18th European Symposium on Computer Aided Process Engineering – ESCAPE 18
Bertrand Braunschweig and Xavier Joulia (Editors)

Collaboration among companies for better energy management

Mujtaba H. Agha[a], Raphaele Thery [a], Gilles Hetreux [a], Alain Hait[a], Jean Marc Le Lann [b]

[a] *Laboratoire de Génie Chimique (UMR 5503), 5 rue Paulin Talabot, 31106 TOULOUSE Cedex 1*
[b] *Office National d'Etude et de Recherche Aérospatiale, centre de Toulouse, BP 4025, 31055 TOULOUSE Cedex 4*

Abstract

The objective of this article is to analyze the benefits of collaboration among companies for better energy management. A multi-period mixed-integer linear programming (MILP) model is developed which engrains the concept of collaboration among companies through exchange of electricity and steam at different pressure levels. Operating constraints like delays due to boiler shut-downs and restarts as well as structure of steam exchange network are modeled to simulate a real time environment. Results from the model indicate reduction in global cost as well as emissions of harmful gases.

Keywords: Collaboration, CHP plant, MILP, Harmful emissions.

1. Introduction

Harmful gases produced during the burning of fossil fuels are the chief cause of the phenomenon of global warming and in order to reduce these emissions it is imperative to improve energy efficiency of industrial processes [1]. Most of the current research is focused on finding alternative sources of energy which could replace the fossil fuels as source of energy. However, even by the most optimistic assessments, all these alternatives are long term solutions. In order to find short and medium term solutions one needs to asses energy provisioning (how energy is supplied to industry) and energy consumption (how the industry utilizes its energy).

The energy issue constitutes a complex problem concerning many fields of knowledge (economy, engineering, geopolitics, etc). The focus in this study will be limited to industrial production systems. The basic approaches in industrial process synthesis are the use of heuristics, process integration [2] and optimization techniques [3]. The mathematical optimization methods are especially important in establishing trade-offs between different conflicting targets and finding the most favorable solution. Extensive reviews on optimization problems and methods as well as their future challenges are presented by Biegler and Grossmann [4, 5].

Supply chain management has played a pivotal role in improved efficiency and cost reduction in manufacturing industry. In the same vein, industries located close to one another can collaborate for a better utilization of their energy resources [6, 7]. In this study a multi-period mixed-integer linear programming (MILP) model is developed which engrains the concept of collaboration among companies to meet their energy requirements through exchange of electricity and steam at different pressures. In this article, a MILP model is presented and subsequently the result obtained from a two company collaboration effort is demonstrated.

2. Problem Formulation

A combined heat and power (CHP) plant is an ideal source of energy supply to industrial systems. Significant energy efficiency and carbon emissions reduction can be achieved by using CHP plant. A typical CHP based industrial system comprises of fuel storage tanks, boilers for high pressure steam production, steam turbines for electricity generation, valves for reducing pressure and mixing equipment for mixing likewise material (as shown in fig.1):

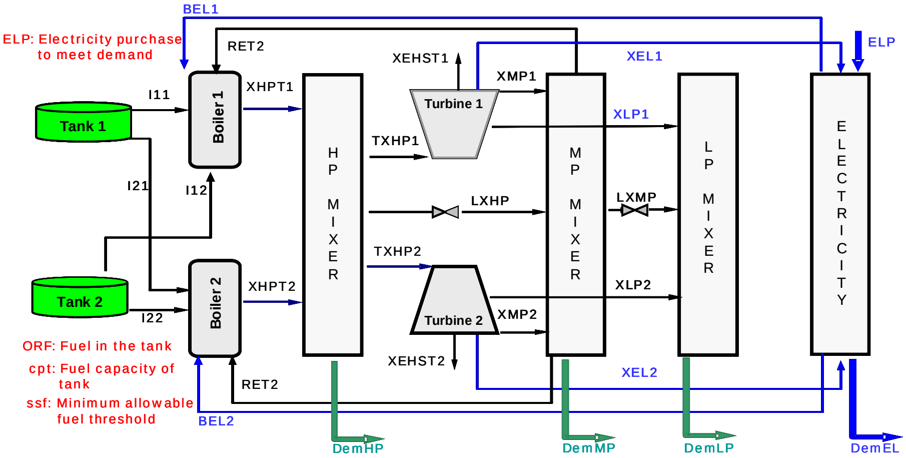

Figure 1: Typical CHP based Energy Production System

This study is based on the model proposed by Soylu et al [8]. Several new operational constraints are added to bring model closer to real world environment. These include delays and costs incurred due to boiler shut-down and restart as well as the steam exchange network.

