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A MULTIOBJECTIVE PROGRAMMING APPROACH TO WASTE MINIMIZATION IN THE UTILITY SYSTEMS OF CHEMICAL PROCESSES

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Abstract—In the field of process synthesis, heat integration methodologies have been matured considerably during the past two decades. Today, these techniques are widely accepted as effective tools for improving chemical processes in terms of capital investment and energy consumption. However, as the problems of environmental pollution have become more and more serious in recent years, the development of process integration methods for waste reduction is now recognized as an area of urgent research. In this paper, mathematical programming models, which take into account both economical incentives and environmental penalties, are formulated for the design of "best" utility systems. The pollution problem associated with a utility system can be mainly attributed to gas emissions (e.g. CO_x, NO_x and SO_x) caused by burning fuels for generating power and/or heating utilities. In some cases, in order to satisfy the additional demand for power, electricity is imported from a central power plant which may also consume fuels. This demand for external electricity should therefore be considered as a hidden source of emission indirectly caused by running the utility plant. To address these environmental concerns, an improved version of the traditional MILP model for utility network design is proposed in this work. Not only the problem of cost minimization can be handled efficiently with an elaborate heat recovery scheme embedded in the modified superstructure, but also the concept of *global emission* can be incorporated in the model formulation. By making use of the goal programming techniques, appropriate designs of the utility networks can be obtained according to the decision maker's priority. From the experiences we have gathered so far in solving the improved MILP model, it can be concluded that the proposed techniques are applicable for a wide variety of processes having extremely different utility demands and, also, it is a sensible design approach for establishing a compromise among conflicting evaluation criteria. Copyright © 1996 Elsevier Science Ltd

Keywords: waste minimization, utility system, multiobjective programming.

INTRODUCTION

During the past several decades, the use of integration techniques as a design tool to minimize the operating and capital costs of a chemical plant has matured considerably and evolved into a common practice in the process industries, e.g. see Gunderson (1991). Also, as a result of serious concerns about environmental problems in recent years, development of process synthesis methods for waste reduction purpose has become a research issue of growing importance. The "wastes" resulted from chemical-producing activities can generally be classified into two types, i.e. the *process wastes* discharged from the chemical process itself and the *utility wastes*, which are mainly the gases (CO_x, SO_x and NO_x) and ashes created in the process of generating utilities. The direct consequences of using utilities are essentially air pollution problems caused by burning fuels (e.g. natural gas, fuel oil and coal, etc.) in equipments such as boilers and furnaces. However, the demand for imported electricity should also be viewed as an indirect source of utility wastes resulting from operating a chemical plant. Thus, the proper design criteria for a modern utility plant should include both economical and environmental requirements. In other words, not only the capital investment of a utility plant but also the corresponding direct and indirect utility wastes must be minimized.

Apparently, the direct gas emissions can be lowered by minimizing the utility consumption. This task can be accomplished with heat integration techniques. There are in general two approaches reported in the literature. The first is to synthesize the process manually with design heuristics developed from thermodynamic principles and engineering insights, i.e. the "pinch" analysis (Linnhoff, 1994). The second approach is to generate the system structure automatically with the aid of mathematical programming software packages, e.g. Cerda and Westerburg (1983), Papoulias and Grossmann (1983b), Floudas *et al.* (1986), Ciric and Floudas (1989), Yee *et al.* (1990a, b), Yee and Grossmann (1990) and Chang *et al.* (1994).

The most obvious method to reduce the indirect utility wastes is to cut down the need for imported electricity with local cogeneration systems. There have already been a number of publications concerning

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heat and power integration in the past. On the basis of the supply-and-demand relation implied in a grand composite curve, principles for the appropriate placement of heat engines and heat pumps were developed by Townsend and Linnhoff (1983a, b) and Linnhoff (1989). Studies on the optimal design of power generation system can also be found in Nishio *et al.* (1980), Petroulas and Reklaitis (1984), Doldan *et al.* (1985) and Chou and Shih (1987). The mathematical programming approach to utility system synthesis was adopted in several other recent works. Papoulias and Grossmann (1983a) developed a superstructure which includes the options for incorporating steam and gas trubines in the utility plants. The best system configuration was obtained by solving the corresponding MILP model. Also, Colmenares and Seider (1987, 1989) combined models of heat engines, heat pumps and utility systems into a NLP formulation and generated minimum-cost designs with standard optimization methods.

It should be noted that all studies mentioned above addressed essentially only economical issues and none of them adopted waste reduction as one of their design criteria. Research in the latter area has not received much attention until recently. Smith *et al.* (1990) proposed an approach to the minimization of environmental emissions through improved process integration, i.e. the Pinch technology. Smith and Petela (1991a, b; 1992a–c) then presented the specific design techniques for waste reduction in a series of papers. In addition, Smith and Delaby (1991) tried to establish the minimum targets for flue gas emissions in the utility system. More importantly, they introduced the concept of *global emissions* which allows us to address the design problem from a broader perspective. Finally, Douglas (1992) also developed a hierarchical decision procedure for waste reduction in process design.

From a review of the current literature, one can find that the results obtained with the programming approach should in general be more comprehensive and less error-prone as long as *all* the essential engineering insights are formulated in the mathematical models (Linnhoff, 1994). However, this type of numerical optimization method has never been adopted to generate utility system designs which satisfy both economical and environmental constraints. Thus, the main objective of this study is to assess the feasibility and practical value of incorporating gas emission models into existing mathematical formulations and solving the resulting problem with multiobjective optimization techniques. It should also be noted that these mathematical programs are basically nonlinear in nature. Although effective algorithms have been developed for NLPs, e.g. Floudas and Visweswaran (1990); Visweswaran and Floudas (1990), their application in solving the multiobjective problems still requires an extremely large number of iterations. One of the proven remedial measures is to approximate the original model with a mixed-integer linear program (Popoulias and Grossmann, 1983a). Since equally acceptable designs can be obtained with much less computational effort, this alternative approach was thus adopted in the present work.

