SYNERGY ANALYSIS OF COLLABORATIVE SUPPLY CHAIN MANAGEMENT IN ENERGY SYSTEMS USING MULTI-PERIOD MILP

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Abstract

Energy, a fundamental entity of modern life, is usually produced using fossil fuels as the primary raw material. A consequence of burning fossil fuels is the emission of environmentally harmful substances. Energy production systems generate steam and electricity that are served to different process customers to satisfy their energy requirement. The improvement of economical and environmental performance of energy production systems is a major issue due to central role of energy in every industrial activity. A systematic approach to identify the synergy among different energy systems is addressed in this paper. The multi-period and discrete-continuous nature of the energy production systems including investment costs are modeled using MILP. The proposed approach is applied on two examples that are simplified versions of an industrial problem. It is shown that the approach presented in this paper is very effective in identifying the synergy among different companies to improve their economical and environmental performance significantly.

Keywords: Mixed-integer programming; Energy systems; Supply chain management; Energy integration; Kyoto Protocol

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1. Introduction

Supply chain management involves all of the activities in industrial organizations from raw material procurement to final product delivery to customers. The decisions regarding to these activities are leveled as strategic, tactical and operational level decisions having long, medium and short term impacts respectively in the supply chain literature. Regardless of the level of the decision, studies on supply chain management highlight the importance of the coordination among companies, which enables to increase the financial and operational performance of each member by reductions in total cost and inventories throughout the supply chain and increased levels of shared information (Malone and Crowston, 1994; Reyniers, 1992; Sox et al., 1997; Whang, 1995). Partnering between firms is an increasingly common way for firms to find and maintain competitive advantage (Mentzer, 1999; Mohr and Spekman, 1994: Mentzer et al., 2000). Strategic alliances are collaborative arrangements between firms to enhance their competitive position and performance by sharing resources (Hitt et al., 2000). The nature of strategic alliances in supply chain management has been widely studied in the review paper by Ireland et al. (2002).

An increasing number of organizations have begun to realize the strategic importance of planning, controlling and designing a supply chain as a whole. Min and Zhou (2002) summarized the supply chain modeling efforts and identified key challenges and opportunities associated with supply chain modeling. They emphasized the need to analyze the synergy created by inter-functional and inter-organizational integration. Integrated process management has to deal with economic, quality related and environmental aspects and link them to management decisions on the organization, control and improvement of processes (Schiefer, 2002). Process integration for the design of utility systems has been addressed by Marechal and Kalitventzeff (1998). The optimal configuration of utility systems was determined for the minimization of energy requirements. Saeed et al. (1996) addressed the fuel consumption reduction by applying a pinch-point implementation. These approaches targeted minimization of the total cost of supplying energy to process systems.

Financial costs and environmental impact of energy generation has been studied by Gonzales-Monroy and Cordoba (2002). A single energy production system for satisfying electricity demand in a city was considered and a solution to this problem was reported using simulated annealing.

An important issue in the industrial supply chain is the satisfaction of all production requirements and achieving high profits while observing environmental regulations. Performance of a company can be evaluated from two points of views. One of them is financial improvement: companies compete to produce with low costs and high levels of quality. Also many companies are integrating their operations in order to get the benefit of economics of scale that can be achieved by better coordination of their assets. The other consideration is environmental improvement: there are environmental protection laws and protocols that organizations must follow. Integration of systems promises both environmental and financial benefits; therefore it is desirable to integrate these production systems to improve operational and economic aspects from supply chain management point of view.

The industrial activities are usually carried out at designated areas that are referred to as industrial zones. An industrial zone is a collection of production systems belonging to different companies with distinct characteristics in the same geographical area. Some of the production systems in the industrial zone have close interaction among each other due to supplier-producer relationships. We can classify the industrial zone as the overall system while the individual production systems can be considered as sub-systems that are integral part of the overall system. A strong interaction among the production systems can be observed as the supply chain integration of the energy. Since all of the subsystems require energy for production, there is almost always a central power production facility in the industrial zone, and also a number of subsystems may produce their energy in their own power plants. Consequently, supply chain integration of energy at an industrial zone is as important as any material in the system. A distinct feature of energy that differentiates it from the other materials is the storage: energy cannot be stored in its most effective form, as electricity or steam. The production rate at a subsystem is proportional to the supply amount of energy; therefore, energy supply is an important factor that determines the capacity and efficiency. Another important characteristic of energy is the fact that energy generation systems release a large quantity of environmentally harmful chemicals such as NO_x, SO_x and gases that create the greenhouse effect, greenhouse gases (GHG). Since these gases are environmentally harmful their impact on the environment must be minimized.

Stefanis et al. (1995) proposed a methodology for environmental impact minimization by defining a vector for each pollutant representing environmental impact with the corresponding environmental indices. These indices measure air pollution, water pollution, solid wastes, global warming, photochemical oxidation and stratospheric ozone depletion. The impact of GHG emissions on global warming can be measured in units of metric tons of carbon dioxide (CO_2) equivalent units. The measurements are regulated by states and legalized as some environmental protection laws and protocols that organizations have to obey. Kyoto Protocol that is signed by 175 countries sets limits on GHG emission levels according to The United Nations Framework Convention on Climate Change that took effect on 21 March 1994 (UNFCC, 2004). It sets an "ultimate objective of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system". It directs that "such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner". The Kyoto Protocol affects all major sectors of the industry and put limits on GHG emissions of countries within a time frame. As mentioned, energy sector release a large quantity of environmentally harmful substances and will be seriously affected with Kyoto Protocol.

Air pollution management has been studied in operational research literature. Cooper et al. (1997) gives a survey of mathematical modeling problems in air pollution management and suggests that "multi-tiered" study with time periods should be developed. Although they suggest chance constraints, in our model we use deterministic data. Oliveira and Antunes (2004) studied "economy-energy-environment" relationships in their mathematical model. Unlike our study, instead of process integration, they consider the inter-industry production linkages in a country-wide basis. Turkay et al. (2004) analyzed the benefits of collaborations with financial and environmental objectives for a single-period without considering the investment required to establish such collaboration.

In this paper a systematic approach to identify the synergy by collaboration of different companies to overcome difficulties in their economical an environmental performance is addressed. The detailed process models that are derived from fundamental laws of conservation of mass and energy and actual process data are presented. An important feature of these models is the inclusion of realistic operating characteristics of energy generation systems such as selection of alternative raw materials and turning on/off some of the equipment depending on the energy demand in various forms. In addition, the investment costs required to establish collaboration is considered for each entity that is exchanged between two companies in the energy generation network.

Our hypothesis in this paper is "The multi-organization collaborative SCM creates a synergy among organizations to overcome economical and environmental obstacles and difficulties". We show that a systematic approach can identify the synergy among a number of process systems and detect improvements in the financial and environmental performance of process systems. The first step in our systematic approach is the development of process models. The process unit models are developed using fundamentals of thermodynamics, mass and energy conservation and existing process data. The process models for the most common units in the utility systems are given in the following section. The second step is the development of an MILP model for each process system that is a collection of process units. The optimization model integrates the process systems in the industrial zone in a multi-period setting. We incorporate discrete nature of the process system such as turning some of the production nodes on and off depending on the energy demand, selection of raw materials to optimal economic and environmental criteria considering purchasing from market and available inventory. The complex discrete nature of the system is modeled using Generalized Disjunctive Programming (Turkay and Grossmann, 1996). The last step is the identification of financial and environmental improvements if the process systems are integrated through material and energy exchanges.

2. Problem Formulation

The objective in energy production systems is to satisfy the energy demand without the possibility of storing the final products (i.e., steam and electricity). A typical energy production system consists of storage tanks to inventory raw materials, boilers that convert fuel into steam at high pressures, turbines that expand higher pressure steam to lower pressure steam and convert the mechanical energy released during this expansion in the electricity and mixing equipment for mixing compatible materials originating from different sources in the system. Energy systems utilize fuel, air and other materials to generate electricity and steam. The models for these most common units in the energy systems are given in the following subsections.

2. 1. Boiler Models

Boilers generate high pressure steam by burning fuel. As a consequence of burning fossil fuels, boilers generate environmentally harmful chemical substances such as SO_x and

GHGs. Boilers require electricity for operating the mechanical equipment and also medium pressure steam for heating the boiler feed water. Material flow around a typical boiler is given in Fig.1.