3. Mathematical Model

The mathematical model represents behavior of the plant during one fully operational day. The MILP model is divided in 24 one hour periods. The constraints for the model are provided by applying mass and energy balance on the main components of CHP plant. Simplifying assumptions make it possible to use linear equations and binary variables for modeling the behavior of main components of CHP plant.

3.1. Fuel Storage Tank Model:

The amount of fuel *I* belonging to company *c* leaving tank *i* and entering the boiler *j* in time period *t* is represented by $I_{t,c,j,i}$. Each fuel tank has a certain capacity and initial amount of fuel stored in the tank is $ORF_{0,c,j,i}$. To simplify the modeling it is assumed that there are no fuel purchases during the day. Fuel tank equations are as follows:

Table 1. Fuel Tank Model

Description	Equation	
Fuel tank mass balance	$ORF_{t,c,i} = ORF_{t-1,c,i} - \sum_{j} \left(I_{t.c,\,j,\,i} - SI_{t,c,\,j,\,i} \right)$	(1)
Fuel limiting constraint	$cpt_{c,i} \geq ORF_{t,c,i} \geq ssf \cdot cpt_{c,i}$	(2)

3.2. Boiler Model:

It is assumed that boiler *j* has uninterrupted supply of air and water. Fuel coming from the storage tank *i* is used to generate high pressure (HP) steam and results in emissions of green house gases (GHG) and SOx. The boiler *j* is provided with medium pressure steam (to pre-heat water) and electricity. Even though boiler can be fired by multiple fuels, but for a particular period only one type of fuel can be used in the boiler.

Eq. (3) models the amount of fuel $I_{t,c,j,i}$ consumed for production of $XHP_{t,c,j,i}$ amount of steam. However the efficiency of boiler is significantly less when it operates at part load, i.e., operating at less than maximum output capacity. Eq. (4) to (8) use binary variables *B1*, *B2* and *B3* to develop a piecewise linear curve quantifying fuel consumption with the varying steam load. Binary variables $\mathrm{SB}_{t,c,j,i}$ and $FSB_{t,c,j,i}$ in a particular time period *t* define boiler being operational or being restarted respectively. It is assumed that boiler takes one hour to shut-down and also one hour to restart. During restart phase the boiler uses $SIdem_{t,c,j,i}$ amount of fuel without producing any steam.