THE SUPERSTRUCTURE OF UTILITY SYSTEMS

To incorporate design options for waste minimization and for further reduction in capital costs, the superstructure developed by Papoulias and Grossmann (1983a) has been modified in this study. This modified version is presented in Fig. 1.

Notice first that there are several steam headers at different pressure levels in this generalized utility system. Although three are shown in Fig. 1, the actual number of headers in the superstructure is determined on a case-by-case basis. Specifically, their pressure levels are selected at the saturated steam pressures corresponding to the hot stream supply temperatures of the above-pinch temperature intervals in which heat-deficit values are positive. Since superheated steams are needed to drive the steam turbines, the degree of superheating associated with each chosen pressure is treated as a decision variable in optimization. In particular, several discrete temperature levels in each header are allowed, but only one operating state can be chosen in the final design.

Steam can be generated with either fired or waste heat boilers operating at conditions consistent with those of the steam headers. The available steam in each header can be used to provide a required demand of hot utility, drive steam turbines or be transferred to the steam header at the next lower level with a pressure reducer where water is added to match the steam quality. After heating a process stream with high-pressure steam, the resulting high-pressure saturated water can be utilized in several downstream equipments. Firstly, it can be introduced directly into the deaerator for heating the fresh make-up water. Secondly, it can also be flashed at a lower pressure. The overhead stream of the flash drum then can be used to heat cold process streams at lower temperatures. The bottom stream is again sent to the deaerator or lower-pressure flash drum. Finally, in order to provide hot utility at a steady temperature, this water can be recycled and mixed with the superheated steam in a saturator to produce saturated steam at the pressure of the header.

There are basically three power-generating devices in the superstructure, i.e. steam turbines, gas turbines and electric motors. Both the condensing and back-pressure steam turbines are considered. Due to operational constraints, they are not connected to the low-pressure headers. A complete gas turbine system includes a turbine, a compressor, a combustor and a regenerator. The one adopted here is of the simple open-cycle type, with air as the working medium. The hot air exiting the turbine section can be used in a regenerator to preheat the compressed air before it enters the combustor, or it can be used as preheated air for further combustion in fired boilers or as heating medium in process heaters and waste heat boilers.

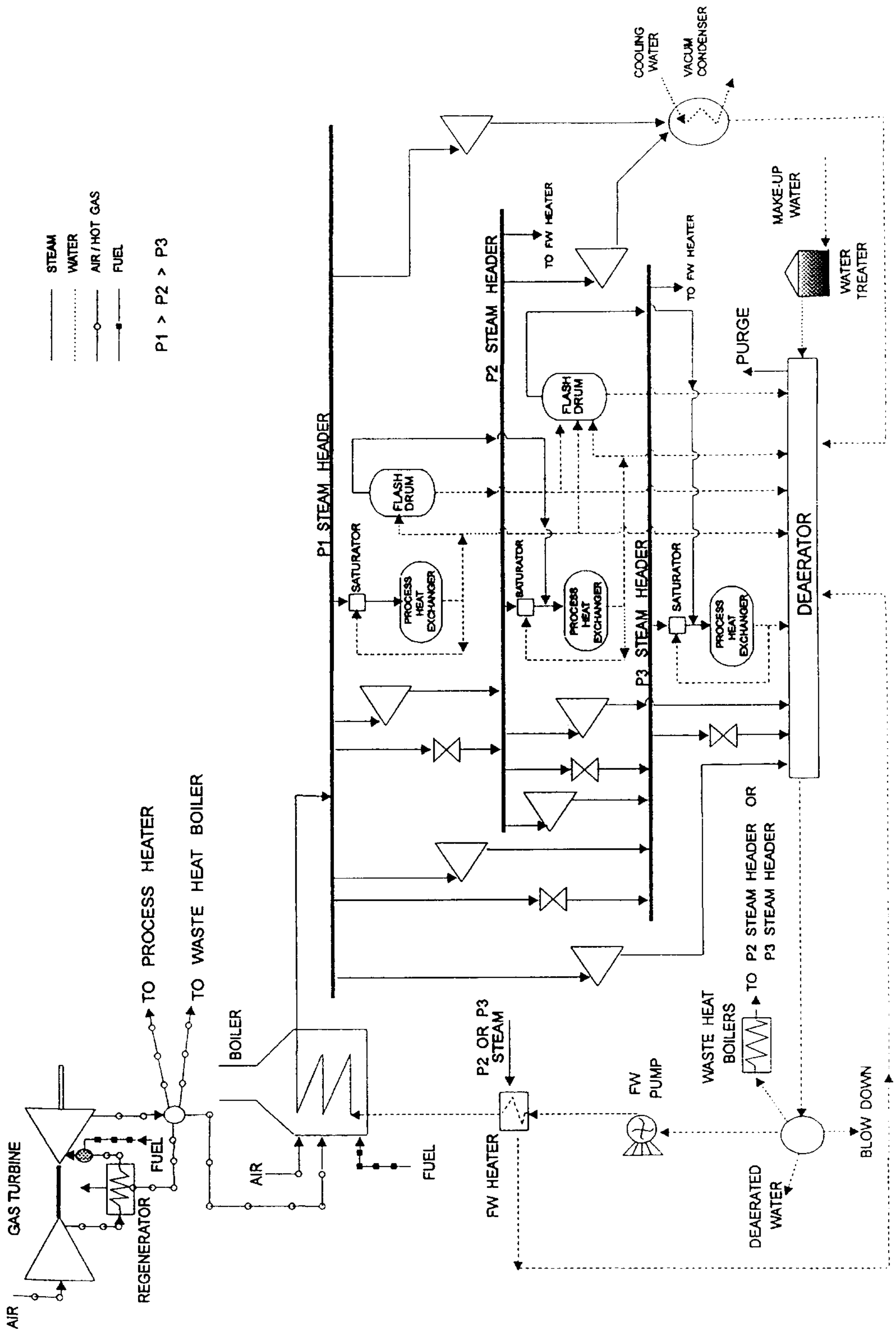

Fig. 1. The superstructure of a utility network.

