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Exploitation of multi-objective optimization in retrofit analysis: a case study for the iron and steel production

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Abstract

Over the past few decades the issues related to the energy consumption and the climate change have been increased and they have achieved a significant position on the sustainability agenda of the steel industry. Steel production is among the largest energy-intensive industrial processes in the world, as well as one of the most important CO_2 emission sources. However, the major role of steel utilisation in the modern society is undeniable.
The challenges of industrial energy systems aim at achieving CO_2 minimization, without neglecting energy efficiency as well as the development of effective models and strategies for process optimization. The application of Process Integration (PI) methods to the integrated steelmaking route, aims at achieving a reduction in the CO_2 emission by optimizing material and energy systems.
The work presented in this paper is devoted to the development of a model for optimal exploitation of energy resources and by-products in integrated steelworks through application of multi-objective optimisation techniques. Cases of exploitation of the system within the management of the process gases are presented in a retrofit scenario and compared to the case of nominal operation.

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Keywords: Steel industry; multi-objective optimization; cost savings; industrial energy system; process simulation and optimization; CO_2 emissions reduction

Introduction

Iron and steel industries are very energy- and carbon-intensive [1]. Optimal uses of resources (materials and energy) and emissions control are thus essential and different exemplar techniques to tackle such issues exist in the literature [2-3]. An effective way to improve the energy management of steel industries as well as reduce the CO_2 emissions is through exploitation of process modelling and optimization. Integrated process models to formulate optimization problems considering multiple objectives have been used in past research to simultaneously minimize CO_2 emissions and cost in an integrated steelwork by optimizing an existing process gas network [4-5]. The proposed solution exploited a dynamic

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mathematical model of a fixed gas network structure, embedded in a software decision support system, to recommend optimal gas distribution patterns. Here an extension of such an approach is proposed, considering the possibility of realizing new connections among existing gas producers and consumers. A cost function is introduced for installation of new pipelines, although the possibility of exploiting the existing network is kept; possibilities for a retrofit design of the gas distribution system are explored by comparing the results of the new optimization approach to the old ones. In the paper, the formulation of the extended process gas model is presented and experimental results in the different cases are compared.

Model description

Let P and C be the sets of producer and consumers processes, respectively. Noticeably there are processes belonging to both sets and in this case we consider in our model 2 copies of the same process: one as a producer and one as consumer. Each producer has a correspondent gasholder and let G be the set of gasholders; gasholders are both producers and consumers. Finally let T and PP be the sets of torches and power plants, which are consumers. Among the production processes a special one represents natural gas, which might serve other processes and is denoted by v.

We consider a network of pipes connecting producers with consumers. In other words, we have a bipartite digraph with vertex set $P \cup C$ and arcs directed from the elements of P to some elements of C. Let x_{ij} be the amount of gas flowing in the pipe ij linking producer i to consumer j. The binary variables y_{ij} represent the use of the pipe ij: $y_{ij}=0$ if $x_{ij}=0$ and $y_{ij}=1$ if $x_{ij}>0$. For every pipe ij that cannot be part of the network, we impose the constraint $x_{ij}=0$. This is the case, for instance, of pipes connecting gasholders and producers of gases different from the one in the gasholder. Each producer i, apart from natural gas, has to produce an exact amount of gas p_i, thus $\forall i \in P - v \ \sum_{j \in C} x_{ij} = p_i$. On the other hand, consumers have a demand to meet: let d_j be the demand for consumer j, for each consumer the constraint $\sum_{i \in P} x_{ij} \geq d_j$ holds. When two different gases are sent to the same consumer, a mixing occurs. The lower heating value of the mix at process j is expressed by $\sum_{i \in P} x_{ij} \Big/ \sum_{i \in P} \frac{x_{ij}}{LHV_i}$ and must lie within a lower (l_j), and upper bound (u_j), namely $l_j \leq \sum_{i \in P} x_{ij} \Big/ \sum_{i \in P} \frac{x_{ij}}{LHV_i} \leq u_j$. Also the volumes are constrained. Each pipe connecting the i-th process to the j-th one is characterised by a minimum and maximum volumes, v_{ij} and V_{ij} respectively, i.e. $v_{ij} \leq x_{ij} / LHV_i \leq V_{ij}$. Moreover the volume of gas arriving at the j-th consumer must be lower than a value M_j, i.e. $\sum_{i \in P} x_{ij} / LHV_i \leq M_j$. Finally there is an upper bound g_i on the outgoing gas volume of the gasholders, which means that for the i-th gasholder we have the inequality $\sum_{j \in C} x_{ij} / LHV_j \leq g_i$.