Table 2. Boiler model

Description	**Equation**
Associating Fuel Consumption with steam production	
HP steam generated by the boiler *j*	$XHP_{t,c,j,i} = \frac{I_{t,c,j,i} \cdot HHV_{c,i} \cdot \eta_{c,j,i}}{\left(h_{b,c} - h_{fw,c}\right)}$ (3)
Quantity of HP steam generated in boiler $Load\ \ Factor = \frac{Operating\ \ Load}{Maximum\ \ Load}$	$XHP_{t,c,j,i} =$ $B1_{t,c,j,i} \cdot XHP\,min_{c,j} + x1_{t,c,j,i} \cdot \left(0.5 \cdot XHP\,max_{c,j} - XHP\,min_{c,j}\right) +$ $0.5 \cdot B2_{t,c,j,i} \cdot XHP\,max_{c,j} + 0.25 \cdot x2_{t,c,j,i} \cdot XHP\,max_{c,j} +$ $0.75 \cdot B3_{t,c,j,i} \cdot XHP\max_{c,j} + 0.25 \cdot x3_{t,c,j,i} \cdot XHP\max_{c,j}$ (4)
Fuel of type *i* consumed in the boiler while producing steam	$I_{t,c,j,i} = B1_{t,c,j,i} \cdot Imin_{c,j,i} + x1_{t,c,j,i} \cdot \left(I50_{c,j,i} - Imin_{c,j,i}\right) +$ $B2_{t,c,j,i} \cdot I50_{c,j,i} + x2_{t,c,j,i} \cdot \left(I75_{c,j,i} - I50_{c,j,i}\right) +$ $B3_{t,c,j,i} \cdot I75_{c,j,i} + x3_{t,c,j,i} \cdot \left(Imax_{c,j,i} - I75_{c,j,i}\right)$ (5)
Operating point linking fuel consumption $I_{t,c,j,i}$ with loading factor, i.e., $XHP_{t,c,j,i}$ steam generated in the boiler	$B1_{t,c,j,i} + B2_{t,c,j,i} + B3_{t,c,j,i} \le 1$ (6) $0 \le x1_{t,c,j,i} \le B1_{t,c,j,i}$; $0 \le x2_{t,c,j,i} \le B2_{t,c,j,i}$; $0 \le x3_{t,c,j,i} \le B3_{t,c,j,i}$ (7) $\sum_i B1_{t,c,j,i} \le 1$; $\sum_i B2_{t,c,j,i} \le 1$; $\sum_i B3_{t,c,j,i} \le 1$ (8)
Boiler shut-down, restart and emission constraints	
Boiler capacity constraint	$XHP\min_{c,j} \cdot SB_{t,c,j,i} \le XHP_{t,c,j,i} \le XHP\max_{c,j} \cdot SB_{t,c,j,i}$ (9)
Boiler shutdown and restart phase	$SB_{t+1,c,j,i} \le SB_{t,c,j,i} + \left(1 - SB_{t-1,c,j,i}\right)$ (10) $FSB_{t,c,j,i} \le SB_{t+1,c,j,i}$ (11) $FSB_{t,c,j,i} \ge SB_{t+1,c,j,i} - SB_{t,c,j,i}$ (12)
Fuel consumed at restart	$SI_{t,c,j,i} = FSB_{t,c,j,i} \cdot SIdem_{c,j,i}$ (13)

Table 2. Boiler model

Description	Equation	
Single fuel constraint	$\sum_i FSB_{t,c,j,i} \le 1$ and $\sum_i SB_{t,c,j,i} \le 1$	(14)
SO$_x$ emissions, where $sox_{c,i}$ is emission coefficient	$XSOX_{t,c,j} = \sum_i sox_{c,i} \cdot \left(I_{t,c,j,i} + SI_{t,c,j,i} \right)$	(15)
GHG emissions, where $ghg_{c,i}$ is emission coefficient	$XGHG_{t,c,j} = \sum_i ghg_{c,i} \cdot \left(I_{t,c,j,i} + SI_{t,c,j,i} \right)$	(16)
MP steam return to boiler	$RET_{t,c,j} = a_{c,j} \cdot XHP_{t,c,j}$ where $a_{c,j}$ is a parameter	(17)
Electricity return to boiler	$BEL_{t,c,j} = b_{c,j} \cdot XHP_{t,c,j}$ where $b_{c,j}$ is a parameter	(18)

3.3. Steam Turbine Model

Steam turbines use expansion to convert HP steam into LP steam. The mechanical energy released during this expansion is then exploited for electricity generation. The MP and LP steam are extracted from turbine at appropriate levels to meet demand. Remaining MP and LP steam demands are met by expanding steam through PRVs.