In this study, *all* power demands are assumed to be satisfied with electric motors. Since the electric motors are operated independently in the utility system, the corresponding symbols are not presented in Fig. 1 for the sake of overall clarity. Electricity can be either imported or produced by a combination of steam and/or gas turbines connected with a common shaft on an electric generator. In other words, the power produced by steam and gas turbines in the proposed utility system is used *solely* for generating electricity. Finally, the options for selling surplus electricity to the neighboring plants or community are also included in the superstructure.

For high-temperature processes, furnaces may be needed to produce flue gas as a hot utility. It is assumed in this study that the heat content between the theoretical flame temperature (1800°C) and the stack temperature (160°C) is utilized exclusively for heating process streams (Linnhoff and de Luer, 1988; Smith and Delaby, 1992). Since the operation of furnaces can also be decoupled from other equipments in the utility system, they are thus not shown in Fig. 1.

Several essential auxiliary equipments are included in the superstructure. If a condensing turbine is chosen in the utility system design, then a vacuum condenser is necessary for its operation. Also, there should be a water treater for the make-up water and a deaerator to provide feedwater to the boilers and to meet the process water demand. Before entering the boilers, the water is raised to the operating pressure with a feedwater pump and preheated with steam. Notice that the water leaving the deaerator is assumed to be maintained at 100°C and 1 atm by appropriately flashing the high-pressure water before entering the deaerator. The flashed stream can be used to heat cold process streams above the pinch. If this is not possible, i.e. the pinch temperature is higher than 100°C, then it is purged to the atmosphere.

Finally, several alternative fuels should be allowed to be burned in the fired boilers, gas turbines and furnaces. The links between the energy consumption and gas emission can then be established with the corresponding combustion models.

THE CONSTRAINTS OF MILP MODEL

Having developed the superstructure for the utility system, one can then formulate a mathematical program accordingly for the synthesis of a utility system. Let us first consider the constraints. Naturally, the material and energy balance equations associated with every unit in the system should all be included as the equality constraints of the optimization problem. Since 0–1 binary variables are needed to signify the non-existence or existence of units in the superstructure and many of the balance equations are nonlinear, the resulting optimization problem is inevitably a mixed integer nonlinear program (MINLP). To reduce the effort in solving the corresponding process synthesis problem, Papoulias and Grossmann (1983) developed a general procedure to transform this MINLP model into a MILP problem. This study follows essentially the same approach. Since the discretized balance equations are not novel, their descriptions are thus omitted in this paper for the sake of brevity. Specific formulations of these equations can be found in Hwang (1994).

Other than the balance equations associated with all units, models of gas emission, electricity utilization and process heat exchange have also been integrated into the mixed integer linear program in this study. For convenience, let us define the set of all units as

$$\mathbf{N} = \{n \mid n \text{ is the label of a unit in the superstructure}\}. \tag{1}$$

These units are fired and waste heat boilers, steam headers at different pressure levels, steam and gas turbines, furnaces, flash drums, pressure reducers and all other auxiliary equipments. In order to describe the consumption of different fuels in various units, a subset of $\mathbf{N}$ is defined:

$$\mathbf{N}_F = \{n \mid n \text{ is the label of a fuel-burning unit}\} \tag{2}$$

Specifically, the fired boilers, the gas turbines and the furnaces are included in the set. The set of all alternative fuels that can be used in a unit n is defined as

$$\mathbf{Z}_n = \{z \mid \text{fuel } z \text{ can be used to meet the heat demand of unit } n, n \in \mathbf{N}_F\}. \tag{3}$$

Thus, the demands for fuels can be represented with the following equation:

$$Q_n^{NF} = \eta_n \sum_{z \in \mathbf{Z}_n} \Omega_z \tilde{F}_{zn}, \quad n \in \mathbf{N}_F \tag{4}$$

where Q_n^{NF} is the heat *absorbed* by the utility stream, i.e. water or air, in a fuel-burning unit n, Ω_z denotes the heat released by burning a unit mass fuel z, $\tilde{F}_{zn}$ is the mass flow rate of fuel z in unit n and η_n represents the overall efficiency (including combustion efficiency and heat transfer efficiency) of unit n. If only one fuel is allowed to be used in a fuel-burning unit, then binary variables $\tilde{y}_{zn}$s should be introduced to represent this restriction, i.e.

$$\sum_{z \in \mathbf{Z}_n} \tilde{y}_{zn} = 1, \quad n \in \mathbf{N}_F \tag{5}$$

$$\tilde{F}_{zn} - U_z^F \tilde{y}_{zn} \leqslant 0, \quad z \in \mathbf{Z}_n, \quad n \in \mathbf{N}_F \tag{6}$$

where

$$\tilde{y}_{zn} = \begin{cases} 1 & \text{fuel } z \text{ is selected in unit } n \\ 0 & \text{otherwise} \end{cases}$$

and U_z^F is an arbitrarily chosen large number, usually the maximum supply rate of fuel z. The emission rates of various air pollutants, can be computed according to the mass flow rates of fuels, i.e.

$$E_\kappa = \sum_{n \in \mathbf{Z}_F} \sum_{z \in \mathbf{Z}_n} \gamma_{\kappa z} \tilde{F}_{zn}, \quad \kappa \in \mathscr{G} \tag{7}$$

where $\mathscr{G} = \{\kappa\}$ is the set of air pollutants considered in design, E_κ is the emission rate of pollutant κ, and $\gamma_{\kappa z}$ represents the mass of pollutant κ produced after burning a unit mass of fuel z. The values of $\gamma_{\kappa z}$ are assumed to be constants and determined according to Smith and Delaby (1991).