Figure 1

Boiler models include the following equations:

$$X_{ijk_{HP}l_{gen}t} = \frac{1}{\mathrm{\eta_{ijk_{fuel}}}} \mathrm{cc_{k_{fuel}}} X_{ijk_{fuel}l_{con}t} \qquad \forall\ i,j,t \tag{1}$$

$$X_{ijk_{MP}l_{con}t} = \mathrm{a_{ijk_{MP}}} X_{ijk_{HP}l_{gen}t} + \mathrm{b_{ijk_{HP}}} \qquad \forall\ i,j,t \tag{2}$$

$$X_{ijk_{EL}l_{con}t} = \mathrm{a_{ijk_{EL}}} X_{ijk_{HP}l_{gen}t} + \mathrm{b_{ijk_{EL}}} \qquad \forall\ i,j,t \tag{3}$$

$$X_{ijk_{SO_x}l_{gen}t} = \mathrm{s_{SO_x k_{fuel}}}\ X_{ijk_{fuel}l_{con}t} \qquad \forall\ i,j,t \tag{4}$$

$$X_{ijk_{GHG}l_{gen}t} = \mathrm{s_{GHG\,k_{fuel}}}\ X_{ijk_{fuel}l_{con}t} \qquad \forall\ i,j,t \tag{5}$$

$$X_{ijkl_{in}t} + X_{ijkl_{gen}t} = X_{ijkl_{out}t} + X_{ijkl_{con}t} \qquad \forall\ i,j,k,t \tag{6}$$

$$X_{ijkl^{'}t} = 0 \qquad \forall\ i,j,k,t \tag{7}$$

$$C_{ijk_{fuel}t} = \mathrm{c_{k_{fuel}}}\ X_{ijk_{fuel}l_{con}t} \qquad \forall\ i,j,t \tag{8}$$

The variables X_{ijklt} represent the amount of material k in the unit j that belongs to company i in state l at any period t. Any material can have four distinct states: input, output, consumption or generation. Specific materials or states of a material are indicated with subscripts in variables. Eq. (1) models the amount of HP steam generation as a function of the fuel consumption. Amount of steam generation is a function of the fuel consumption, the calorific value of the fuel and boiler efficiency, η, which depends on the fuel type. Eqs. (2) and (3) model the electricity and MP steam consumption in the boiler as a function of the HP steam generation and a fixed consumption constant. SO_x and GHG generations are proportional to the composition of the fuel and the amount of fuel consumption in the boilers as given in Eqs. (4) and (5). Eqs. (6) and (7) relate the states of materials in the boiler considering conservation of mass. In order to maintain consistency in the material balances, Eq. (7) fixes some of the states of materials to zero (e.g., since there is no HP steam consumption and HP steam input to the boilers, corresponding states of HP are fixed to 0 in the boilers). Finally, Eq. (8) models the total cost of fuel consumption in the boiler.

Boilers can be turned off if the energy demand is too low making the operation of more boilers unprofitable. Also, boilers can be supplied with different fuels as raw material with minimal adjustments in the operating conditions. There are many reasons for considering alternative fuels: one of the most important reasons is the insufficient amounts of fuel available in the inventory forcing the utility system to buy more fuel or use an alternative fuel that is available in the fuel inventory (fuel purchasing and inventory are discussed in detail in section 2.3). Other reasons include the selection of economically and/or environmentally attractive fuel among the available alternatives. The selections corresponding to the use of alternative fuels in boilers and turning them on or off are modeled using disjunctions. Binary variable Y_{ijt} is used to model the turning on and off consideration and YF_{ijkt} is used in modeling fuel selection.

$$\mathop{\vee}_{m \in D_{ij}} \left[\begin{array}{c} Y_{ijt} \\ \left[\begin{array}{ll} \multicolumn{2}{c}{YF_{ijk_{fuel_m}t}} \\ X_{ijk_{HP}l_{gen}t} = \dfrac{1}{\eta_{\mathrm{ijk_{fuel}}}} \mathrm{cc}_{\mathrm{k_{fuel}}} X_{ijk_{fuel}l_{con}t} & \forall\ i,j,t \\ X_{ijk_{MP}l_{con}t} = \mathrm{a}_{\mathrm{ijk_{MP}}} X_{ijk_{HP}l_{gen}t} + \mathrm{b}_{\mathrm{ijk_{MP}}} & \forall\ i,j,t \\ X_{ijk_{EL}l_{con}t} = \mathrm{a}_{\mathrm{ijk_{EL}}} X_{ijk_{HP}l_{gen}t} + \mathrm{b}_{\mathrm{ijk_{EL}}} & \forall\ i,j,t \\ X_{ijk_{SOx}l_{gen}t} = \mathrm{s}_{\mathrm{SO_x k_{fuel}}} X_{ijk_{fuel}l_{con}t} & \forall\ i,j,t \\ X_{ijk_{GHG}l_{gen}t} = \mathrm{s}_{\mathrm{GHGk_{fuel}}} X_{ijk_{fuel}l_{con}t} & \forall\ i,j,t \\ C_{ijk_{fuel}t} = \mathrm{c}_{\mathrm{k_{fuel}}} X_{ijk_{fuel}l_{con}t} & \forall\ i,j,t \\ \mathrm{X^L}_{\mathrm{ijk_{HP}l_{gen}t}} \le X_{ijk_{HP}l_{gen}t} \le \mathrm{X^U}_{\mathrm{ijk_{HP}l_{gen}t}} & \forall\ i,j,t \end{array} \right] \end{array} \right] \vee \left[\begin{array}{ll} \multicolumn{2}{c}{\neg Y_{ijt}} \\ X_{ijk_{HP}l_{gen}t} = 0 & \forall\ i,j,t \\ X_{ijk_{SOx}l_{gen}t} = 0 & \forall\ i,j,t \\ X_{ijk_{MP}l_{con}t} = 0 & \forall\ i,j,t \\ X_{ijk_{EL}l_{con}t} = 0 & \forall\ i,j,t \\ X_{ijk_{fuel}l_{con}t} = 0 & \forall\ i,j,t \end{array} \right] \tag{9}$$

The above disjunction is included in the optimization model after the convex hull formulation as shown by Turkay and Grossmann (1996). The derivation of convex hull formulation for Eq. (9) is given in the Appendix A.

2.2. Turbine Models

Turbines expand steam at higher pressures to steam at lower pressures and generate electricity by converting the mechanical energy released during expansion into electricity. A typical multi-stage turbine receives HP steam and produces electricity and MP and LP steams and condensate as shown in Fig. 2. Turbine models include the following equations:

$$X_{ijk_{EL}l_{gen}t} = \mathrm{e}_{\mathrm{ijk_{HP}}} X_{ijk_{HP}l_{in}t} - \sum_k \mathrm{g}_{\mathrm{ijk}} X_{ijkl_{gen}t} + \mathrm{f}_{\mathrm{ij}} \qquad \forall\ i,j,t \tag{10}$$

$$X_{ijk_{HP}l_{in}t} = X_{ijk_{MP}l_{gen}t} + X_{ijk_{LP}l_{gen}t} \qquad \forall\ i,j,t \tag{11}$$

$$\mathrm{X^L}_{\mathrm{ijk_{EL}l_{gen}}} \le X_{ijk_{EL}l_{gen}t} \le \mathrm{X^u_{ijk_{EL}l_{gen}}} \qquad \forall\ i,j,t \tag{12}$$

Electricity generation in a turbine is a function of the amounts of HP steam input and MP and LP steam and condensate generation as shown in Eq. (10). The material balance around turbines is expressed in Eq. (11). Eq. (12) determines the upper and lower bounds on the amount of electricity generation in turbines respectively. In addition, Eqs. (6) and (7) are also included for all materials and their corresponding states for turbines. Turbines can also be turned off if it is more profitable. This selection is modeled using disjunctions (Turkay and Grossmann, 1996). The derivation of convex hull formulation for Eq. (13) is given in the Appendix B.

Figure 2

$$\begin{bmatrix} Y_{ijt} \\ X_{ijk_{EL}l_{gen}t} = \mathrm{e}_{\mathrm{ijk_{HP}}} X_{ijk_{HP}l_{in}t} - \sum_{\mathrm{k}} \mathrm{g}_{\mathrm{ijk}} X_{ijkl_{gen}t} + \mathrm{f}_{\mathrm{ij}} \;\; \forall\, i,j,t \\ X_{ijk_{HP}l_{in}t} = X_{ijk_{MP}l_{gen}t} + X_{ijk_{LP}l_{gen}t} \quad \forall\, i,j,t \\ \mathrm{X}^{\mathrm{L}}_{\mathrm{ijk_{EL}l_{gen}}} \le X_{ijk_{EL}l_{gen}t} \le \mathrm{X}^{\mathrm{U}}_{\mathrm{ijk_{EL}l_{gen}}} \quad \forall\, i,j,t \end{bmatrix} \vee \begin{bmatrix} \neg Y_{ijt} \\ X_{ijk_{HP}l_{in}t} = 0 \;\; \forall\, i,j,t \\ X_{ijk_{EL}l_{gen}t} = 0 \;\; \forall\, i,j,t \\ X_{ijk_{MP}l_{gen}t} = 0 \;\; \forall\, i,j,t \\ X_{ijk_{LP}l_{gen}t} = 0 \;\; \forall\, i,j,t \end{bmatrix} \tag{13}$$

