SUPPLY CHAIN INTEGRATION AT INDUSTRIAL ZONES: ENERGY INTEGRATION

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Abstract

Process systems must interact with other systems by exchanging materials and utilities such as steam and electricity in order to attain production goals; such exchange of materials among different processes that may belong to different companies makeup the supply chain for a particular product. The integration of different process systems for improvement of financial and environmental performance is one of the most important issues in the industrial supply chain. A systematic approach to identify the synergy for improving financial and environmental performance among different process systems has been developed. This approach is composed of three steps; the first step is the generation of models for process units. The process unit models are developed using fundamentals of thermodynamics, mass and energy conservation and existing process data. The second step is the development of an MILP model for each process system that is a collection of process units. The last step is the identification of financial and environmental improvements if the process systems are integrated through material and energy exchanges. The approach is illustrated with an example that is a simplified version 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 different process systems at an industrial zone.

Keywords

Supply chain management, energy integration, environmental protection, mixed-integer programming.

Introduction

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. Therefore, it is desirable to integrate these production systems to improve operational and economic and operational aspects from supply chain management perspective. A strong interaction in the overall systems is observed in the energy: all of the subsystems require energy for production, there is usually a central power production facility in the industrial zone, and a number of subsystems may produce their own energy in their power plant. 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

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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 COx, NOx, and SOx.

Marechal and Kalitventzeff (1998) have addressed process integration for the design of utility systems. The objective of this work is to determine the optimal configuration of utility systems for 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.

An important issue in the industrial supply chain is the satisfaction of all production requirements and achieving high profits while observing environmental regulations. 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.

In this paper, it is 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 the 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 (process models for the most common units in the utility systems is 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. The last step is the identification of financial and environmental improvements if the process systems are integrated through material and energy exchanges.

Problem Formulation

Energy systems utilize fuel, air and other materials to generate electricity and steam as shown in Fig.3. The models for the most common units in the energy systems are given in the following subsections.

Boiler Models

Boilers generate high-pressure steam by burning fuel supplied. Because of burning fossil fuels, boilers generate environmentally harmful chemical substances such as SOx, NOx, and COx. Boilers require electricity for operating the mechanical equipment and medium pressure steam for heating the boiler feed water. Material flow around a typical boiler is given in Fig.1.

Boiler models include the following equations:

$$x_{ijk_{HP}l_{gen}} = \frac{1}{\eta_{ijk_{\mathrm{fuel}}}} \mathrm{cc}_{\mathrm{f_{fuel}}} x_{ijk_{fuel_m}l_{con}} \tag{1}$$

$$x_{ijk_{MP}l_{con}} = \mathrm{a}_{\mathrm{ijk_{MP}}} x_{ijk_{HP}l_{gen}} \tag{2}$$

$$x_{ijk_{EL}l_{con}} = \mathrm{a}_{\mathrm{ijk_{EL}}} x_{ijk_{HP}l_{gen}} \tag{3}$$

$$x_{ijk_{SOx}l_{con}} = \mathrm{s}_{\mathrm{f_{fuel}}} x_{ijk_{fuel}l_{con}} \tag{4}$$

$$x_{ijkl_{in}} + x_{ijkl_{gen}} = x_{ijkl_{out}} + x_{ijkl_{con}} \tag{5}$$

$$x_{ijkl'} = 0 \tag{6}$$

$$C_{ijk_{fuel}} = \mathrm{c}_{\mathrm{f_{fuel}}} x_{ijk_{fuel}l_{con}} \tag{7}$$

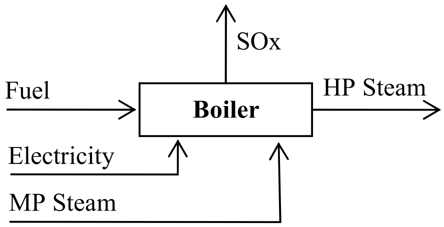

Figure 1. Schematic diagram for a boiler.

The variables x_{ijkl} represent the amount of material k in the unit j that belongs to company i in state l. Any material can have four distinct states: input, output, consumption or generation. Specific materials or states of a material are indicated with subscripts in equations. Equation (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 and the calorific value of the fuel. In addition, boiler efficiency, η, is a function of the fuel type. Equations (2) and (3) model the electricity and MP steam consumption in the boiler as a function of the HP steam generation. SOx generation is proportional to the sulfur content of fuel and the amount of fuel consumption in the boilers as given in (4). Equations (5) and (6) relate the states of materials in the boiler considers conservation of mass. In order to maintain consistency in the material balances equation (6) fixes some of the states of materials to zero (e.g., since there is no HP steam consumption and inlet to the boilers, corresponding states of HP are fixed to 0 in the boilers). Finally, equation (7) models the total cost of fuel consumption in the boiler.