In this study, the electricity produced by the stream and/or gas turbines can be used to meet the needs of the utility plant itself, the chemical process and the neighboring community. These demands can also be satisfied with electricity imported from the central power station. Thus, an overall balance equation can be written accordingly:

$$\sum_{m\in\mathbf{M}} \hat{W}_m + \sum_{n\in\mathbf{N}_P^D} \hat{W}_n + \hat{W}_O^D = \sum_{n\in\mathbf{N}_P^S} \hat{W}_n^S + \hat{W}_I^S \quad (8)$$

where

$\mathbf{M} = \{m|m$ is the label of an electricity-consuming unit in the chemical process$\}$ (9)

$\mathbf{N}_P^D = \{n|n$ is the label of an electricity-consuming unit in the utility system$\}$ (10)

$\mathbf{N}_P^S = \{n|n$ is the label of an electricity-producing unit in the utility system$\}$ (11)

Notice that $\hat{W}_O^D$ denotes the electricity demand of the neighboring community and $\hat{W}_I^S$ represents the electricity imported from the central power station. The $\hat{W}_m$s and $\hat{W}_n$s in the first and second terms on the left-hand side of eq. (8) are the demands of electricity-consuming equipments in the chemical process and in the utility plant, respectively. On the other hand, $\hat{W}_n^S$ represents electricity produced with a gas or steam turbine.

In the case of electric motors, a constant conversion efficiency, η_{mc}, is introduced to account for the energy loss in the process of transforming electricity into work, i.e.

$$W_m = \eta_{mc}\hat{W}_m, \quad m\in\mathbf{M} \quad (12)$$

and

$$W_n = \eta_{mc}\hat{W}_n, \quad n\in\mathbf{N}_P^D \quad (13)$$

where W_m and W_n denote the power *produced* by unit m in the chemical process and unit n in the utility system, respectively. Notice that all other power-producing units in the utility system, i.e. the steam turbines and gas turbines, are used to generate electricity in our design. Thus, another conversion efficiency, η_{gen}, must also be introduced to describe the energy balance in the process of transforming work W_n into electricity $\hat{W}_n^S$, i.e.

$$\hat{W}_n^S = \eta_{\text{gen}} W_n, \quad n\in\mathbf{N}_P^S. \quad (14)$$

It is further assumed in this study that the electricity produced by the utility system cannot be exported unless the demands in itself and also the chemical process are both satisfied. Thus, the following constraints must be imposed in the MILP model:

$$y_{WI} + y_{WO} \leqslant 1 \quad (15)$$

$$\hat{W}_O^D - U^{WO} y_{WO} \leqslant 0 \quad (16)$$

$$\hat{W}_I^S - U^{WI} y_{WI} \leqslant 0 \quad (17)$$

where, y_{WO} and y_{WI} are 0–1 binary variables and U^{WO} and U^{WI} are arbitrarily chosen large numbers. In other words, only one of the two quantities $\hat{W}_O^D$ and $\hat{W}_I^S$ can be larger than zero. If there is surplus electricity, i.e. $\sum_{m\in\mathbf{M}}\hat{W}_m + \sum_{n\in\mathbf{N}_P^D}\hat{W}_n < \sum_{n\in\mathbf{N}_P^S}\hat{W}_n^S$, then there is no need for importing electricity. Otherwise, exporting electricity is not reasonable practice. In addition, depending upon the capacity of the market demands, there should be an upper limit $\hat{W}^U$ for exporting electricity, i.e.

$$\hat{W}_O^D \leqslant \hat{W}^U. \quad (18)$$

In order to set the pressure levels of the steam headers appropriately, the MILP model of the utility system should be integrated with the transshipment model of HEN in the chemical process. Usually, the first step to construct such a model is to partition the entire temperature range of all process and utility streams into K temperature intervals for which any suitable partition method can be adopted, e.g. Cerda *et al.* (1983). These intervals are labeled from the highest level ($k = 1$) down to the lowest level ($k = K$) of temperature. In this study, a modified version of the P1 model (Papoulias and Grossmann, 1983b) is used, i.e.

$$R_k - R_{k-1} - \sum_{h\in\mathbf{HU}_k} Q_{hk}^S = \sum_{i\in\mathbf{H}_k} Q_{ik}^H - \sum_{j\in\mathbf{C}_k} Q_{jk}^C,$$
$$k = 1,2,\ldots,p \quad (19)$$

$$R_0 = R_p = 0 \quad (20)$$

$$R_k \geqslant 0, \quad k = 1,2,\ldots,p-1. \quad (21)$$

Here, eq. (19) represents the energy balance around the temperature interval k. Since the facilities for producing cold utilities are not included in the superstructure, p in this formulation is chosen to be the number of temperature intervals above the highest pinch temperature and $p \leqslant K$. Notice that the pinch temperatures can be determined by solving the conventional P1 model with fictitious hot utilities available at an arbitrarily high temperature.

From eq. (19), one can see that the heat inputs to interval k are coming from several sources, i.e. the residual heat from interval $k-1\,(R_{k-1})$ and the hot streams and heating utilities whose temperature range includes interval k. Notice that $\mathbf{HU}_k$ is the set of all hot utilities in interval k. If the utility is steam, then its temperature equals T_{k-1} and

$$Q_{hk}^S = F_{hk}^{HU}\Delta H_{hk} \quad (22)$$

where ΔH_{hk} is the latent heat of steam and F_{hk}^{HU} denotes the corresponding flow rate. On the other hand, if the hot utility is the flue gas coming from a furnace, then

$$Q_{hk}^S = F_{hk}^{HU} C_{hk}^{HU}(T^U - T^L) \quad (23)$$

and

$$T^U = \min(T_{tft}, T_{k-1}) \quad (24)$$

$$T^L = \max(T_{\text{stack}}, T_k) \quad (25)$$

where C_{hk}^{HU} is the heat capacity of flue gas in temperature interval k, T_{tft} is the theoretical flame temperature and T_{stack} is the stack temperature. Notice also that the flow rate F_{hk}^{HU} should remain unchanged in all temperature intervals between T_{tft} and T_{stack}. Also, if the flue gas is coming from a gas turbine, then T_{tft} in eq. (24) should be replaced by the temperature of exhaust gas.