2.3. Fuel Tank Models

Fuel tanks contain different types of fuel that are used as raw material in boilers. The amount of fuel k in tank j of company i at period t is represented with I_{ijkt}. The fuel tanks have certain capacities and contain an initial inventory represented by $\mathrm{I}_{\mathrm{ijk0}}$. Tank models include the following equations:

$$X_{ijk_{fuel}l_{out}t} = \sum_{j'\in \mathrm{boilers}} X_{ij'k_{fuel}l_{in}t} \qquad \forall\, i,j,t \tag{14}$$

$$I_{ijk(t-1)} + X_{ijkl_{in}t} - I_{ijkt} - \sum_{\mathrm{j'}\in boilers} X_{ij'kl_{in}t} = 0 \quad \forall\, i,j,k,t \tag{15}$$

$$\mathrm{cpt_{ijk}}\ \mathrm{ssf} \le I_{ijkt} \le \mathrm{cpt_{ijk}} \quad \forall\, i,j,k,t \tag{16}$$

$$\mathrm{p}^{\mathrm{L}}_{\mathrm{ijk_{fuel_m}}} \quad YP_{ijk_{fuel_m}t} \leq X_{ijk_{fuel_m}l_{IN}t} \leq \mathrm{p}^{\mathrm{U}}_{\mathrm{ijk_{fuel_m}}} \quad YP_{ijk_{fuel_m}t} \quad \forall\ i, j, m, t \tag{17}$$

$$CP_{ijk_{fuel}t} = \mathrm{cpo}_{\mathrm{ijk_{fuel_m}}} \quad YP_{ijk_{fuel_m}t} \quad \forall\ i, j, m, t \tag{18}$$

$$HC_{ijk_{fuel}t} = \mathrm{h}_{\mathrm{ijk_{fuel_m}}} \quad I_{ijk_{fuel_m}t} \qquad \forall\ i, j, m, t \tag{19}$$

The total amount of fuel that leaves a fuel tank must be equal to the total amount of fuel that is received by the boilers that are connected to that particular fuel tank. Eq. (14) models the material balance between a fuel tank and the boilers that use the particular fuel in the fuel tank. The amount of fuel used in the boilers that are operational may vary from one period to another due to multi-period nature of the problem. Material balance around a fuel tank is modeled by Eq. (15), which updates the amount of inventory in a fuel tank for every period. Eq. (16) enforces the inventory at any period to be between the total storage capacity of the fuel tank and the safety stock level. The safety stock parameter, ssf, is defined as a fraction of the storage capacity, $\mathrm{cpt}_{\mathrm{ijk}}$. It is also possible to purchase fuel from other sources when there is insufficient inventory in the fuel tanks. Binary variable YP_{ijkt} is 1 if fuel k is purchased for tank j of company i in period t. There is an upper and a lower limit for the fuel purchase amount as shown in Eq. (17). Eq. (18) models the fixed cost of purchase in terms of the fixed cost of purchase $\mathrm{cpo}_{\mathrm{ijk}}$ and the binary variable YP_{ijkt}. Finally, Eq. (19) models the holding cost of fuel inventory, HC_{ijt}, in terms of unit holding cost, $\mathrm{h}_{\mathrm{ijk}}$ and inventory level, I_{ijkt}.

2.4. Mixer Models

Mixers are the units which receive and send the same type of material from and to different units. There is a mixer for each type of material in the system. (HP steam mixer, LP steam mixer, MP steam mixer, electricity mixer). Material flow around a typical steam mixer is given in Fig.3.

Figure 3

Steam comes from boilers, from other mixers and from other companies, and is transferred to turbines, to boilers, to other mixers and to other companies. Mixer models include the following equation:

$$\sum_j X_{ijkl_{out}t} + \sum_j XE_{iji'j't} = \sum_j X_{ijkl_{in}t} + \sum_j XE_{i'j'ijt} + \mathrm{d_{i'j't}} \quad \forall\ i,j,i',j',k,t \tag{20}$$

The variables $XE_{iji'j't}$ represent the amount of material exchange from unit j of company i to unit j' of company i' in period t. Eq. (20) represents the material balances around mixers. If this is a typical steam mixer, the total amount of steam that flows into the mixer from boilers, from other mixers and from other companies is equal to the total amount of steam that flows from the mixer to the turbines, to the boilers, to other mixers and to other companies.

2.5. Environmental Considerations

There are limits on total SO_x and GHG emissions which are calculated as a sum over all periods. Here, total emission is calculated by multiplying the emission rate by the length of period t, n_t.

$$\sum_t \sum_i \sum_j X_{ijk_{SOx}l_{gen}t}\ \mathrm{n_t} \le \mathrm{s^U_{k_{SOx}}} \tag{21}$$

$$\sum_t \sum_i \sum_j X_{ijk_{GHG}l_{gen}t}\ \mathrm{n_t} \le \mathrm{s^U_{k_{GHG}}} \tag{22}$$

2.6. Objective Function

The objective function of the problem is the minimization of the total cost, which is composed of operating cost and investment costs. Operating costs consist of the cost of fuel that is used in the boilers, fixed cost of purchasing fuel, holding cost of fuel inventory, cost of purchasing electricity from the utility company and penalty cost of harmful gas release. One of the largest contributors to the operating cost is the cost of fuel used in the boilers which is represented by the variable $C_{ijk_{fuel}t}$. Other items that contribute to the operating cost are the total fuel purchase cost and the fuel inventory holding costs as mentioned in Eqs. (18) and (19) respectively. In addition, the cost of electricity purchase from the utility company is represented as a function of the amount of electricity purchased and the price of the electricity. Finally, the last term is the penalty cost of SO_x release. The companies do not pay penalty for GHG emissions; however they must decrease the GHG emissions levels according to Kyoto Protocol.

Investment has to be made for inter-company material exchanges, in order to integrate the system. For example, pipelines with certain capacities must be constructed to transfer steam from one company to another. The capacity of the investment is determined by the following inequality.

$$XEC_{iji'j'} \geq XE_{iji'j't} \quad \forall\ i, j, i', j', t \tag{23}$$

The variable $XEC_{iji'j'}$ represents the maximum amount of material that will be exchanged between unit j of company i and unit j' of company i' over the total time horizon. Therefore, the investment cost should be proportional to the variable $XEC_{iji'j'}$.

$$CEC_{iji'j'} = XEC_{iji'j'}\ \beta_{jj'} + \alpha_{jj'}\ YE_{iji'j'} \quad \forall\ i, j, i', j' \tag{24}$$

$$XE_{iji'j't} \leq \mathrm{M}\ YE_{iji'j'} \quad \forall\ i, j, i', j', t \tag{25}$$

Eq. (24) gives the cost of investment required to establish a link between two companies i and i' in units j and j' respectively: the first term is the variable cost of investment where $\beta_{jj'}$ is the cost coefficient, and the second term is the fixed cost of investment where $\alpha_{jj'}$ is a constant. The binary variable $YE_{iji'j'}$ represents the establishment of a link between company i and i' to exchange resources in units j and j'. Eq. (25) relates the binary variable $YE_{iji'j'}$ to exchange of materials, where M is an arbitrarily large number.

The objective function is formulated as the minimization of the total cost including operating and investment costs as follows:

$$
\begin{aligned}
\min Z = & \sum_i \sum_j \sum_k \sum_t C_{ijk_{fuel}t} \\
& + \sum_i \sum_j \sum_k \sum_t CP_{ijk_{fuel}t} \\
& + \sum_i \sum_j \sum_k \sum_t HC_{ijk_{fuel}t} \\
& + \sum_i \sum_j \sum_{i'} \sum_{j'} \sum_t (XE_{iji'j't}\ \mathrm{ce}_{\mathrm{iji'j'}}) \\
& + \sum_i \sum_j \sum_t X_{ijk_{SO_X}l_{GEN}t}\ \mathrm{cr}_{\mathrm{k_{SO_X}}} \\
& + \sum_i \sum_j \sum_{i'} \sum_{j'} (XEC_{iji'j'}\ \beta_{\mathrm{jj'}} + \alpha_{\mathrm{jj'}}\ YE_{iji'j'})
\end{aligned} \tag{26}
$$

The optimization model and the analysis of the results are illustrated in the following section with examples that are derived from an industrial system.

3. Examples

The multi-period mixed-integer programming model is applied on two examples that are constructed by using data from an industrial problem. The first example considers two companies that have identical process networks with different capacities and demand profiles. The second example contains three companies.

3.1. 2-Company Problem

We consider two energy systems each having two fuel tanks with different fuels, two boilers and two turbines as shown in Fig. 4. The energy systems must fulfill the electricity and steam requirement of processes they serve. The demands for steam (HP, MP, and LP) and electricity are functions of production rate and energy requirement characteristics of the industrial processes that the energy systems are serving. The example is solved for three periods with the parameters given in Tables 1, and 2. The problem is modeled in GAMS (GAMS, 2004) and solved using CPLEX Solver (Ilog, 2002). Table 3 summarizes some statistics about the model size and the solution of the problem.