Turbine Models

Turbines convert higher-pressure steam into electricity and lower pressure steam. A typical multi-stage turbine receives HP steam and produces electricity and MP and LP steams as shown in Fig.2.

Electricity generation in a turbine is a function of the amount of HP steam feed and the amounts of HP and LP steam generation. As shown in equation (8).

$$x_{ijk_{EL}l_{gen}} = \mathrm{a}_{\mathrm{ijk_{HP}}} x_{ijk_{HP}l_{in}} - \mathrm{a}_{\mathrm{ijk_{MP}}} x_{ijk_{MP}l_{gen}} - \mathrm{a}_{\mathrm{ijk_{LP}}} x_{ijk_{LP}l_{gen}} \tag{8}$$

$$x_{ijk_{HP}l_{in}} = x_{ijk_{MP}l_{gen}} + x_{ijk_{LP}l_{gen}} \tag{9}$$

$$x_{ijk_{EL}l_{gen}} \le \mathrm{x}^{\mathrm{u}}_{\mathrm{ijk_{EL}l_{gen}}} \tag{10}$$

In addition, equations (6) and (7) are also included for all materials and their corresponding states for turbines.

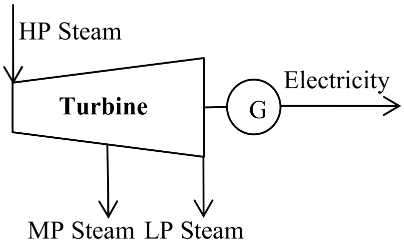

Figure 2. Schematic diagram for a turbine.

Fuel Selection

Boilers can burn different fuels with some adjustment of the operating conditions of boiler equipment. The main reasons for considering alternative fuels include insufficient fuel inventory, selecting the most economical fuel, and selecting an environmentally attractive fuel.

The alternative fuels in boilers are modeled using disjunctions (Turkay and Grossmann, 1996).

$$\bigvee_{m\in D_{ij}} \begin{bmatrix} Y_{ijk_{fuel_m}} \\ x_{ijk_{HP}l_{gen}} = \dfrac{1}{\eta_{\mathrm{ijk_{fuel_m}}}}\mathrm{cc}_{\mathrm{f_{fuel_m}}}\, x_{ijk_{fuel_m}l_{con}} \\ x_{ijk_{MP}l_{con}} = \mathrm{a}_{\mathrm{ijk_{MP}}}\, x_{ijk_{HP}l_{gen}} \\ x_{ijk_{EL}l_{con}} = \mathrm{a}_{\mathrm{ijk_{EL}}}\, x_{ijk_{HP}l_{gen}} \\ x_{ijk_{SOx}l_{con}} = \mathrm{s}_{\mathrm{f_{fuel_m}}}\, x_{ijk_{fuel_m}l_{con}} \\ C_{ijk_{fuel}} = \mathrm{c}_{\mathrm{f_{fuel_m}}}\, x_{ijk_{fuel_m}l_{con}} \\ x_{ijk_{HP}l_{gen}} \le \mathrm{x}^{\mathrm{u}}_{\mathrm{ijk_{HP}l_{gen}}} \end{bmatrix} \tag{11}$$

The above disjunction is included in the optimization model after the convex hull formulation as shown by Turkay and Grossmann (1996).

The limit on the SOx emission is expressed in equation (12) as follows:

$$\sum_i \sum_j x_{ijk_{SOx}l_{gen}} \le s^{U}_{k_{SOx}} \tag{12}$$

The objective function is defined as the minimization of the cost:

$$\min \mathrm{Z} = \sum_i \sum_j \sum_{k_{fuel}} C_{ijk} + \sum_i \sum_j \sum_{i'} \sum_{j'} xe_{iji'j'} \tag{13}$$

The first term of the objective function gives the total cost of fuel, and the second term gives the total cost for exchange of materials (e.g., electricity purchase from a utility company). This single objective of optimization model can be reformulated as a multi-objective optimization model to minimize the SOx generation as well by defining equation (4) as the second objective.

Example

Consider two energy systems with each system having two fuel tanks with different fuels, two boilers and two turbines as shown in Fig. 3. The energy systems must fulfill the electricity and steam requirement of processes they serve. The demand for steam (HP, MP, and LP) and electricity is a function of production rate and energy requirement characteristics of the processes that the energy systems are serving. For simplicity of the example, we will consider only a single period and fixed demand for processes. The parameters and energy requirements of the example are given in Table 1 and 2 respectively.

Table 1. Operating characteristics for the utility system in the example problem.