Two objective functions must be minimized: the total CO_2 emission Z_1, and the total monetary cost, Z_2. Let f_i be the CO_2 unitary emission factor of the i-th producer (for some non polluting producers, such as the gasholders, $f_i=0$). The expression for the total CO_2 emission is:

$$Z_1 = \sum_{i \in P, j \in C} x_{ij} \cdot f_i \tag{1}$$

On the costs side, there are 4 components: the purchase of natural gas, the purchase/sale of CO_2 allowances, the sale of gas to power plants and the cost of building a pipe ij. Let c be the unitary price of natural gas. Let z_j be such that $z_j=-1,+1$ or 0 if at consumer j there is a loss, a gain or no change of CO_2 allowances, respectively. Let pp_j be the unitary gain for selling gas at power plant j. Finally let c_{ij} be the cost of building the pipe ij ($c_{ij}=0$ if the pipe already exists) and recall that $y_{ij}=1$ if the pipe ij is in use, 0 otherwise. The total cost is given by:

$$Z_2 = \sum_{j \in C} c \cdot x_{vj} + \sum_{i \in P, j \in C} z_j \cdot f_i \cdot x_{ij} \cdot p_{CO_2} + \sum_{i \in P, j \in PP} x_{ij} \cdot pp_j + \sum_{i,j} y_{ij} \cdot c_{ij} \tag{2}$$

In order to cope with multi-objective optimization we use the ε-approximation technique to generate a good approximation of the Pareto optimal solutions, namely all those solutions such that no other solution can have better values of both Z_1 and Z_2. More precisely we solve the Mixed Integer Linear Programming (MILP) problem *min* Z_1 subject to the above-described constraints, the constraints linking y_{ij} to x_{ij} and the constraints on the unacceptable pipes ($x_{ij}=0$ in this case). From this MILP we get an optimum value Z^* for Z_1, then we subsequently solve the m problems that are defined as follows for $i=1,2,\ldots,m$: min Z_2 subject to the previous constraints plus the constraint $Z_1 \leq Z^*+\varepsilon_i$, for a suitable choice of $\varepsilon_1 \leq \varepsilon_2 \leq \ldots \leq \varepsilon_m$. When i increases, we get decreasing optimum values for Z_2 and increasing values of Z_1.The m pairs obtained in this way allow describing a good approximation of the Pareto front of the solutions.
This MILP model is also used as a discretization of a continuous process: let us consider N intervals of duration Δt and run the MILP N times. The variable $x_{ij}(k)$ at the k-th iteration represents the amount of gas flowing from process i to process j in $[(k-1)\,\Delta t,\ k\,\Delta t]$. The only parameters changing over time in the MILP are the gasholders volumes (while the costs are considered as costs per unit of time). The volume $V_g(k)$ of gasholder g at time k is determined as follows:

$$V_g(k) = V_g(k-1) + \sum_{i \in P} x_{igc} / LHV_i - \sum_{i \in P} x_{igp} / LHV_{gp} \tag{3}$$

Where gp and gc are the indices of the gasholder g as a producer and as a consumer, respectively. There is an additional constraint to the time dependent model, stating that $\forall g V_g(k)$ is limited.

Experimental results

The proposed model has been tested against a model formerly developed and described in [4-5], built for a particular network structure and not taking into account the possibility of constructing new pipes. In the same network structure, under reasonable assumptions for the costs of building pipes, the present model outperformed the previous, realizing a better and wider Pareto front in the time independent case, as it is shown in Figure 1, where on the x-axis the CO_2 emissions are shown and on the y-axis the cost. It is evident from the picture that the new model has better local minima both for the CO_2 consumption and for the cost (the negative value for the cost corresponds to a profit in every scenario). In particular, the profit can be increased by up to 7.1% with respect to the old model (corresponding to an increase in the CO_2 emissions by 14.2%), whereas on the opposite side of the Pareto front a reduction of 1.1% of CO_2 emissions can be reached at the expense of 20.8% cost increase. It is worth noticing that in any case the two Pareto

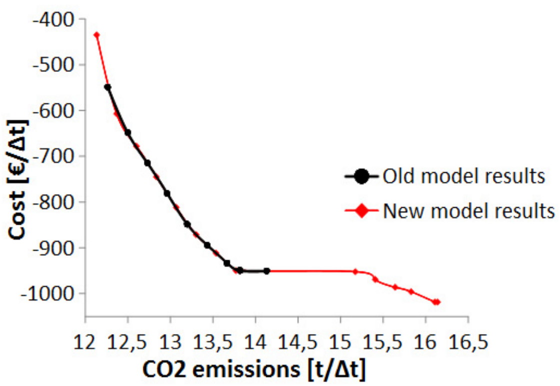

Figure 1: Approximation of the Pareto fronts in two different models

fronts coincide in the interval where there is an intersection, due to the permanence of plant constraints in the new model as well as the old one. The comparison between the two models in the time dependent case cannot be performed since, in general, after the first iteration(s) the volume of the gasholders is different, due to different optimal values of the gas flow rates in the network. Therefore the subsequent problems have different initial conditions and cannot be compared.

Conclusions and future work.

A model for the optimal management of process gases in integrated steelworks has been presented. With regard to what has been achieved in the previous literature, an extension has been made that allows taking into account possibilities for retrofit design of the systems through addition of network connections (installation of new pipework). The innovative approach has been compared to an existing system, pointing out the incremental benefits of the proposed approach.

Future work will be focused on the development of a model that can optimize the costs of the network globally, i.e. over the entire time period instead of at every discretization step. An observation that will also be analysed in further detail in future work is that an excessive initial volume of the gasholders often proves inefficient in the long run.

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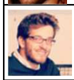

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