Figure 4

Table 1

Table 2

Table 3

The same problem is solved under two cases: first the operations of energy production systems are optimized without the possibility of collaboration and second with collaboration under the same demand profiles and operating characteristics. When the results of the integrated solution are compared with the results of the nonintegrated solution, it is observed that with integration steam expansion decreases and steam exchange exists. Steam flow from higher pressure to lower pressure means steam expansion, since steam that has a higher energy level loses energy and becomes steam that has a lower energy level. For example, there is steam flow from the higher pressure steam mixers to the lower pressure steam mixers of the same company in the non-integrated system indicating that some energy is lost as shown in Table 4. When the exchange of steam is not allowed, it is observed that boilers must produce more HP steam than the required amount for fulfilling the MP and LP steam requirement through expansion. This is a common practice in energy systems that must satisfy electricity and steam demand simultaneously: higher pressure steam must be expanded to fulfill lower pressure steam requirement. On the other hand, the energy integrated solution satisfies the energy requirement of both of the companies with steam and electricity exchange between the integrated companies. Because, there exist material flows between the equivalent mixers of the two companies in the integrated case. As can be seen in Table 5, there still exists some steam expansion, but its magnitude decreases significantly with integration.

Table 4

Table 5

Table 6

In Table 6, some monetary and environmental improvements as a result of the integration are illustrated. In this example, it is possible to serve the same energy requirement with a 3.12% lower cost by integrating two companies. It is also important to notice that a significant reduction in the SO_x and GHG emissions (10.40% and 9.10%, respectively) is possible through supply chain integration. The proposed approach identified simultaneous improvements in the economical and environmental performances. An interesting result is the amount of reduction in GHG emission. Japan has committed to reduce its GHG emissions by 6% relative to 1990 according to the Kyoto Protocol (Japan modified its commitment to a reduction of 8.5% on June 4, 2002 (UNFCC, 2004)). Our results show that integration offers great opportunity to get a step closer to achieve this goal.

3.2. 3-Company Example

A similar problem with three companies is solved with corresponding data given in Tables 7 and 8. The topology of the energy system is given in Fig. 5. Table 9 gives some statistics on the model size and the solution of the problem. From Tables 10 and 11 it can be seen that with integration steam expansion decreases and steam exchange between integrated companies is formed. The steam and electricity demands of the companies are supplied by exchange of materials rather than steam expansions, as discussed in 2-company example.

Figure 5

Table 7

Table 8

Table 9

Table 10

Table 11

As the results in Table 12 shows, the synergy by the integration increases when the number of companies is increased. With integration, 2.47% cost improvement is achieved in this example. There is a 13.97% improvement in SO_x emissions and a 9.60% improvement in GHG emissions with integration. These values show that integration improves the companies both economically and environmentally. The improvement in costs is proportionally less than 2-company case, but the environmental improvement is higher. Since integrating three companies would cost more than integrating two companies it is an expected result. Once an exchange system is formed between the companies, it results in high return in environmental considerations. But it is more expensive and complicated to form an exchange system as the number of companies increase. These examples indicates that by increasing number of companies the improvement in the environmental criteria gets larger but financial improvement gets smaller due to the increased investment costs.

Table 12

4. Conclusions

The energy integration of process systems in the same industrial zone has been addressed in this paper. A systematic approach that consists of modeling process units through fundamentals of unit operations and statistical analysis of process data, an MILP model for the integration of different process systems, and comparative analysis of the results has been developed. The proposed approach has been illustrated with two examples that are simplified versions of a real problem.

It is shown that important improvements in the cost and release of environmentally harmful chemicals can be accomplished by integration of process systems. Nonintegrated solution results in inefficiencies because of large amount of steam expansions which means lost energy. Integrated solution allows the companies satisfy their demands with steam exchanges rather than steam expansion resulting in improvements of environmental and economical performance.

An important finding of our study is that, the cost of integrating companies affects the improvements seriously. Once an exchange system is formed between the companies, it results in high improvement in environmental criteria. The economical improvement with respect to nonintegrated solution gets smaller with the increasing number of companies due to higher cost of integrating large number of production systems..

References

Cooper, W.W., Hemphill, H., Huang, Z., Li, S., Lelas, V. and Sullivan, D. W., 1997. Survey of mathematical programming models in air pollution management, European Journal of Operational Research 96 (1) 1-35.

GAMS IDE, 2.0.26.8 License date Jan 19, 2004. Build VIS 21.3 138.

Gonzales-Monroy, L.I and Cordoba, A., 2002. Financial costs and energy impact minimization of the energy supply systems. Int. J. of Energy Res., 26, 27-44.

Hitt, M. A., Dacin, M.T., Levitas, E., Arregle, J.L., and Borza, A., 2000. Partner selection in emerging and developed market contexts: Resource-based and organizational learning perspectives, Academy of Management Journal, 43 449–467.

Ilog (2002). OPL Studio Reference & User Manual, Version 3.5.

Ireland R.D., Hitt. M.A. and Vaidyanath, D., 2002. Alliance Management as a Source of Competitive Advantage, Journal of Management 28 (3) 413-446.

Malone, T.W., Crowston, K.G., 1994. The interdisciplinary study of coordination, ACM Computing Surveys 26 (1) 87-119.

Marechal, F. and Kalitventzeff, B., 1998. Process Integration: Selection of the optimal utility system, Computers and Chemical Engineering 22 S149-S156.

Mentzer, M. S., 1999. Two heads are better than one if your company spans the globe, The Academy of Management Executive 13 89–90.

Mentzer, J. T., Min, S., Zacharia, Z.G., 2000. The Nature of Interfirm Partnering in Supply Chain Management, Journal of Retailing 76(4) 549–568.

Min, H. and Zhou, G., 2002. Supply chain modeling: past, present and future, Computers and Industrial Engineering 43 231-249.

Mohr, J., and Spekman, R., 1994. Characteristics of partnership success: partnership attributes, communication behavior, and conflict resolution techniques, Strategic Management Journal 15 135–152.

Oliveira, C., and Antunes, C.H., 2004. A Multiple Objective Model to Deal with Energy-Environment Interactions, European Journal of Operational Research, 153 370-385.

Reyniers, D.J., 1992. Supplier-customer interaction in quality control, Annals of Operations Research 34 307-330.

Saeed. A.E., Blakemore, F.B. and Doulah, M.S., 1996. Effect of process integration on the reduction of fuel consumption, Applied Energy 54 287-300.

Schiefer G., 2002. Environmental control for process improvement and process efficiency in supply chain management, International J. of Production Economics 78 197-206.

Sox, C.R., Thomas, L.J., McClain, J.O., 1997. Coordinating production and inventory to improve service, Management Science 43 (9) 1189-1197.

Stefanis S.K., Livingston, A.G. and Pistikopoulos, E.N., 1995. Minimizing the environmental impact of process plants: a process systems methodology, Computers and Chemical Engineering 19, S39-S44.

Turkay, M and Grossmann, I.E., 1996. Disjunctive programming techniques for the optimization of process systems with discontinuous investment costs-Multiple size regions, Industrial and Engineering Chemistry Research 35 2611-2623.

Turkay, M., Oruc, C., Fujita, K. and Asakura, T., 2004, Multi-company collaborative supply chain management with economical and environmental considerations, Computers and Chemical Engineering 28 985-992.

UNFCC, 2004, Climate Change Information kit, Retrieved June 27, 2004 from http://www.unfccc.int/resource/iuckit/cckit2001en.pdf.

Whang, S., 1995. Coordination in operations: A taxonomy, Journal of Operations Management 12 413-422.

Appendix A – Derivation of the Convex Hull Formulation for Boiler Disjunction

Given the nested disjunction in Eq. (9), the convex hull formulation is developed as follows:

Step 1. Disaggregate all continuous variables for each term of the disjunction.

