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Process integration. Tests and application of different tools on an integrated steelmaking site

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ABSTRACT

The energy network in Luleå consists of the steel plant, heat and power production and district heating. Global system studies are necessary to avoid sub-optimization and to deliver energy and/or material efficiency. SSAB began work with global simulation models in 1978. After that several more specialized process integration tools have been tested and used: Mathematical programming using an MILP method, exergy analysis and Pinch analysis. Experiences and examples of results with the different methods are given and discussed. Mathematical programming has been useful to study problems involving the total system with streams of different types of energy and material and reaction between them. Exergy is useful to describe energy problems involving different types of energy, e.g. systematic analysis of rest energies. Pinch analysis has been used especially on local systems with streams of heat energy and heat exchange between them.

1. Introduction

1.1. Short description of plant site

The system studied in this work is the energy system consisting of the integrated steel plant of SSAB EMEA in Luleå, the Lulekraft Combined Heat and Power (CHP) plant and the Luleå Energi district heating system. The main units of the steel plant are a Coke oven plant, a Blast Furnace, two BOF converters, Ladle metallurgy and two Slab casters. The cast slabs are transported approximately 800 km to SSAB's site in Borlänge where they are rolled into strip material. Normally, integrated steel mills use residual gases from the steel plant as fuel for reheating in the rolling mill. In this case that is not possible because of the distance. Instead a surplus of process gases remains which are fired in a local CHP plant (Lulekraft). This plant produces electricity covering the needs of the steel plant and district heating covering the needs of the community. See Fig. 1.

1.2. Process integration

The energy system of a process industry is a complicated network of units that exchange energy and material between each other. Improved efficiency in one unit does not necessarily improve the total output because of the interaction with its neighbours. A system approach is needed to improve the efficiency of the total site. The following broad definition of process integration was formulated by the International Energy Agency (see Ref. [1]). The Process Integration approach was first developed for Heat Integration studies aiming at energy efficiency improvements, driven by the energy crisis of the 1970s. This led to the development of Pinch Technology. Much of the methodologies for heat integration were developed and pioneered by the Department of Process Integration at UMIST in the UK. A user's guide to Pinch analysis was published by Linnhoff et al. [2] and played a key role in the dissemination of Heat Integration methodology. An excellent overview of further developments of the methodology is presented in [3]. Later on other process integration tools were introduced including exergy analysis, see Refs. [4–7] as well as different mathematical programming methods, e.g. MILP (Mixed Integer Linear Programming, see Refs. [8–13]) and genetic algorithms [14]. Combinations of different methods have been suggested in some cases, e.g. Ref. [15].

SSAB's work in this area began in 1987 with the building and use of in-house models of the energy system consisting of the SSAB site, the Lulekraft CHP plant and Luleå's district heating network. The work was successful and was continued by building a process integration tool based on MILP mathematical programming (reMIND). Later on also exergy analysis and Pinch analysis have been introduced in a number of specific studies.

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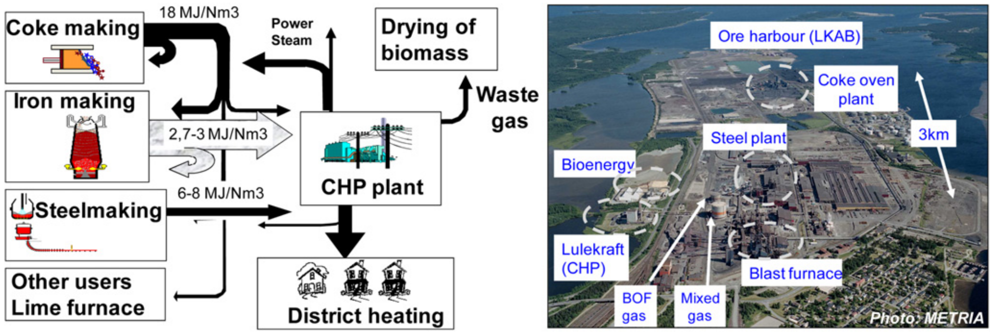

Fig. 1. Energy system of Luleå. Flow sheet (left) and photo (right).