THE DESIGN OBJECTIVES

If only economical criteria are considered in designing the utility system, the objective function of the MILP model should be the sum of annualized capital and operating costs. The former includes the fixed and variable costs of all plant units. The latter consists of the costs of fuels, fresh water and purchased electricity. The capital cost of a unit $n \in \mathbf{N}$ is in general a nonlinear function of the equipment capacity G_n, where G_n is usually represented by the total output flow rate of the equipment or the total work load if n denotes a turbine or motor. To establish the MILP model, the objective function must be approximated by a piecewise linear function. Specifically, G_n is first divided into l_n intervals and then, in each interval, linear approximation is introduced (see Fig. 2). Let us adopt a set of l_n variables G_{nm}s to express G_n in an alternative formulation, i.e.

$$G_n = \sum_{m \in \mathbf{L}_n} G_{nm}. \tag{26}$$

The set $\mathbf{L}_n$ is defined as follows:

$$\mathbf{L}_n = \{m | m \text{ is the label of an interval of } G_n \text{ in which } G_{nm}^L \leqslant G_n \leqslant G_{nm}^U\}. \tag{27}$$

It should also be noted that only one of the variables G_{nm} in eq. (26) is not zero. The variable adopted to replace G_n in the objective function should be the one corresponding to the interval containing the actual value of G_n. Thus, additional constraints must be imposed, i.e.

$$G_{nm}^L \left(\sum_{\xi \in \mathbf{K}_n} y_{n\xi m} \right) \leqslant G_{nm} \leqslant G_{nm}^U \left(\sum_{\xi \in \mathbf{K}_n} y_{n\xi m} \right)$$
$$m = 1, 2, \ldots, l_n \tag{28}$$

$$\sum_{\xi \in \mathbf{K}_n} \sum_{m \in \mathbf{L}_n} y_{n\xi m} \begin{bmatrix} \leqslant \\ = \end{bmatrix} 1 \tag{29}$$

where $\mathbf{K}_n$ is the set of operating conditions of unit n and $y_{n\xi m}$ is a 0–1 binary variable signifying the nonexistence or existence of G_n in the interval $[G_{nm}^L, G_{nm}^U]$ under operating condition ξ. In the case that unit n *must* exist in the final design the equality in eq. (29) should be used, whereas in the case when unit n may not exist the inequality should be adopted in the MILP model. The piecewise linear objective function C can thus be written as

$$C = \sum_{n \in \mathbf{N}} \sum_{m \in \mathbf{L}_n} \left(\beta_{nm} G_{nm} + \sum_{\xi \in \mathbf{K}_n} (\alpha_{n\xi m} - \beta_{nm} G_{nm}^L) y_{n\xi m} \right)$$
$$+ c_e \hat{W}_I^S + c_w F^W + \sum_{n \in \mathbf{N}_F} \sum_{z \in \mathbf{Z}_n} c_z \tilde{F}_{zn} \tag{30}$$

where F^W is the flow rate of make-up water entering the water treater and $\alpha_{n\xi m}$, β_{nm}, c_e, c_w and c_z are cost coefficients.

If, on the other hand, environmental concerns were to be addressed in the design of utility systems, emission targets of various waste gases must be lowered as much as possible. Thus, objective functions other than the annualized cost should be adopted in the MILP model. In this study, the concept of *global emission* (Smith and Delaby, 1991), i.e. the emissions corresponding to both the utility generation within the utility plant and outside the plant boundary, is used to establish these objective functions. The global emissions can be calculated with the following formula:

$$\begin{Bmatrix} \text{Global} \\ \text{emissions} \end{Bmatrix} = \begin{Bmatrix} \text{Emissions from on-site} \\ \text{utilities (local emissions)} \end{Bmatrix}$$
$$+ \begin{Bmatrix} \text{Emissions from the central} \\ \text{power station corresponding} \\ \text{to the amount of electricity} \\ \text{imported} \end{Bmatrix}$$
$$- \begin{Bmatrix} \text{Emissions saved at the central} \\ \text{power station corresponding} \\ \text{to the amount of electricity} \\ \text{exported from the site} \end{Bmatrix}. \tag{31}$$

Since the scope of this study is limited to the design of utility plants, the chemical processes are thus considered to be *outside* the system boundary. The corresponding global emission rates can be formulated on this basis, i.e.

$$E_\kappa^G = E_\kappa + \frac{\gamma_{\kappa z'}}{\Omega_{z'} \eta_{\text{cps}}} \hat{W}_I^S - \frac{\gamma_{\kappa z'}}{\Omega_{z'} \eta_{\text{cps}}} \left(\hat{W}_O^D + \sum_{n \in \mathbf{M}} \hat{W}_n \right) \tag{32}$$

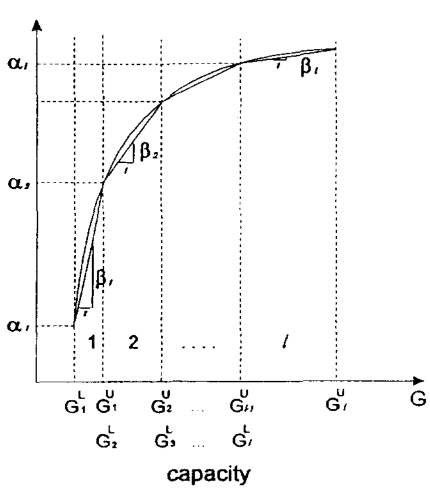

Fig. 2. Piecewise linear approximation of the cost function.

where $\kappa \in \mathscr{G}$, z' is associated with the fuel adopted in the central power station and η_{cps} represents the overall efficiency of generating and delivering electricity from the power station to the end users, i.e. the amount of electricity delivered per unit of energy released by burning fuels. In this study, it is assumed that coal is used in the power station to produce the steam needed for driving turbines. A constant overall efficiency η_{cps} of 0.28 is adopted in our model, which is also a value suggested by Smith and Delaby (1991).