Step 2. Summation of all disaggregated variables is equal to the original variable.

$$X_{ijk_{HP}l_{gen}t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{HP}l_{gen}t} \quad \forall\ i, j, t \tag{A1}$$

$$X_{ijk_{fuel}l_{con}t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{fuel_m}l_{con}t} \quad \forall\ i, j, t \tag{A2}$$

$$X_{ijk_{MP}l_{CON}t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{MP}l_{CON}t} \quad \forall\ i, j, t \tag{A3}$$

$$X_{ijk_{EL}l_{CON}t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{EL}l_{CON}t} \quad \forall\ i, j, t \tag{A4}$$

$$X_{ijk_{SOx}l_{GEN}t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{SOx}l_{GEN}t} \quad \forall\ i, j, t \tag{A5}$$

$$X_{ijk_{GHG}l_{GEN}t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{GHG}l_{GEN}t} \quad \forall\ i, j, t \tag{A6}$$

$$C_{ijk_{fuel}t} = \sum_{m \in D_{ij}} CD^{m}_{ijk_{fuel_m}t} \quad \forall\ i, j, t \tag{A7}$$

Step 3. Replicate the constraints for each term of the disjunction:

$$XD^{m}_{ijk_{HP}l_{gen}t} = \frac{1}{\eta_{\mathrm{ijk_{fuel_m}}}} \mathrm{cc}_{\mathrm{k_{fuel_m}}} XD^{m}_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i, j, m, t \tag{A8}$$

$$XD^{m}_{ijk_{MP}l_{CON}t} = \mathrm{a}_{\mathrm{ijk_{MP}}} XD^{m}_{ijk_{HP}l_{gen}t} + \mathrm{b}_{\mathrm{ijk_{MP}}} \qquad \forall\ i,j,m,t \tag{A9}$$

$$XD^{m}_{ijk_{EL}l_{CON}t} = \mathrm{a}_{\mathrm{ijk_{EL}}} XD^{m}_{ijk_{HP}l_{gen}t} + \mathrm{b}_{\mathrm{ijk_{EL}}} \qquad \forall\ i,j,m,t \tag{A10}$$

$$XD^{m}_{ijk_{SOx}l_{gen}t} = \mathrm{s}_{\mathrm{SO_x k_{fuel_m}}} XD^{m}_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i,j,m,t \tag{A11}$$

$$XD^{m}_{ijk_{GHG}l_{gen}t} = \mathrm{s}_{\mathrm{GHGk_{fuel_m}}} XD^{m}_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i,j,m,t \tag{A12}$$

$$CD^{m}_{ijk_{fuel_m}t} = \mathrm{c}_{\mathrm{k_{fuel_m}}} XD^{m}_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i,j,m,t \tag{A13}$$

$$\mathrm{X^L}_{\mathrm{ijk_{HP}l_{gen}t}} \le XD^{m}_{ijk_{HP}l_{gen}t} \le \mathrm{X^U}_{\mathrm{ijk_{HP}l_{gen}t}} \qquad \forall\ i,j,m,t \tag{A14}$$

Step 4. Introduce a binary variable for each term of the disjunction and multiply all constants in constraints by the corresponding binary variable.

$$XD^{m}_{ijk_{HP}l_{gen}t} \le \mathrm{X^U}_{\mathrm{ijk_{HP}l_{gen}t}}\ YF_{ijk_{fuel_m}t} \qquad \forall\ i,j,m,t \tag{A15}$$

$$XD^{m}_{ijk_{HP}l_{gen}t} \ge \mathrm{X^L}_{\mathrm{ijk_{HP}l_{gen}t}} YF_{ijk_{fuel_m}t} \qquad \forall\ i,j,m,t \tag{A16}$$

$$XD^{m}_{ijk_{MP}l_{CON}t} = \mathrm{a}_{\mathrm{ijk_{MP}}}\ XD^{m}_{ijk_{HP}l_{gen}t} + \mathrm{b}_{\mathrm{ijk_{MP}}}\ YF_{ijk_{fuel_m}t} \qquad \forall\ i,j,m,t \tag{A9}$$

$$XD^{m}_{ijk_{EL}l_{CON}t} = \mathrm{a}_{\mathrm{ijk_{EL}}}\ XD^{m}_{ijk_{HP}l_{gen}t} + \mathrm{b}_{\mathrm{ijk_{EL}}}\ YF_{ijk_{fuel_m}t} \qquad \forall\ i,j,m,t \tag{A10}$$

Step 5. Summation of all binary variables is equal to 1.

$$\sum_{m} YF_{ijk_{HP}l_{fuel_m}t} = 1 \qquad \forall\ i, j, t \tag{A17}$$

Step 6. Make necessary algebraic simplifications to eliminate unnecessary variables and constraints:

$$X_{ijk_{HP}l_{gen}t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{HP}l_{gen}t} \qquad \forall\ i, j, t \tag{A18}$$

$$X_{ijk_{fuel}l_{con}t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i, j, t \tag{A19}$$

$$X_{ijk_{SOx}l_{gen}t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{SOx}l_{gen}t} \qquad \forall\ i, j, t \tag{A20}$$

$$X_{ijk_{GHG}l_{GEN}t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{GHG}l_{GEN}t} \qquad \forall\ i, j, t \tag{A21}$$

$$XD^{m}_{ijk_{HP}l_{gen}t} = \frac{1}{\eta_{\mathrm{ijk_{fuel_m}}}} \mathrm{cc}_{\mathrm{k_{fuel_m}}}\ X_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i, j, m, t \tag{A22}$$

$$XD^{m}_{ijk_{SOx}l_{gen}t} = \mathrm{s}_{\mathrm{SO_x k_{fuel_m}}}\ X_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i, j, m, t \tag{A23}$$

$$XD^{m}_{ijk_{GHG}l_{gen}t} = \mathrm{s}_{\mathrm{GHGk_{fuel_m}}}\ X_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i, j, m, t \tag{A24}$$

$$XD^{m}_{ijk_{HP}l_{gen}t} \le \mathrm{X^{U}}_{\mathrm{ijk_{HP}l_{gen}t}}\ YF_{ijk_{fuelm}t} \qquad \forall\ i, j, m, t \tag{A25}$$

$$XD^{m}_{ijk_{HP}l_{gen}t} \ge \mathrm{X^{L}}_{\mathrm{ijk_{HP}l_{gen}t}}\ YF_{ijk_{fuel_m}t} \qquad \forall\ i, j, m, t \tag{A26}$$

$$\sum_{m} YF_{ijk_{HP} l_{fuel_m} t} = 1 \qquad \forall\ i, j, t \tag{A27}$$

$$XD^{m}_{ijk_{MP} l_{CON} t} = \mathrm{a}_{\mathrm{ijk_{MP}}}\ XD^{m}_{ijk_{HP} l_{gen} t} + \mathrm{b}_{\mathrm{ijk_{MP}}}\ YF_{ijk_{fuel_m} t} \qquad \forall\ i, j, m, t \tag{A28}$$

$$XD^{m}_{ijk_{EL} l_{CON} t} = \mathrm{a}_{\mathrm{ijk_{EL}}}\ XD^{m}_{ijk_{HP} l_{gen} t} + \mathrm{b}_{\mathrm{ijk_{EL}}}\ YF_{ijk_{fuel_m} t} \qquad \forall\ i, j, m, t \tag{A29}$$

$$C_{ijk_{fuel} t} = \mathrm{c}_{\mathrm{k_{fuel_m}}}\ X_{ijk_{fuel_m} l_{con} t} \qquad \forall\ i, j, m, t \tag{A30}$$

When the turning on-off consideration is added the disjunction model becomes:

$$\begin{bmatrix} Y_{ijt} & \\ X_{ijk_{HP} l_{gen} t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{HP} l_{gen} t} & \forall\ i, j, t \\ X_{ijk_{fuel} l_{con} t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{fuel_m} l_{con} t} & \forall\ i, j, t \\ X_{ijk_{SOx} l_{gen} t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{SOx} l_{gen} t} & \forall\ i, j, t \\ X_{ijk_{GHG} l_{gen} t} = \sum_{m \in D_{ij}} XD^{m}_{ijk_{GHG} l_{gen} t} & \forall\ i, j, t \\ XD^{m}_{ijk_{HP} l_{gen} t} = \dfrac{1}{\eta_{\mathrm{ijk_{fuel_m}}}} \mathrm{cc}_{\mathrm{k_{fuel_m}}}\ X_{ijk_{fuel_m} l_{con} t} & \forall\ i, j, m, t \\ XD^{m}_{ijk_{SOx} l_{gen} t} = \mathrm{s}_{\mathrm{SO_x k_{fuel_m}}}\ X_{ijk_{fuel_m} l_{con} t} & \forall\ i, j, m, t \\ XD^{m}_{ijk_{GHG} l_{gen} t} = \mathrm{s}_{\mathrm{GHGk_{fuel_m}}}\ X_{ijk_{fuel_m} l_{con} t} & \forall\ i, j, m, t \\ XD^{m}_{ijk_{HP} l_{gen} t} \le \mathrm{X^U}_{\mathrm{ijk_{HP} l_{gen}}}\ YF_{ijk_{fuel_m} t} & \forall\ i, j, m, t \\ XD^{m}_{ijk_{HP} l_{gen} t} \ge \mathrm{X^L}_{\mathrm{ijk_{HP} l_{gen}}}\ YF_{ijk_{fuel_m} t} & \forall\ i, j, m, t \\ \sum_{m} YF_{ijk_{HP} l_{fuel_m} t} = 1 & \forall\ i, j, t \\ XD^{m}_{ijk_{MP} l_{con} t} = \mathrm{a}_{\mathrm{ijk_{MP}}}\ XD^{m}_{ijk_{HP} l_{gen} t} + \mathrm{b}_{\mathrm{ijk_{MP}}} YF_{ijk_{fuel_m} t} & \forall\ i, j, m, t \\ XD^{m}_{ijk_{EL} l_{con} t} = \mathrm{a}_{\mathrm{ijk_{EL}}}\ XD^{m}_{ijk_{HP} l_{gen} t} + \mathrm{b}_{\mathrm{ijk_{EL}}} YF_{ijk_{fuel_m} t} & \forall\ i, j, m, t \\ C_{ijk_{fuel} t} = \mathrm{c}_{\mathrm{k_{fuel_m}}}\ X_{ijk_{fuel_m} l_{con} t} & \forall\ i, j, m, t \end{bmatrix} \vee \begin{bmatrix} \neg Y_{ijt} & \\ X_{ijk_{HP} l_{gen} t} = 0 & \forall\ i, j, t \\ X_{ijk_{SOx} l_{gen} t} = 0 & \forall\ i, j, t \\ X_{ijk_{MP} l_{con} t} = 0 & \forall\ i, j, t \\ X_{ijk_{EL} l_{con} t} = 0 & \forall\ i, j, t \\ X_{ijk_{fuel} l_{con} t} = 0 & \forall\ i, j, t \end{bmatrix} \tag{A31}$$