1.3. Scope of paper

The scope of this paper is to describe the application and experience with different process integration tools at the SSAB site in Luleå, including in-house simulation models, mathematical programming, exergy analysis and Pinch analysis.

2. Methods

2.1. Site simulation using spreadsheet models

The first model for optimization of the Luleå energy system was created in 1987 using Supercalc 4 (an early spreadsheet environment) as an internal SSAB project. The model structure is shown in Fig. 2a. The model consisted of three main blocks: the Physical model, the Economic model and the Fluctuation model. The Physical model calculated the process data of all units and calculated the net flows of energy and raw materials in and out of the total system. There were individual models of all units and these models communicated with an INTERFACE model. That model exchanged data between the models and calculated the net flows in and out of the total system. No direct exchange of data between the submodels was allowed. The reason for this was both to prevent errors, and to make it possible to "plug in" other models, e.g. if other reduction processes were considered. Relative to the Economic model, the Physical model is a "black box", where only the net flows in and out of the system are visible. These flows were multiplied by the price and added together. The Fluctuation model considered a table of the variations in flow rates, heat values, etc., over one year, made one calculation for each case and calculated a weighed arithmetic mean of the results.

The most complicated sub-process was the blast furnace (BF). An in-house spreadsheet model of that unit had previously been developed [16] and was directly included. The model worked very successfully. However it was complicated and could only be operated by its original creator. It was later exchanged for a simplified Excel model, see Fig. 2b. The economic and variations models were excluded, so these questions had to be handled separately. The description of the desulphurisation was increased to support the modelling of BOF plant. The rolling had been moved to another plant (SSAB in Borlänge) and was excluded from the model.

2.2. Mathematical programming using MILP (Mixed Integer Linear Programming)

Most often the objective is to find an optimal process configuration within a certain solution space. Doing this with a simulation model involves a trial and error procedure calculating a large amount of different operating cases. It was considered important to find an optimization procedure where the best alternative can be found without having to explicitly enumerate and evaluate all possible alternatives.

The work started from an existing mathematical programming tool, MIND [8]. This was used as a base to develop a refined tool that could be used for steel plant and mining system applications. The work was carried out in cooperation between SSAB-LTU-LiU, MEFOS and later on also LKAB. The new tool (reMIND) is now a standard tool for system studies in the Swedish steel and mining industry. Only a brief description is given here as the method and its theory has been extensively published, e.g. in Refs. [8–13]. The optimization problem can generally be described by a set of equations, the equality and inequality constraints describing an area of possible solutions and an objective function describing the parameter that should be minimized or maximized. The reMIND tool is of the MILP type (Mixed Integer Linear Programming) which means that constraints and object functions are described by linear equations. Also integer parameters can be used to describe discrete events, e.g., decisions to start or stop a unit at certain conditions.

Definition of the constraints can be a considerable, and very important, part of the modelling effort, in order to get realistic optimization results. The general procedure is shown in Fig. 3. Data and equations are collected from the plant and existing process models. After linearization a Java-based interface is used to convert these data

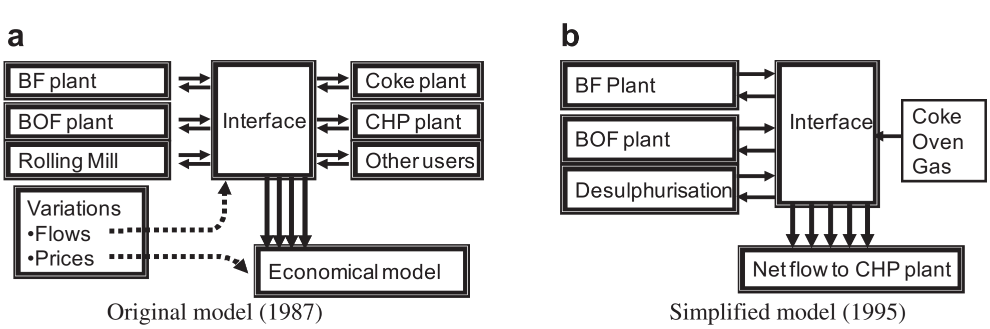

Fig. 2. Spreadsheet simulation of the Luleå energy system. (a) Original model (1987). (b) Simplified model (1995).

into an equation matrix. In this interface the plant site is represented as a network of nodes (units) and their connections and equation data can be written into these nodes. The equation matrix can thereafter be used as input to the optimization module. That module is commercial software, so far most often CPLEX, which selects the most optimal combination of units and parameters.