	Company 1		**Company 2**	
	Fuel 1	*Fuel 2*	*Fuel 1*	*Fuel 2*
cc_f	10500	9650	6650	10200
$I0_{ijk}$	100	120	40	100
s_f	7.80	1.42	1.20	5.13
c_f	120	76	83	145
	Boiler1	*Boiler 2*	*Boiler 1*	*Boiler 2*
$\eta_{\mathrm{ijk_{fuel1}}}$	0.590	0.575	0.560	0.565
$\eta_{\mathrm{ijk_{fuel2}}}$	0.600	0.595	0.605	0.600
$\mathrm{a}_{\mathrm{ijk_{MP}}}$	0.11	0.12	0.11	0.12
$\mathrm{a}_{\mathrm{ijk_{EL}}}$	0.002	0.003	0.003	0.0028
$\mathrm{x}^{\mathrm{u}}_{\mathrm{ijk_{HP}}l_{gen}}$	550	550	600	600
	Turbine 1	*Turbine 2*	*Turbine 1*	*Turbine 2*
$\mathrm{a}_{\mathrm{ijk_{HP}}}$	0.150	0.175	0.160	0.170
$\mathrm{a}_{\mathrm{ijk_{MP}}}$	0.070	0.080	0.070	0.075
$\mathrm{a}_{\mathrm{ijk_{LP}}}$	0.009	0.010	0.012	0.010
$\mathrm{x}^{\mathrm{u}}_{\mathrm{ijk_{EL}}l_{gen}}$	70	60	70	65

Table 2. Energy demand in the example problem.

	Company1	**Company 2**
Electricity	150	140
HP Steam	10	10
MP Steam	620	300
LP Steam	300	680

The problem is modeled in GAMS and solved using CPLEX version 6.5 (Brooke et al, 1992). When the exchange of materials (HP, MP, and LP steam) is not allowed, it is observed that large amounts of HP steam is lowered to HP and LP steam for fulfilling the HP and LP steam requirement through expansion. This is a common practice in process systems: utility systems are so tightly integrated with other processes that frequently higher-pressure steam must be expanded to fulfill lower pressure steam requirement. On the other hand, the energy-integrated solution fulfills the energy requirement of both of the companies at a lower cost. It is possible to serve the same energy requirement by a 2.3% lower by integrating two companies. It is also important to notice that a significant reduction (7.62%) in the SOx emission is possible through supply chain integration. The proposed approach identified simultaneous improvements in the financial and environmental performances for both companies.

Table 3. Comparison of the results.

	No Integration	**Integrated**	**Saving (%)**
Cost	16,051	15,690	2.30
SOx Emission	375.84	349.23	7.62

Conclusions

The energy integration of process systems in the same industrial zone is addressed in this paper. A systematic approach that consists of modeling process units through fundamentals of unit operations and process data, an MILP model for the integration of different process systems, and comparative analysis of the results is developed. The proposed approach is illustrated with an example that is a simplified version 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 different process systems at an industrial zone.

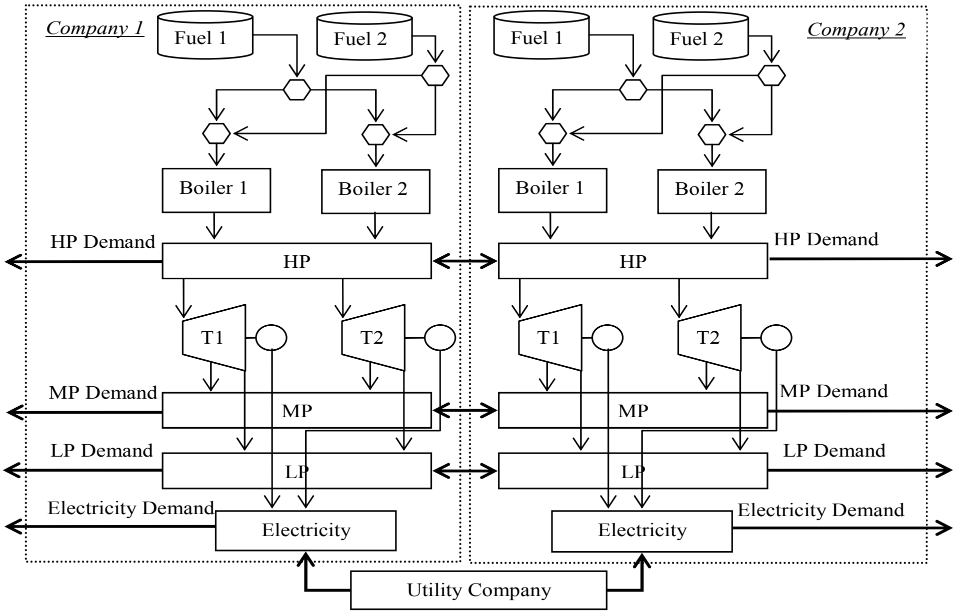

Figure 3. Flowsheet of the example problem.

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