The final convex hull formulation can be obtained by applying the given procedure.

$$X_{ijk_{HP}l_{gen}t} = \sum_{m\in D_{ij}} XD^m_{ijk_{HP}l_{gen}t} \qquad \forall\ i,j,t \tag{A32}$$

$$X_{ijk_{fuel}l_{con}t} = \sum_{m\in D_{ij}} XD^m_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i,j,t \tag{A33}$$

$$X_{ijk_{SO_x}l_{gen}t} = \sum_{m\in D_{ij}} XD^m_{ijk_{SO_x}l_{gen}t} \qquad \forall\ i,j,t \tag{A34}$$

$$X_{ijk_{GHG}l_{gen}t} = \sum_{m\in D_{ij}} XD^m_{ijk_{GHG}l_{gen}t} \qquad \forall\ i,j,t \tag{A35}$$

$$XD^m_{ijk_{HP}l_{gen}t} = \frac{1}{\eta_{\mathrm{ijk_{fuel_m}}}}\mathrm{cc}_{\mathrm{k_{fuel_m}}} X_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i,j,m,t \tag{A36}$$

$$XD^m_{ijk_{SOx}l_{gen}t} = \mathrm{s}_{\mathrm{SO_x k_{fuel_m}}} X_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i,j,m,t \tag{A37}$$

$$XD^m_{ijk_{GHG}l_{gen}t} = \mathrm{s}_{\mathrm{GHGk_{fuel_m}}} X_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i,j,m,t \tag{A38}$$

$$\mathrm{X^L}_{\mathrm{ijk_{HP}l_{gen}}}\ YF_{ijk_{fuel\,m}t} \le XD^m_{ijk_{HP}l_{gen}t} \le \mathrm{X^U}_{\mathrm{ijk_{HP}l_{gen}}} YF_{ijk_{fuel\,m}t} \qquad \forall\ i,j,m,t \tag{A39}$$

$$\sum_m YF_{ijk_{HP}l_{fuel_m}t} \le 1 \qquad \forall\ i,j,t \tag{A40}$$

$$XD^m_{ijk_{MP}l_{CON}t} = \mathrm{a}_{\mathrm{ijk_{MP}}}\ XD^m_{ijk_{HP}l_{gen}t} + \mathrm{b}_{\mathrm{ijk_{MP}}} YF_{ijk_{fuel_m}t} \qquad \forall\ i,j,m,t \tag{A41}$$

$$XD^m_{ijk_{EL}l_{CON}t} = \mathrm{a}_{\mathrm{ijk_{EL}}}\ XD^m_{ijk_{HP}l_{gen}t} + \mathrm{b}_{\mathrm{ijk_{EL}}} YF_{ijk_{fuel_m}t} \qquad \forall\ i,j,m,t \tag{A42}$$

$$C_{ijk_{fuel}t} = \mathrm{c}_{\mathrm{k_{fuel_m}}} X_{ijk_{fuel_m}l_{con}t} \qquad \forall\ i,j,m,t \tag{A43}$$

$$\mathrm{X^L}_{\mathrm{ijk_{MP}l_{con}}}\ Y_{ijt} \le X_{ijk_{MP}l_{con}t} \le \mathrm{X^U}_{\mathrm{ijk_{MP}l_{con}}}\ Y_{ijt} \qquad \forall\ i,j,t \tag{A44}$$

$$\mathrm{X^L}_{\mathrm{ijk_{EL}l_{con}}}\ Y_{ijt} \le X_{ijk_{EL}l_{con}t} \le \mathrm{X^U}_{\mathrm{ijk_{EL}l_{con}}}\ Y_{ijt} \qquad \forall\ i,j,t \tag{A45}$$

$$\mathrm{X^L}_{\mathrm{ijk_{fuel_m}l_{con}}}\ Y_{ijt} \le X_{ijk_{fuel_m}l_{con}t} \le \mathrm{X^U}_{\mathrm{ijk_{fuel_m}l_{con}}}\ Y_{ijt} \qquad \forall\ i,j,t \tag{A46}$$

$$\mathrm{X^L}_{\mathrm{ijk_{HP}l_{gen}}}\ Y_{ijt} \le X_{ijk_{HP}l_{gen}t} \le \mathrm{X^U}_{\mathrm{ijk_{HP}l_{gen}}}\ Y_{ijt} \qquad \forall\ i,j,t \tag{A47}$$

$$\mathrm{X^L_{ijk_{SO_x}l_{gen}}} Y_{ijt} \le X_{ijk_{SO_x}l_{gen}t} \le \mathrm{X^U_{ijk_{SO_x}l_{gen}}}\ Y_{ijt} \quad \forall\ i,j,t \tag{A48}$$

$$\mathrm{X^L}_{\mathrm{ijk_{GHG}l_{gen}}}\ Y_{ijt} \le X_{ijk_{GHG}l_{gen}t} \le \mathrm{X^U}_{\mathrm{ijk_{GHG}l_{gen}}}\ Y_{ijt} \qquad \forall\ i,j,t \tag{A49}$$

Appendix B – Derivation of the Convex Hull Formulation for the Turbine Disjunction

The convex hull formulation of the disjunctions given in Eq.(13) is as follows.

$$X_{ijk_{EL}l_{gen}t} = \mathrm{e}_{\mathrm{ijk_{HP}}}\ X_{ijk_{HP}l_{in}t} - \sum_{k} \mathrm{g}_{\mathrm{ijk}}\ X_{ijkl_{gen}t} + \mathrm{f}_{\mathrm{ij}}\ Y_{ijt} \qquad \forall\ i,j,t \tag{B1}$$

$$X_{ijk_{HP}l_{in}t} = X_{ijk_{MP}l_{gen}t} + X_{ijk_{LP}l_{gen}t} \qquad \forall\ i,j,t \tag{B2}$$

$$\mathrm{X}^{\mathrm{L}}_{\mathrm{ijk_{EL}l_{gen}}}\ Y_{ijt} \le X_{ijk_{EL}l_{gen}t} \le \mathrm{X}^{\mathrm{U}}_{\mathrm{ijk_{EL}l_{gen}}}\ Y_{ijt} \qquad \forall\ i,j,t \tag{B3}$$

$$\mathrm{X}^{\mathrm{L}}_{\mathrm{ijk_{HP}l_{in}}}\ Y_{ijt} \le X_{ijk_{HP}l_{in}t} \le \mathrm{X}^{\mathrm{U}}_{\mathrm{ijk_{HP}l_{in}}}\ Y_{ijt} \qquad \forall\ i,j,t \tag{B4}$$

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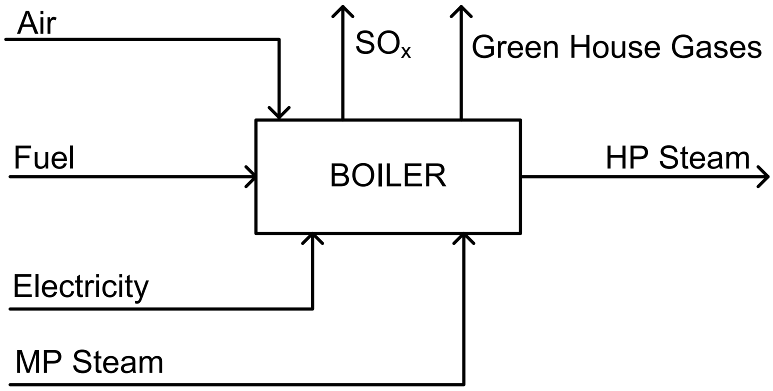

Figure 1. Schematic diagram of a boiler.