Notice that a better understanding of the emission reduction problem can be obtained by studying eq. (32). Specifically, from its first term E_κ, one can see that one of the dominant factors contributing to a certain emission κ is fuel selection. This is due to the fact that the value of $\gamma_{\kappa z}$ associated with a given fuel $z(z \in \mathbf{Z}_n$ and $n \in \mathbf{N}_F)$ may be significantly different from that of another. On the other hand, from the second, third and fourth terms in eq. (32), one may conclude that another general guideline to reduce emission is to generate all the electricity needed in the chemical process and the neighboring community *within* the utility plant. The effectiveness of this approach, however, hinges upon the overall efficiency of energy utilization η_{eut} and this efficiency is defined as

$$\eta_{eut} = \frac{\begin{Bmatrix}\text{total amount of useful energies produced} \\ \text{per unit time by the utility system}\end{Bmatrix}}{\begin{Bmatrix}\text{amount of the energy released} \\ \text{per unit time by burning fuels}\end{Bmatrix}} \tag{33}$$

where the useful energies include work for driving the generators and heat for heating the process streams. If the value of η_{eut} is too low, the amount of emissions saved at the central power station may be offset by a large increase in local emissions.

THE SINGLE-OBJECTIVE SYSTEM DESIGN

From the previous discussions, it is clear that a realistic utility system design should be evaluated with multiple criteria. A reasonable solution to the multiobjective programming problem can usually be established on the basis of several single-objective solutions (Ignizio and Cavaliar, 1994). In order to illustrate the solution steps of the single-objective MILP problem and to show the insights gained from this exercise, an example is presented as follows.

Example 1: Let us consider the HEN and utility system design problems associated with three cold streams and two hot streams in a chemical process. The corresponding stream data are presented in Table 1. The electricity and water demands of the chemical process are presented in Table 2. The operating conditions of the equipments in the utility plant are specified in Table 3. Notice that definitions of the abbreviations used in the above tables can be found in the Notation section. The options of fuels for the boilers and furnaces include coal, natural gas and low sulfur diesel fuel. Due to operability considerations, only the latter two can be used in gas turbines.

Table 1. The stream data of example 1 ($\Delta T_{MIN} = 20°C$)

Stream type and number	FC (kW/°C)	T_{IN} (°C)	T_{OUT} (°C)	Heat load (kW)
C1	600	100	230	78,000
C2	1200	80	160	96,000
C3	150	40	200	24,000
H1	450	180	60	54,000
H2	1050	220	100	126,000

Table 2. The electricity and water demands of the chemical process in example 1

Electricity		
	General use	6800 kW
	Motor no. 1	375 kW
	Motor no. 2	820 kW
	Motor no. 3	540 kW
Water		
	Deaerated water	35 kg/s

Cost coefficients in this study were obtained by approximating the cost data given in Ulrich (1984) with piecewise-linear functions. The installation costs of the equipments were updated to 1994 price levels on the basis of the CE plant cost index. The purchase costs of fuels, water and electricity were adopted from government reports such as *Monthly Statistics of Imports* and *Commodity-Price Statistics Monthly* for the Taiwan area.

The standard Problem Table Algorithm (Linnhoff and Hindemarsh, 1983) has been performed according to Table 1. The hot and cold pinch temperatures were found to be 120 and 100°C, respectively. The heat deficit of each temperature interval has also been determined (see Table 4). On the basis of these results, two levels of steam-header pressures can be selected, i.e. 10 and 40 bar. They are essentially the saturated steam pressures at 180 and 250°C, respectively. In this example, the operating temperatures are chosen to be 240, 280 and 300°C for the former header and 350, 375 and 400°C for the latter.

Having determined the operating conditions of the steam headers, the modified MILP can be solved with any of the previously formulated objective functions. In this example, both the emission rate of CO_x and the annualized cost have been considered. A summary of the solutions can be found in Table 5 and in Figs 3(a) and 3(b). Notice that the SO_x emission rate of case I is negative. This is due to the fact that the emission rate of SO_x caused by importing electricity from central power station to the chemical process is much larger than that by cogeneration. From Table 5, one can also see that the fuels chosen for the two cases are different. In case I, natural gas is the best choice for reducing pollution. On the other hand, the logical choice for case II must be the cheaper coal.

Table 3. The operating conditions/parameters for equipments in the utility system of example 1

Deaerator	$P = 1.1013$ bar, $T = 100°C$
Feedwater heater	BFW heated by MP steam
Boiler	Blow-down rate = 5%
	Exhaust gas temperature = 160°
	Overall efficiency = 90.5%
Furnace	Exhaust gas temperature = 160°
	Overall efficiency = 90.5%
Steam turbine	Efficiency = 85%
Gas turbine	Compression ratio = 10
	Expansion ratio = 9.8
	Compressor efficiency = 85%
	Turbine efficiency = 87%
	Overall heat recovery efficiency = 80%
	Turbine inlet temperature = 1027°C
Generator	98%
Electric motor	95%
Vacuum condenser	Exhaust steam $P = 0.16$ bar and $T = 55°C$
	Cooling water inlet $T = 25°C$
	Cooling water outlet $T = 45°C$
Cooling water pump	Inlet pressure = 1.013 bar
	Outlet pressure = 7.94 bar

Table 4. The heat deficits of the temperature intervals in example 1 ($T^H_{pinch} = 120°C$ and $T^C_{pinch} = 100°C$)

k	$T_{h,k}$ (°C)	$T_{c,k}$ (°C)	ΔT_k (°C)	$\sum(F_cC_c - F_hC_h)_k$ (kW/°C)	ΔH_k (kW)
0	250	230			
1	220	200	30	600	18,000
2	180	160	40	300	− 12,000
3	120	100	60	450	27,000
4	100	80	20	− 150	− 3000
5	60	40	40	− 300	− 12,000

Table 5. The solutions of single-objective MILP model in example 1

Case no.	I	II
Objective function	CO_x rate	Cost
Cost (10^6 USD/yr)	13.25	9.43
CO_x rate (kg/h)	1489.30	15783.70
SO_x rate (kg/h)	− 139.70	231.10
NO_x rate (kg/h)	10.70	61.80
GTW (kW)	5386.00	—
GTF	Natural gas	—
BOF	Natural gas	Coal

The flow diagrams presented in Figs 3(a) and 3(b) represent the optimal designs of cases I and II, respectively. Notice that the design in Fig. 3(a) uses a combination of gas and steam turbines to satisfy the demand for power, but only steam turbines are required in case II. The overall efficiency in energy utilization of the former design is obviously higher than that of the latter. In the latter case, a large excess of steam and high-temperature saturated water must be purged after supplying the specified demands for power and heating utilities. [see Fig. 3(b)]. This is due to the facts that the deaerator is required to be operated at 100°C and the hot pinch point is 120°C. Thus, although the second design costs less, the emission rates of CO_x, SO_x and NO_x are much higher due to the requirements for burning more fuel and using a fuel that creates more serious pollution problems.