2.3. Exergy analysis

Energy balances, based on the first law of thermodynamics, are a common tool in technical energy studies. However, a real energy system is also restricted by the second law of thermodynamics, e.g., energies of different quality cannot be freely exchanged with each other. The second law states that the entropy in a closed system cannot decrease. One way of doing this is to include exergy expressions. Most practical cases describe a system in contact with its surroundings. In this case the same appears for the total entropy of system and surroundings. A certain media can produce work only if there is a difference, e.g. in temperature and pressure with respect to the surroundings. The exergy expression describes the theoretically possible production of work as a function of that difference:

$$E = \Delta H - T_0 \times \Delta S \qquad (1)$$

The theory is described in detail e.g., in Ref. [4]

Extensive exergy studies were carried out at the Luleå site in 1989, 2007, 2009 and 2010. Energy and exergy balances were made for the individual sub-units as well as total balances for the system or sub-system that was studied. The studies 1989–2009 covered the steel plant site with different degree of coverage. Data of internal material flows were collected and full energy and exergy balances were created from these data. In the study of 2010 the scope was extended to include also the heat and power plant and the distribution of hot water for district heating. The steel plant balance was based on steel plant data for 2009 [17]. Some data on rest energies were recalculated from the previous studies. The data on power plant and district heating were calculated using 2009 production data from their process computers. For the power plant full data were available only for the period March 2009–February 2010, so those data were used. More data on the calculations are described in a previous publication [18].

2.4. Pinch analysis

The methodology is only discussed briefly as it was described in some detail in a previous paper that investigated application of Pinch analysis methodology to steelmaking [19].

The general principle is visible in Fig. 4. Heat streams are characterized as hot streams that must release heat and cold streams that have to be heated in the process. Corresponding curves in a (T, Q) diagram can be combined to one hot and one cold composite curve (left hand diagram). The curves are then shifted horizontally so as to achieve maximum overlap (corresponding to maximum internal heat recovery within the process), limited by the minimum allowable temperature difference (ΔT_{min}) for heat exchanging between hot and cold streams. The location at which this occurs is the Pinch point. The curves are then shifted upwards and downwards by $(1/2)\Delta T_{min}$, so that they touch at the Pinch point (middle diagram). The horizontal distance between the shifted curves is then plotted as the "Grand Composite Curve".

The Pinch analysis study at SSAB investigated in detail the gas cleaning unit of the Coke Oven Plant. A pre-study had indicated that this unit was most suited. Data was collected together with coke plant staff. The energy streams were compiled and characterized as hot or cold streams. These were compiled into composite and grand composite curves according to the procedure illustrated in Fig. 4.

Fig. 5 shows the resulting Grand Composite Curve for the gas cleaning area. The curve has a "pocket" (shaded in the figure). This pocket indicates possible internal process heat recovery. Similar evaluations were also made for other process units and for the SSAB plant as a whole.

3. Implementation and results

3.1. Site simulation using spreadsheet models

The first model (Fig. 2a) came into immediate use to generate updated heat and gas balances when the coke plant was revamped and working on 60% capacity for 1.5 years. A solution was suggested involving restart of an old oxygen plant, increase of oxygen and coal injection at the BF plant, thus freeing coke oven gas and avoiding the use of purchased oil. Some general results are shown in Fig. 6.