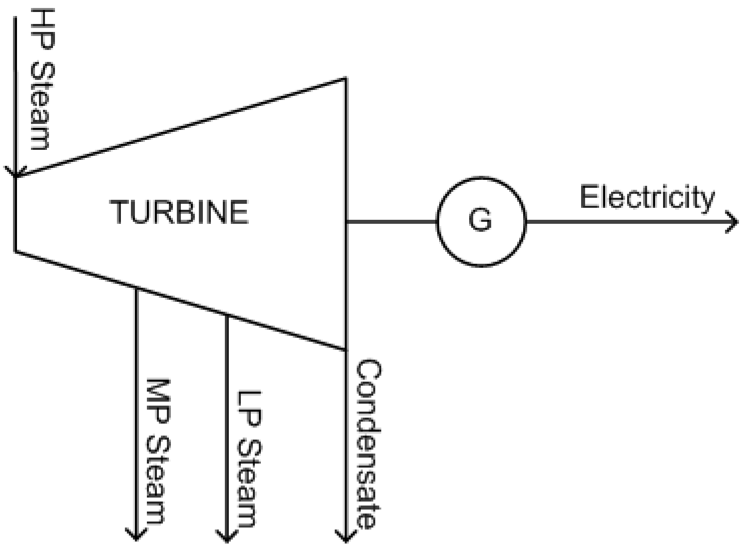

Figure 2. Schematic diagram of a turbine.

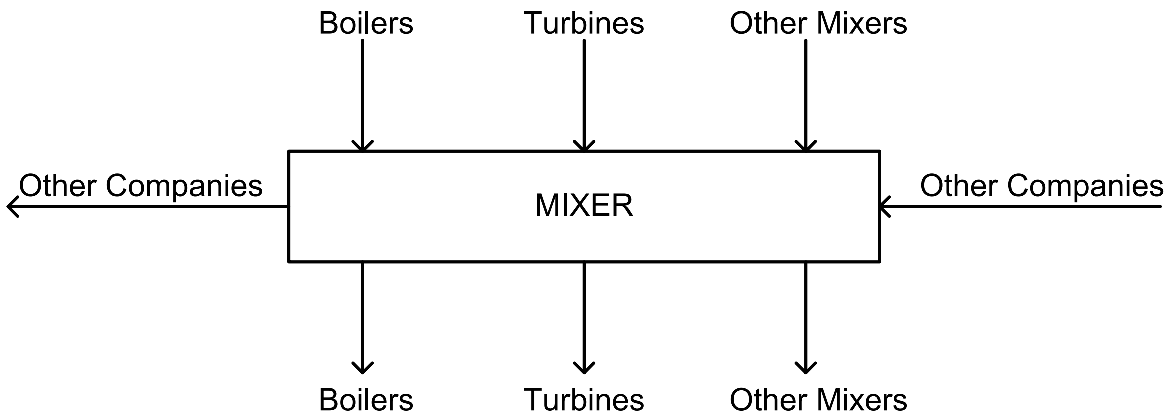

Figure 3. Schematic diagram of a mixer.

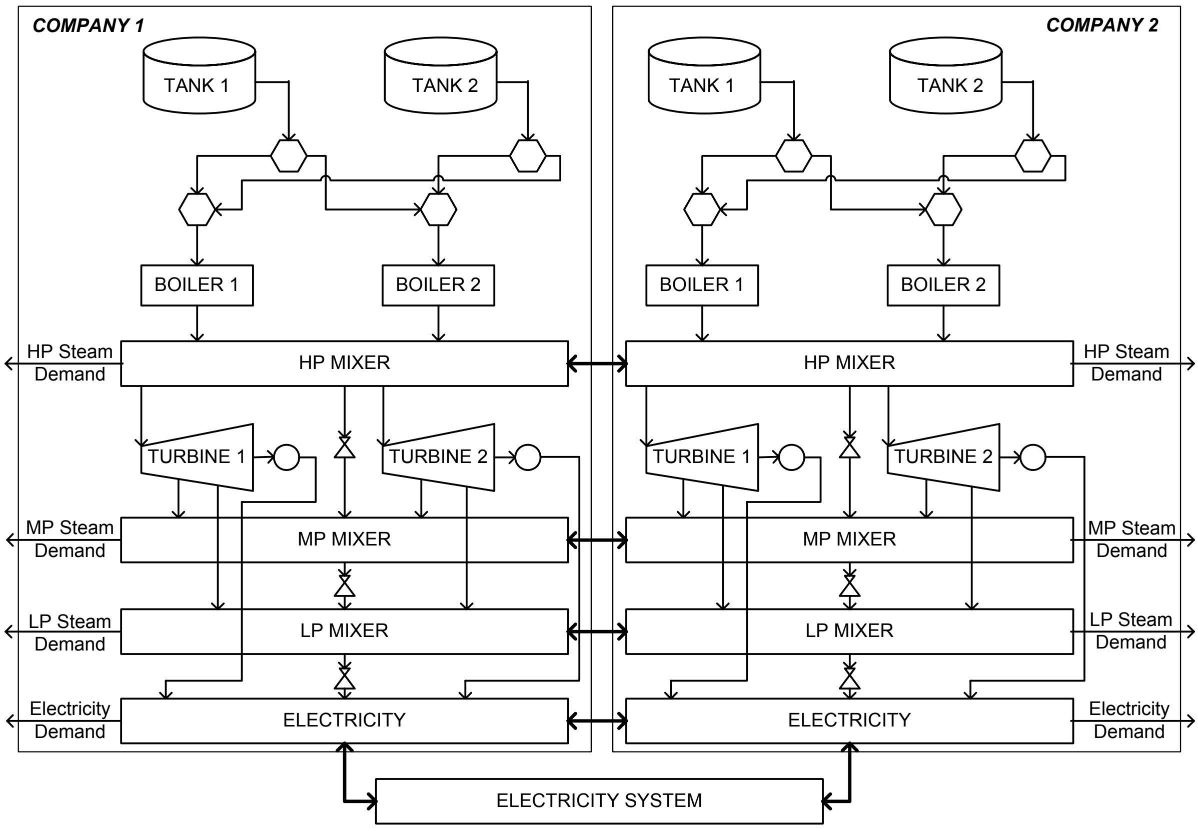

Figure 4. Flowsheet of the 2-company problem.

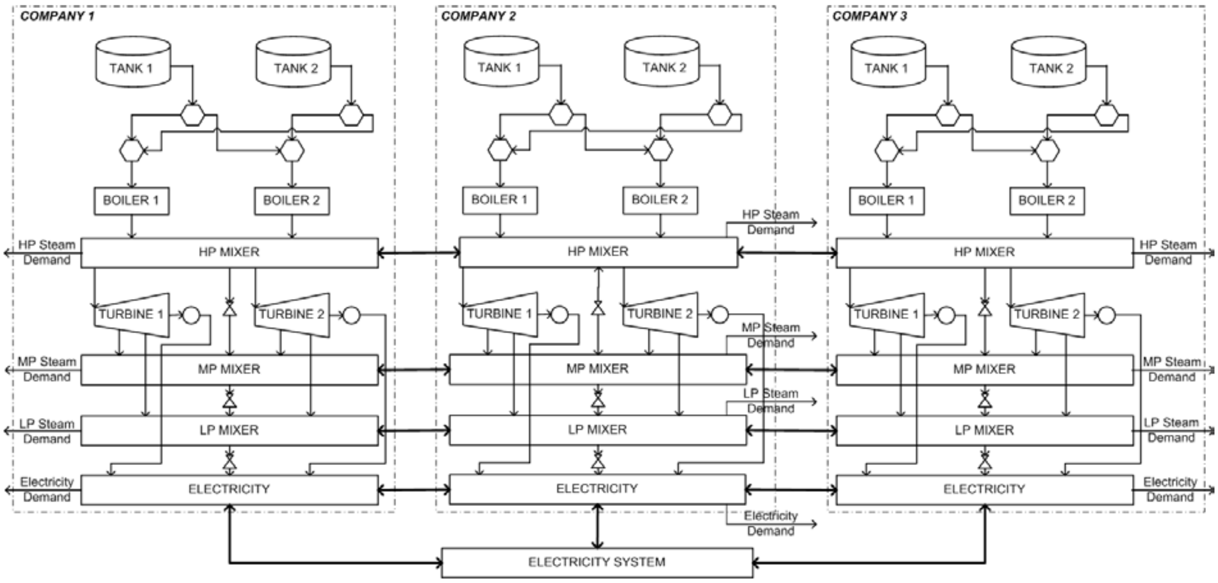

Figure 5. Flowsheet of the 3-company problem.

List of Tables

Table 1. Operating characteristics for the energy system in the 2-company problem.

	Company 1		Company 2	
	Fuel 1	Fuel 2	Fuel 1	Fuel 2
cc_k	10.50	9.65	6.65	10.20
I_{ijkt0}	100	40	120	100
cpt	120	50	130	110
s_{SOxk}	7.80	1.42	1.20	5.13
s_{GHGk}	17	5	3	10
c_k	200	76	83	145
	Boiler 1	Boiler 2	Boiler 1	Boiler 2
$\eta_{ijk_{fuel1}}$	0.590	0.575	0.560	0.565
$\eta_{ijk_{fuel2}}$	0.600	0.595	0.605	0.600
$a_{ijk_{MP}}$	0.11	0.12	0.11	0.12
$a_{ijk_{EL}}$	0.002	0.003	0.0025	0.0028
$X^u_{ijk_{HP}l_{gen}}$	550	550	600	600
$b_{ijk_{HP}}$	0.001	0.001	0.001	0.001
$b_{ijk_{EL}}$	0.001	0.001	0.001	0.001
	Turbine 1	Turbine 2	Turbine 1	Turbine 2
$e_{ijk_{HP}}$	0.150	0.175	0.160	0.170
$e_{ijk_{MP}}$	0.070	0.080	0.070	0.075
$e_{ijk_{LP}}$	0.009	0.010	0.012	0.010
$X^u_{ijk_{EL}l_{gen}}$	70	60	70	65
$X^u_{ijk_{HP}l_{in}}$	900	900	900	900
$X^u_{ijk_{MP}l_{gen}}$	300	300	400	400
$X^u_{ijk_{LP}l_{gen}}$	70	60	70	65
	HP	MP	LP	
$\alpha_{jj'}$	0.39	0.35	0.15	
$\beta_{jj'}$	0.11	0.10	0.04	

Table 2. Energy demand in the 2-company problem.