Finally, it should be noted that the cost of purchasing electricity is assumed to be 0.067 USD/kW hr in this example. Since this cost is higher than that produced within the utility plant, none of the designs adopts the option of importing electricity. It is also assumed that there is no electricity demand from the neighboring community. Thus, electricity export is not necessary in both cases I and II.

THE MULTIOBJECTIVE SYSTEM DESIGN

From the results obtained with single-objective MILP model, it is clear that it is not possible to optimize multiple performance measures simultaneously. One can observe from Table 5 that, when one of the objectives is minimized, the other aspects of design may be far from satisfactory. Thus, instead of a scalar, the performance of our design problem should be characterized with a vector, i.e.

$$\min z_r = g_r(\mathbf{x}), \quad r = 1, 2, \ldots, R \tag{34}$$

subject to

$$f_m(\mathbf{x}) \left\{ \begin{matrix} \geqslant \\ = \\ \leqslant \end{matrix} \right\} b_m, \quad m = 1, 2, \ldots, M \tag{35}$$

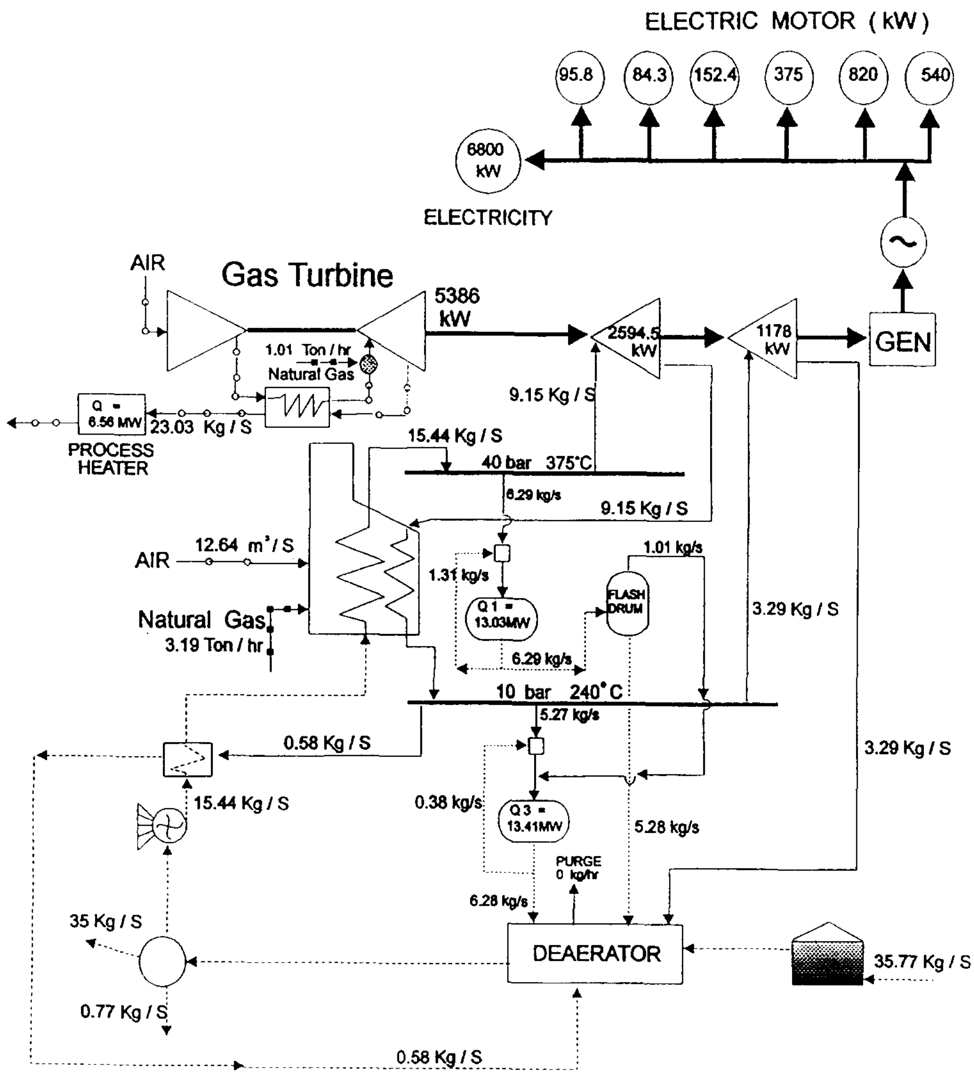

Fig. 3(a). The emission-optimal design for example 1.

where z_r denotes the rth objective function, f_m represents the mth constraint and the b_ms are constants. Notice that the "correct" solution to this problem is now a matter of *philosophy*. The proper trade-off among competing objectives is really dependent upon the preference of the decision maker(s).

If one can identify a common measure of effectiveness by means of which each of the objectives can be expressed, it should be possible to aggregate all of them into an *equivalent* function and solve the resulting problem with a conventional optimization approach. In fact, the well-known utility theory has been devoted, especially for establishing the utility functions that represent the preference of the decision maker, e.g. Keeney and Raiffa (1976). However, in our present case, it is difficult to justify the implied assumption that all objectives are commensurable. First of all, to convert the environmental impacts into equivalent financial implications is by far a trivial task. Further, this approach itself, i.e. to express pollution problems solely in terms of economical losses, is still highly controversial.