The diagram shows that when oxygen production increases the need for coke oven gas in the blast furnace decreases. A cost saving is obtained when this gas displaces firing of purchased oil in the rolling mill and steel plant. When all oil is displaced the cost saving curve turns down and further injection is not profitable. The suggested solution was implemented and also solved the problem. This also created a long-lasting positive attitude towards process integration among the plant management. The model and its simplified successor (Fig. 2b) were later on used to generate decision material on several occasions. One important example was a large revamping of the hot metal production in 2000. The model was used to study the effect of the energy balances of the system. Three cases were studied: revamping of both BFs, revamping of one furnace and building an electric arc furnace or exchange both BFs with a bigger furnace. The latter solution was selected. The model was then used to calculate the

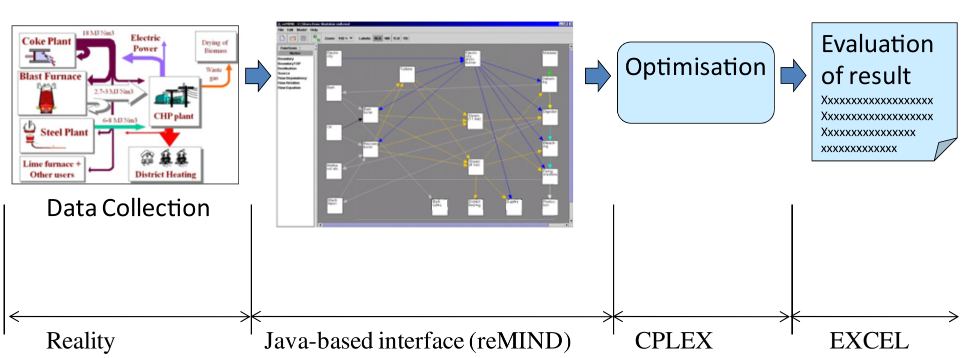

Fig. 3. Mathematical programming of the Luleå system. Procedure steps and their environment.

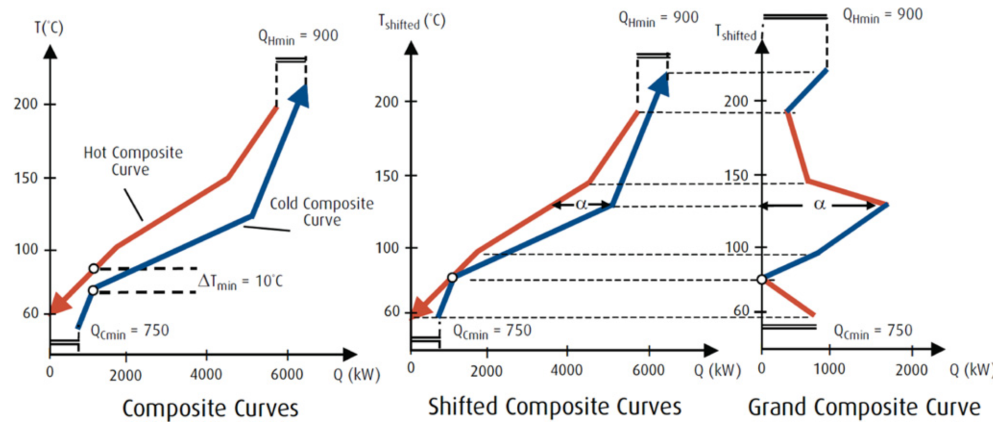

Fig. 4. Principle for construction of Pinch.

modifications needed in the CHP plant (especially cooling because of increased gas delivery).

3.2. Mathematical programming using MILP (Mixed Integer Linear Programming)

The reMIND model was first developed as an energy model and was used for energy studies and optimization in different internal projects. However, the model includes both energy and material balances, and the choice of objective function is optional. This has increased the scope to include studies of material efficiency, environment and emissions of climate change gases, etc. Fig. 7 shows an early example where reMIND was used to optimize raw material flow, recycling and landfill. The first 7 cases show the reference case and simulations of different improvements. In the last 2 cases the model has been allowed to optimize to decrease landfill.

Fig. 8 shows the result of a project where the distribution of scrap between the blast furnace and the BOF converters was optimized to minimize CO_2 emissions. HMR = hot metal ratio in BOF. TSR = Total scrap ratio (scrap in BF + BOF in percent of liquid steel weight from BOF).

3.3. Exergy analysis

Fig. 9 shows a typical result, the energy and exergy balance of the blast furnace from the study of 2007.

The left hand diagram shows the energy balance. The input energies are the chemical energy in coke, coal and coke oven gas, electrical power, +minor sources. The export energy is thermal and chemical energy in hot metal, BF gas and dust. There are also 13.3% losses, mainly thermal energy in flue gases and cooling water and also some additional losses, e.g. surface losses (radiation and convection).