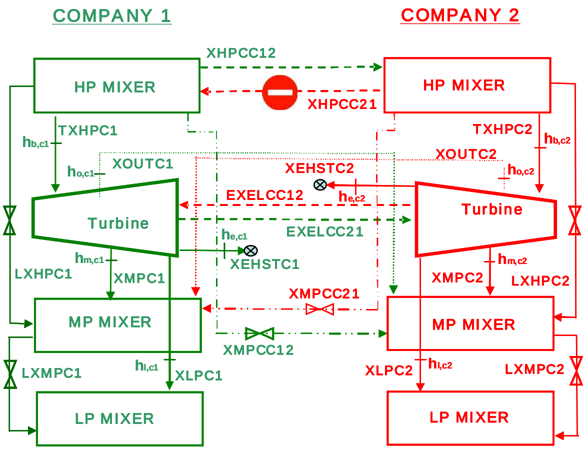

Figure 2. Steam exchange methodology among companies

Table 3. Steam turbine model

Description	Equation	
Turbine mass balance:	$TXHP_{t,c,k} = XOUT_{t,c,k} + XMP_{t,c,k} + XLP_{t,c,k} + XEHST_{t,c,k}$	(19)
Maximum extraction:	$XEHST_{t,c,k} \ge 0.1 \cdot TXHP_{t,c,k}$	(20)
Energy balance for calculating electricity produced by turbine. $\eta_{c,k}$ is the efficiency of the turbine.	$XEL_{t,c,k} =$ $\eta_{c,k} \cdot \big(TXHP_{t,c,k} \cdot (h_{bc} - h_{oc}) + (TXHP_{t,c,k} - XOUT_{t,c,k}) \cdot (h_{oc} - h_{mc}) +$ $\left(TXHP_{t,c,k} - XOUT_{t,c,k} - XMP_{t,c,k} \right) \cdot (h_{mc} - h_{lc}) +$ $\left(TXHP_{t,c,k} - XOUT_{t,c,k} - XMP_{t,c,k} - XEHST_{t,c,k} \right) \cdot (h_{lc} - h_{ec}) \big)$	(21)

3.4. Mixer Model

Mixers are used to mix likewise materials in this case HP, MP and LP steam. Previous work [8] assumed that steam exchange can take place at all three pressure mixer levels (HP, MP and LP mixers). However such exchanges would not be possible if collaborating companies function at different operating pressures. In such cases only possibility of steam exchanges is through HP mixers and turbines. Only HP mixer of company operating at higher pressure supplies steam to HP mixers of other companies. MP steam exchanges takes place among companies from turbines by steam extraction and HP mixers of all companies by using PRVs (figure 2). In case of non-collaboration no exchanges take place ($XHPCC_{t,c} = XMPCC_{t,c} = XOUT_{t,c} = EXELCC_{t,c} = \beta_{x,c} = 0$).

Table 4. Mixer and electricity exchange model

Description	Equation
HP Mixer mass balance, where $XHPCC_{t,c,c}$ is HP steam exchange among companies	$\sum_j \sum_i XHPT_{t,c,j,i} - LXHP_{t,c} - \sum_k TXHP_{t,c,j} + \sum_{x \neq c} XHPCC_{t,x,c} - \sum_{x \neq c} XHPCC_{t,c,x} - \sum_{x \neq c} XMPCC_{t,c,x} \geq DemHP_{t,c}$ (22)
MP mixer mass balance where $XMPCC_{t,c,c}$ is MP steam exchange among companies	$LXHP_{t,c} + \sum_k XMP_{t,c,k} - LXMP_{t,c} + \sum_{x \neq c} XMPCC_{t,c,x} - \sum_j RET_{t,c,j} - \sum_k \sum_{x \neq c} XOUT_{t,x,k} \geq DemMP_{t,c}$ (23)
LP mixer mass balance	$LXMP_{t,c} + \sum_j XLP_{t,c,j} \geq DemLP_{t,c}$ (24)
Electricity Exchange where $EXELCC_{t,c,c}$ is electricity exchange among companies	$\sum_k XEL_{t,c,k} + ELP_{t,c} + \sum_{x \neq c} \beta_{x,c} \cdot EXELCC_{t,x,c} - \sum_j BEL_{t,c,j} - \sum_{x \neq c} EXELCC_{t,x,c} \geq DemEL_{t,c}$ (25)

3.5. Objective Function:

The model minimizes the operational cost comprising of fuel cost, electricity purchase cost and penalty cost incurred due to emission of harmful gases.

$$COST = \sum_t \sum_c \sum_j \sum_i cf_{c,i} \cdot \left(I_{t,c,j,i} + SI_{t,c,j,i} \right) + \sum_t \sum_c ELP_{t,c} \cdot CEL + \sum_t \sum_c \sum_j XSOX_{t,c,j} \cdot CSOx \qquad (26)$$

4. Example

The software XPRESS-MP [9] is used to optimize the operations of the companies with and without collaboration. Several examples and scenarios were tested to gauge the efficiency of the model. The results of a simple two company collaboration are presented in the table 5. The individual demands of the companies are illustrated in figure 3.

