two types of constraints have to be taken into account in the model; *i*) raw material and energy supply limits, and *ii*) equipment restrictions, productivity factors, batch size etc. Also other issues, such as product flexibility and quality, contamination risks, environmental concerns etc. might play an important role in an actual industrial optimisation. In the steelmaking model, it is possible to define correct limits to include e.g. possible raw material and energy constraints. This have been exemplified in Figure 3b, where the feasibility range for the bi-objective problem have been exemplified for different practical constraints in; *i*) scrap supply, *ii*) cokemaking capacity, and *iii*) a combination thereof.

3.4 Conclusions

Process integration methods are powerful for analysis and optimisation of steelmaking systems. Bi- and multi-objective optimisation in an unrestricted system gives a general idea of how different objectives are related and the range of feasible solutions. Insertion of practical constraints, e.g. material and energy supply limits, narrows the range of solutions, and can be helpful for identification of real optimisation trade-offs and bottle-necks in the system. Two types of constraints have to be taken into account in industrial application of the model; *i*) raw material and energy supply limits, and *ii*) equipment and system restrictions. Improved constraint handling is a present issue in this model development.

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