The right hand diagram shows the exergy balance. The Export Energy is of similar magnitude as in the energy balance. This is because it contains mostly chemical energy, which is 100% exergy. The heat loss flows, on the other hand, consist of cooling water and flue gas with a very low content of exergy. Thus the exergy in the heat losses is only 1.7%. There is also a difference of 14% destroyed exergy. This is the exergy that disappears when flows of high value energy are converted to low value flows with lower exergy. That exergy is irreversibly lost because of the second law of thermodynamics.

Fig. 10 shows a similar balance for the whole energy system SSAB + CHP plant + district heating.

Two types of information in these diagrams are of practical importance for the user:

- The destroyed exergy is an indicator of the thermodynamic efficiency of the unit.
- The exergy in the "losses" is the exergy that is theoretically possible to recover, e.g. by ORC (Organic Rankine Cycle) units.

3.4. Pinch analysis

By comparing the minimum process utility requirements indicated in Fig. 5 with the actual utility usage, the study showed that there are potential steam savings of 1290 kW (14%). The study also showed that the selected pressure level of utility steam is

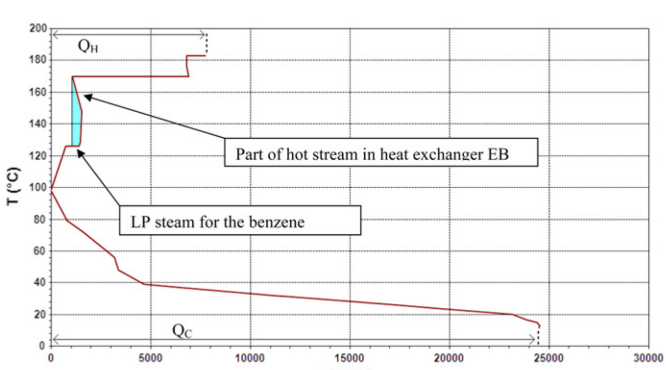

Fig. 5. Grand composite curve for the coking plant's gas cleaning [19].

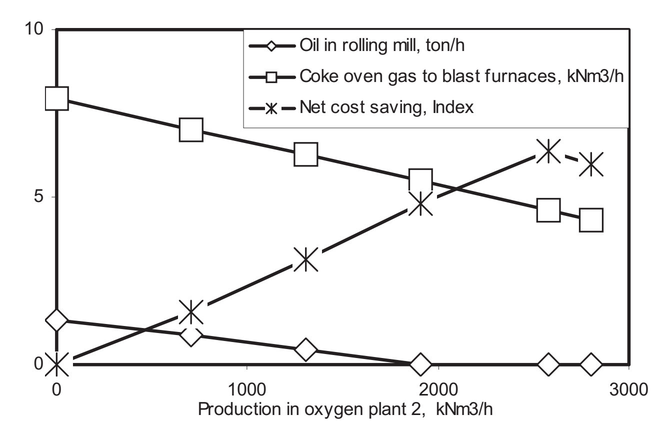

Fig. 6. Simulation to improve the energy balance during coke plant revamping. The units on the vertical axis are those shown in the legend.

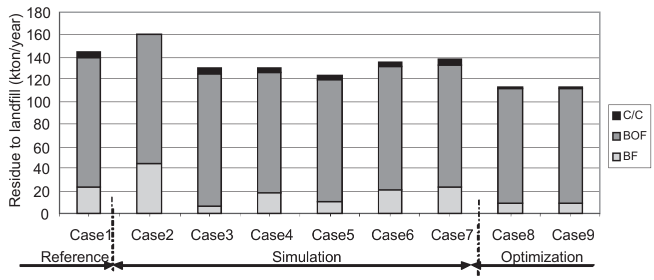

Fig. 7. Use of reMIND to optimize raw material flow, recycling and landfill [11].

unnecessarily high in some process heaters. A further heat recovery potential of 9 MW was indentified if appropriate technology is available to recover heat from the hot uncleaned raw gas. For the Blast furnace and steel plant a potential was shown by using recovered heat for Cowper preheating.