Company 1	Period 1	Period 2	Period 3
Electricity	150	200	180
HP Steam	10	13	8
MP Steam	620	423	510
LP Steam	300	260	350
Company 2	**Period 1**	**Period 2**	**Period 3**
Electricity	140	180	160
HP Steam	10	15	12
MP Steam	300	345	385
LP Steam	680	500	570

Table 3. Model and solution statistics for the 2-company problem.

	Nonintegrated	Integrated
Number of constraints	627	627
Number of variables	665	665
Number of nodes in the branch and bound tree	0	0
Number of iterations	100	162
CPU time (*sec)	0.070	0.070

* On a PC with Pentium 4 2.6 GHz Processor and 512 MB memory.

Table 4. Summary of the results for the non-integrated solution in the 2-company problem.

Company	Unit	Company	Unit	Period	Value
Company1	HP	Company1	MP	1	140.57
Company1	HP	Company1	MP	3	22.11
Company2	HP	Company2	MP	1	0.54
Company2	MP	Company2	LP	1	150.34
CompanyU	Elec	Company1	Elec	1	53.20
CompanyU	Elec	Company1	Elec	2	115.11
CompanyU	Elec	Company1	Elec	3	75.94
CompanyU	Elec	Company2	Elec	1	7.98
CompanyU	Elec	Company2	Elec	2	63.03
CompanyU	Elec	Company2	Elec	3	28.10

Table 5. Summary of the results for the integrated solution in the 2-company problem.

Company	Unit	Company	Unit	Period	Value
Company1	LP	Company2	LP	1	89.22
Company1	LP	Company2	LP	3	89.22
Company2	HP	Company2	MP	3	9.41
Company2	MP	Company1	MP	1	151.98
Company2	MP	Company1	MP	2	151.98
Company2	MP	Company1	MP	3	151.98
Company2	MP	Company2	LP	1	165.05
CompanyU	Elec	Company1	Elec	1	42.00
CompanyU	Elec	Company1	Elec	2	128.41
CompanyU	Elec	Company1	Elec	3	74.22
CompanyU	Elec	Company2	Elec	1	8.15
CompanyU	Elec	Company2	Elec	2	48.04
CompanyU	Elec	Company2	Elec	3	28.08

Table 6. Comparison of the results for the 2-company problem.

	Non-Integrated	Integrated	Improvement (%)
Total Cost	49,019.23	47,488.84	3.12
SO_x Release	2,619,268.07	2,346,686.04	10.40
GHG Release	6,534,323.61	5,939,689.22	9.10

Table 7. Operating characteristics for the energy system in the 3-company problem.

	Company 1		Company 2		Company 2	
	Fuel 1	Fuel 2	Fuel 1	Fuel 2	Fuel 1	Fuel 2
cc_k	10.50	9.65	6.65	10.20	11.00	12.00
I_{ijkt0}	100	40	120	100	120	100
cpt	120	50	130	110	130	110
s_{SOxk}	7.80	1.42	1.20	5.13	4.83	2.62
s_{GHGk}	17	5	3	10	11	8
c_k	200	76	83	145	94	102
	Boiler 1	Boiler 2	Boiler 1	Boiler 2	Boiler 1	Boiler 2
$\eta_{ijk_{fuel1}}$	0.590	0.575	0.560	0.565	0.580	0.595
$\eta_{ijk_{fuel2}}$	0.600	0.595	0.605	0.600	0.570	0.605
$a_{ijk_{MP}}$	0.11	0.12	0.11	0.12	0.1150	0.1210
$a_{ijk_{EL}}$	0.002	0.003	0.0025	0.0028	0.0026	0.0029
$X^u_{ijk_{HP}l_{gen}}$	550	550	600	600	600	600
$b_{ijk_{HP}}$	0.001	0.001	0.001	0.001	0.001	0.001
$b_{ijk_{EL}}$	0.001	0.001	0.001	0.001	0.001	0.001
	Turbine 1	Turbine 2	Turbine 1	Turbine 2	Turbine 1	Turbine 2
$e_{ijk_{HP}}$	0.150	0.175	0.160	0.170	0.160	0.170
$e_{ijk_{MP}}$	0.070	0.080	0.070	0.075	0.070	0.075
$e_{ijk_{LP}}$	0.009	0.010	0.012	0.010	0.012	0.010
$X^u_{ijk_{EL}l_{gen}}$	70	60	70	65	70	65
$X^u_{ijk_{HP}l_{in}}$	900	900	900	900	900	900
$X^u_{ijk_{MP}l_{gen}}$	300	300	400	400	400	400
$X^u_{ijk_{LP}l_{gen}}$	70	60	70	65	70	65
	HP	MP	LP			
$\alpha_{jj'}$	0.39	0.35	0.15			
$\beta_{jj'}$	0.11	0.10	0.04			

Table 8. Energy demand in the 3-company problem.

Company 1	Period 1	Period 2	Period 3
Electricity	150	200	180
HP Steam	10	13	8
MP Steam	620	423	510
LP Steam	300	260	350
Company 2	Period 1	Period 2	Period 3
Electricity	140	180	160
HP Steam	10	15	12
MP Steam	300	345	385
LP Steam	680	500	570
Company 3	Period 1	Period 2	Period 3
Electricity	150	170	170
HP Steam	11	14	13
MP Steam	320	350	440
LP Steam	300	340	450

Table 9. Model and solution statistics for the 3-company problem.

	Non-Integrated	Integrated
Number of constraints	993	993
Number of variables	1,042	1,042
Number of nodes in the branch and tree	0	0
Number of iterations	166	371
CPU time (*sec)	0.080	0.080

* On a PC with Pentium 4 2.6 GHz Processor and 512 MB memory.

Table 10. Summary of the results for the non-integrated solution in the 3-company problem.

Company	Unit	Company	Unit	Period	Value
Company1	HP	Company1	MP	1	140.57
Company1	HP	Company1	MP	3	22.11
Company2	MP	Company2	LP	1	150.23
CompanyU	Elec	Company1	Elec	1	53.20
CompanyU	Elec	Company1	Elec	2	115.11
CompanyU	Elec	Company1	Elec	3	75.94
CompanyU	Elec	Company2	Elec	1	7.96
CompanyU	Elec	Company2	Elec	2	63.03
CompanyU	Elec	Company2	Elec	3	28.1
CompanyU	Elec	Company3	Elec	1	66.73
CompanyU	Elec	Company3	Elec	2	77.44
CompanyU	Elec	Company3	Elec	3	51.25

Table 11. Summary of the results for the integrated solution in the 3-company problem.

Company	Unit	Company	Unit	Period	Value
Company2	HP	Company1	HP	1	126.82
Company2	HP	Company1	HP	2	126.82
Company2	HP	Company1	HP	3	101.38
Company2	MP	Company2	LP	1	25.18
Company2	LP	Company1	LP	2	75.18
Company3	HP	Company3	MP	1	25.58
Company3	MP	Company1	MP	1	278.00
Company3	MP	Company1	MP	2	278.00
Company3	MP	Company1	MP	3	149.02
Company3	MP	Company3	LP	3	41.44
Company3	LP	Company1	LP	1	94.57
Company3	LP	Company1	LP	2	76.40
Company3	LP	Company2	LP	1	54.82
Company3	LP	Company2	LP	3	6.38
CompanyU	Elec	Company1	Elec	1	81.28
CompanyU	Elec	Company1	Elec	2	166.99
CompanyU	Elec	Company1	Elec	3	87.97
CompanyU	Elec	Company2	Elec	1	8.18
CompanyU	Elec	Company2	Elec	2	50.07
CompanyU	Elec	Company2	Elec	3	28.18
CompanyU	Elec	Company3	Elec	1	18.30
CompanyU	Elec	Company3	Elec	2	38.30
CompanyU	Elec	Company3	Elec	3	38.30

Table 12. Comparison of the results for the 3-company problem.

	Non-Integrated	Integrated	Improvement (%)
Total Cost	73,773.87	71,953.60	2.47
SO_x Release	4,100,000.00	3,527,231.44	13.97
GHG Release	10,435,585.95	9,434,073.34	9.60