The results demonstrate that by collaboration companies can reduce costs and emissions of harmful gases. However collaboration results depend greatly on boiler efficiencies, type of fuel used in boilers, distances among collaborating companies and various other operating parameters. The result attained in the model give global values and not of the individual companies. Collaboration can lead to increased expenditures of a company which does more work than before. However other collaborating companies can pay for these energy services thus resulting in win-win situation for all concerned.

Table 5: Results from model

	Without Collaboration	**With collaboration**	**Reduction %**
Cost (€)	160,596.28	145,987.43	9.1
SOx emissions (tons)	15.7068	16.1759	3.0
GHG emissions(tons)	525.202	515.632	1.82

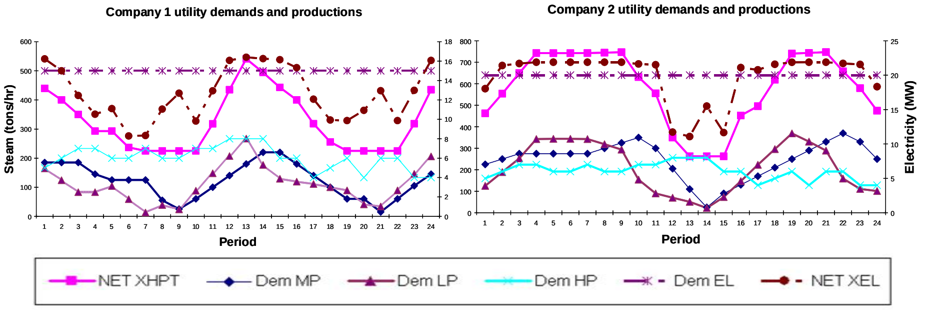

Figure 3. Utility profiles of the two companies

Collaboration among companies is augmented by the fact of deregulation of energy market and presence of many distributed generating companies. The companies who are in close vicinity to one another can combine and form a complete network. This network or *Energy Supply Chain* would be independent of the national electricity grid and fulfill their own energy requirements. Such collaboration would lead to better energy utilization and as a result reduce the emissions of harmful gases.

5. Conclusion

The objective of this article was to analyze the benefits of energy collaboration among different companies. This study is a part of research being conducted at CNRS, whose objective is energy management solutions for mono and multi-sites. Currently coupling between CHP plant and production process is being studied to coordinate process activity with generation of utilities. In future these production constraints will be integrated within the proposed model to view their impact on collaborating companies.

References

[1] B.Metz, O.Davidson, R.Swart, J.Pan, 2001, Climate change 2001: Mitigation, contribuiton of working group III to the third assesmnt report of Intergovernmnetal Panel on Climate Change (IPCC), Cambridge university press, 8-38.
[2] Smith R, 2000, Applied Thermal Engineering, 20, 1337-1345.
[3] I.E. Grossmann, J. Santibanez, , Computers and Chemical Engng, 4, 205-214.
[4] L.T. Biegler, I.E. Grossmann, 2004, Computers and Chemical Engng, 28 (8), 1169-1192.
[5] I.E.Grossmann, L.T. Biegler, 2004, Computers and Chemical Engng, 28 (8), 1193-1218.
[6] O. Rentz, W. Fichtner, M. Frank, 2004, Journal of Cleaner Production, 12, 891-899.
[7] C. Raymond, E.C. Rosenthal,1998, Journal of Cleaner Production, 6, 181-188.
[8] A. Soylu, C. Oruc, M. Turkay, K. Fujita, T. Asakura, 2006, European Journal of Operation Research, 174, 387-403.
[9] XPRESS-MP (optimizer version 18.00.08), Dash optimization.