The coke oven plant was built in a site around 3km from the blast furnace and steel plant. The only connection between the sites is delivery of coke and coke oven gas. In this study they have mainly been treated as two systems. However a limited study of the total plant indicated that there is a match between the two sites, where the steel plant fits in the coking plant's "pocket". This would indicate a large saving potential if heat, e.g. as steam, could be exchanged between these units. It is presently uncertain if this is economically feasible. Some studies have been carried out, but there is no decision so far.

4. Discussion

4.1. Importance of the optimisation in the MILP modelling

The landfill study (compare Fig. 7) contained both simulations and cases where reMIND was used to optimize landfill. The changes in energy consumption, CO_2 emission and landfill are plotted in

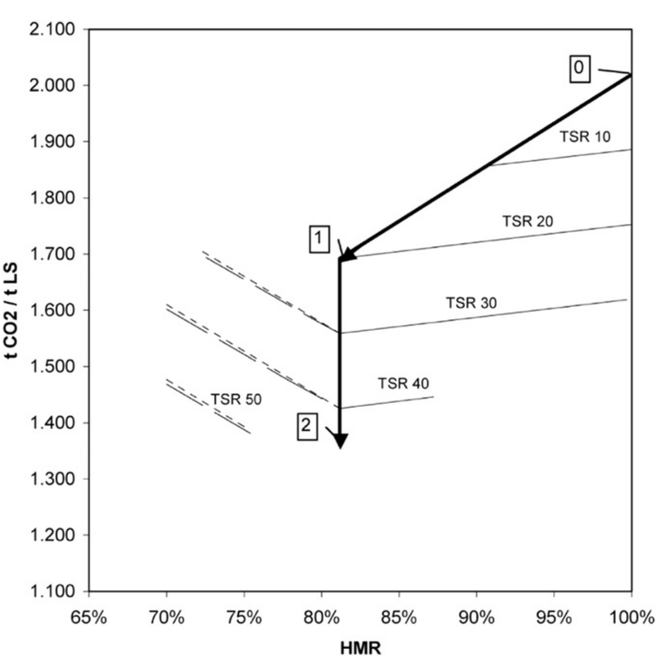

Fig. 8. Optimization of scrap distribution to minimize CO_2 emission [10].

Fig. 11. The values are shown as indexes with the reference case as 100. The figure shows that the simulation model can find solutions with much improved efficiency.

4.2. Exergy: reference data??

Fig. 12 shows exergy data from the heat and power plant in the 2010 exergy study. The data show exergy efficiency of different units in the CHP plant.

The heat exchanger and turbine show relatively good exergy efficiency. The boiler on the other hand destroys around 50% of its exergy. This indicates a low efficiency, which is inherent for boilers that convert fuel energy (100% exergy) into high pressure steam (around 50% exergy). This cannot be achieved without destroying exergy. This illustrates a major difficulty in using exergy values: there is a lack of reference data showing if a certain value is good or bad. A very important future work would be to create a database on expected exergy efficiency for "Good Available Technology".

4.3. Use of Pareto method for optimisation towards multiple targets

Mathematical programming methods, e.g. reMIND, provide the possibility to optimize vs. different parameters by making changes to the objective function. In reality there is often a need to improve several parameters and find a suitable compromise. A method that has been used for this is the Pareto method, see Fig. 13.

The dotted line shows the best possible optimization. The uppermost endpoint of the line shows the result of an optimization for material efficiency. This point is characterized by very high CO_2 emissions. If we instead optimize the CO_2 emissions we get the right hand endpoint with a much lower material efficiency. The dotted curve can be calculated by locking one variable and optimizing the others. For example, if we lock the material efficiency at 96% and optimize for CO_2 emissions we get a point with 1.3 t CO_2 emission per ton iron. If we follow the curve we find a corner with acceptable values of both parameters.

4.4. Which method can be used for which purpose?

The optimal choice of method depends on the situation and the questions that should be answered.

- One typical case is a system dominated by streams transporting thermal energy. In this case the problem is often to optimize heat exchange between the streams. In this case Pinch analysis is an excellent tool. It should be pointed out that most plant sites have sub-systems that match this criterion, even though the plant as a whole does not. This was the case for the Pinch study described in this paper.
- Exergy analysis is especially interesting in applications with chemical reactions, a high proportion of forms of energy other than thermal, such as chemical energy, different pressures and/or production of electricity. A typical example is inventory of rest energy streams, e.g. to study potential for conversion into electricity.
- For a steel plant as a whole the situation is usually more complicated. Heavy liquid, solid and gaseous streams react in a way that affects both material and energy balances. The problem is to optimize both energy and material efficiency. For this case mathematical programming is a superior tool and this is one reason why it is the standard tool for Swedish steel industry.
- Probably it is better to have an arsenal of methods rather than just one. For example, Pinch or exergy studies could suggest changes that are then tested by mathematical programming.

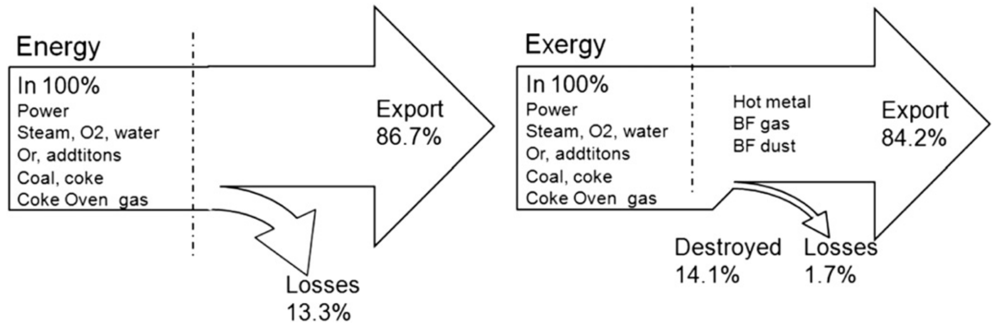

Fig. 9. SSAB study 2007. Energy–exergy diagrams for the blast furnace [7].

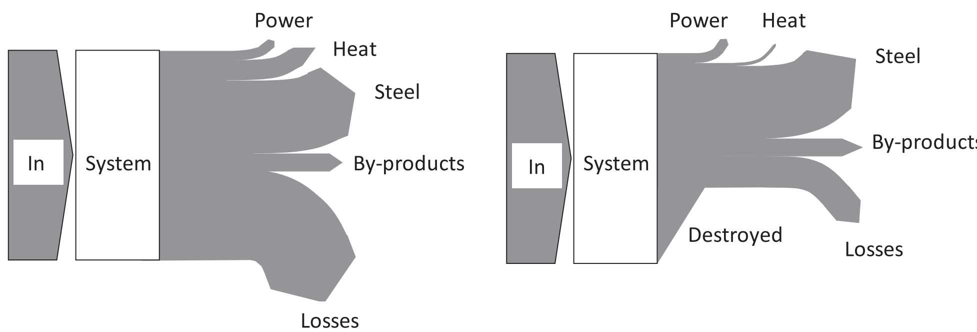

Fig. 10. SSAB study 2010. Energy–exergy diagrams for the total energy system [18].

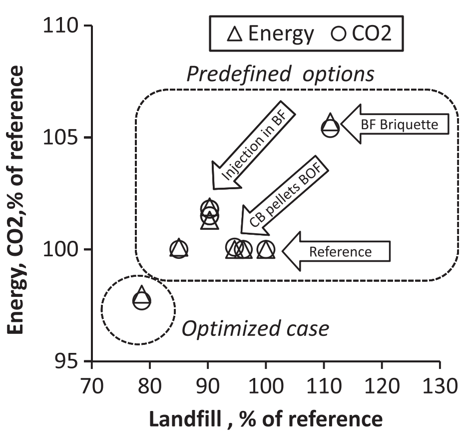

Fig. 11. Comparison of simulation and optimisation. Data from landfill study [11].

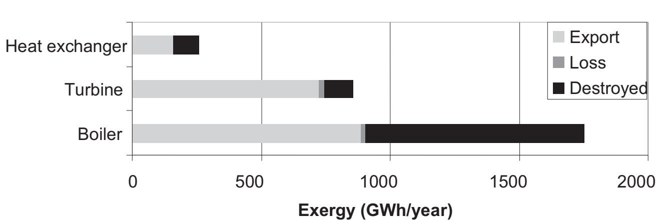

Fig. 12. Example on exergy balances for the heat and power plant.

4.5. Acceptance by plant people?

Process integration can save energy (and material) by suggesting more optimal solutions. However, this requires that these solutions are accepted and implemented by the plant management and production people. Important factors to achieve acceptance are:

- Management support from the start.
- Include plant people in the development throughout the process.
- Plan the work to create practically useful results at an early stage.
- Networks with enough critical mass are important for long term survival of the methodology.
- Sophistication is necessary. Over-sophistication is dangerous!

The following factors have contributed to fulfilling these criteria for the Luleå case:

➢ The spreadsheet simulations, starting point for implementation of process integration studies, were ordered by the management. They were also successful and solved the company's problem.
➢ When the models were further developed into mathematical programming tools, the main work was done by a PhD student with access to an office within the mill area. This forced a close cooperation between plant and university people.
➢ Presently the development gathered in an excellence centre (PRISMA) located on a well-established institute (MEFOS) with several Scandinavian steel plants as partners. This facilitates a wider acceptance and long-term networking.

One observation is that future studies ought to include the study of non-technical factors e.g. stakeholder preferences.

4.6. Generality

The applications described in this work are specific to the steel industry. The tools and the methodology, however, are general and

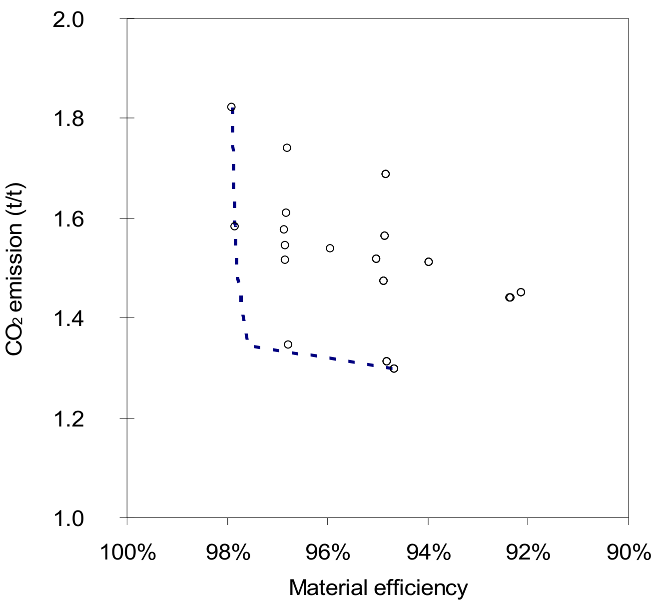

Fig. 13. Illustration of the Pareto method.

sector-independent to a large extent. They are presently introduced as tools in the strategic network Bio4Energy. A study, using the same methods and tools, was recently carried out by the same partners at a Swedish pulp and paper mill. The study included mathematical programming and Pinch analysis [20,21]. Also the possibility to combine with stakeholder analysis was studied [22].

4.7. Comparison with other steel industries

A network for process integration in steel industries (PRISMA) has been created based on the development described in this paper. A large part of the Scandinavian steel industries are now part of the network and in principle they use methods described here. Reg. other plants personal contacts indicate that simulations are practiced, sometimes as a complement to LCA studies. Some exergy studies have been published e.g. on the use of recovered energy for power production [6], which was also the most successful application in the Luleå case, and on process efficiency [5]. In the SSAB case the application for recovered energies was the most useful. The use, e.g. for process efficiency has also practiced in Luleå case, however a drawback was lack of reference data.

5. Conclusions

- Work on global optimization and process integration has been carried out for the Luleå energy system since 1987. The work started with global spreadsheet models and continued with development and/or use of tools for mathematical programming, exergy analysis and Pinch analysis.
- The problems treated in studies on steel plant systems often include material and energy efficiency as well as different types of energy. Mathematical programming has been shown to be an excellent tool for those purposes.
- Exergy is a suitable tool for problems involving different types of energy and transformations between them. In some cases the lack of good reference data is a serious impediment.
- Pinch analysis is the simplest and probably the best tool for problems involving sources and streams of heat energy and possible heat exchange between them.

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