A more sensible tool for our problem seems to be the method of goal programming (GP) (Ignizio, 1982), in which the performance measures are ranked and then minimized *lexicographically*. Notice that, for the decision maker, it is a relatively straightforward task to just set the precedence order among objectives. Since these objectives are handled separately in the solution process, the need for weighting them is thus avoided. Further, the lexicographic notion has been demonstrated to be consistent with the multiobjective decision-making process of human being. Thus, the goal programming model is a better representation of the multicriteria design problem at hand.

There are actually a number of types of goal programs. The one adopted here is the non-Archimedean GP. A brief outline of its fundamental ideas is given below:

The first step in constructing such a GP model is to establish the aspiration levels s_r of all objectives and convert them into goals. Specifically, eq. (34) can be

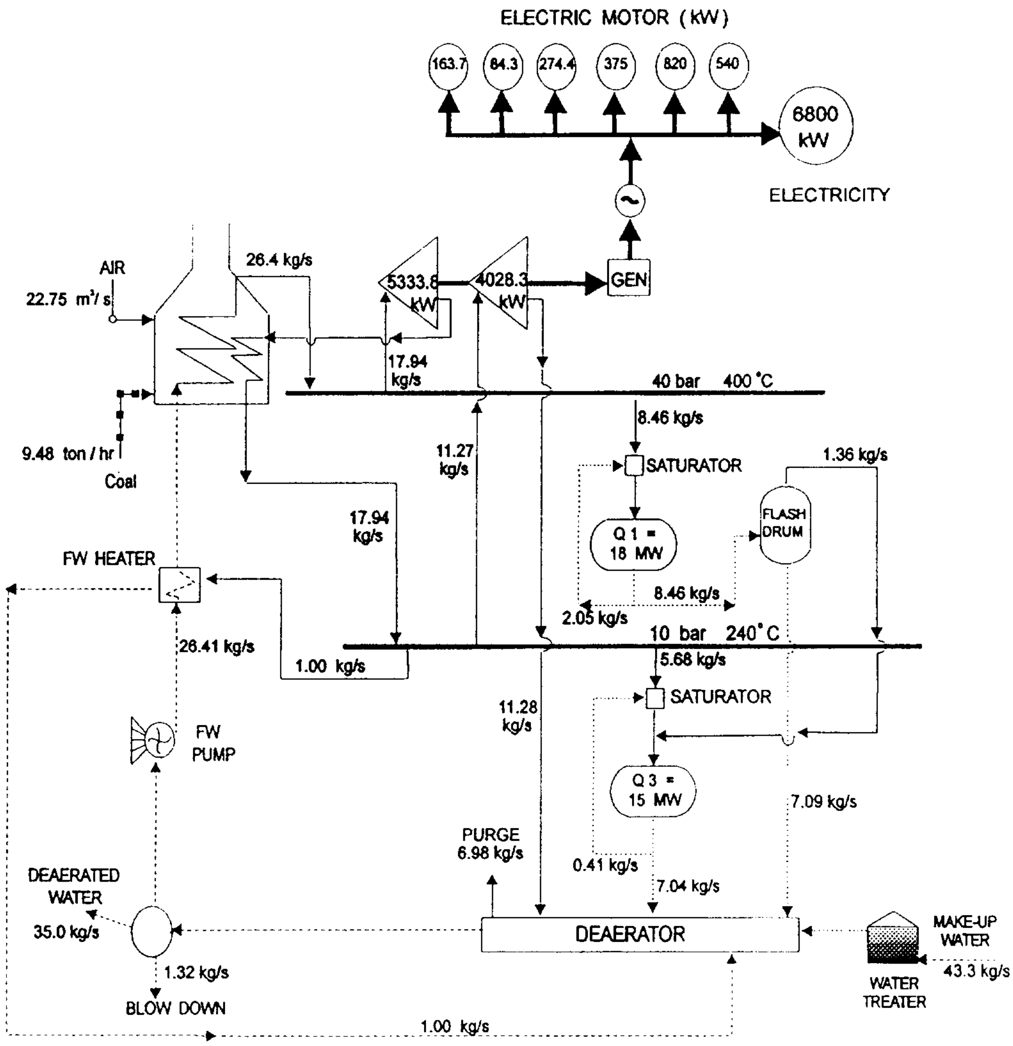

Fig. 3(b). The cost-optimal design for example 1.

transformed into

$$g_r(\mathbf{x}) \leqslant s_r, \quad r = 1, 2, \ldots, R. \tag{36}$$

The aspiration levels are values that the designer hopes to achieve in the final solution. Thus, rather than attempting to achieve solution optimaility (which is meaningful *only* in single-objective problems), the approach of GP is to find a solution that comes as close as possible to satisfying the design goals. Guidelines for determining the values of s_r have been reported in Ignizio and Cavalier (1994).

Notice that eqs (35) and (36) can be written in a generalized form, i.e.

$$F_i(\mathbf{x}) \left\{ \begin{array}{c} \geqslant \\ = \\ \leqslant \end{array} \right\} b_i, \quad i = 1, 2, \ldots, M + R \tag{37}$$

where

$$F_i(\mathbf{x}) = f_i(\mathbf{x}), \quad i = 1, 2, \ldots, M \tag{38a}$$

and

$$F_i(\mathbf{x}) = g_{i-M}(\mathbf{x}), \quad b_i = s_{i-M}$$

$$i = M + 1, M + 2, \ldots, M + R. \tag{38b}$$

Thus, the GP model can be viewed as the one consisting only of goals. These goals can be transformed into equations via negative and positive variables, n_i and p_i, i.e.

$$F_i(\mathbf{x}) + n_i - p_i = b_i, \quad n_i \geqslant 0, \; p_i \geqslant 0. \tag{39}$$

Next, let us define an achievement function a_i for each goal to reflect the degree of violation in the solution, i.e.

- $a_i = n_i$ when $F_i(\mathbf{x}) \geqslant b_i$;
- $a_i = p_i$ when $F_i(\mathbf{x}) \leqslant b_i$;
- $a_i = n_i + p_i$ when $F_i(\mathbf{x}) = b_i$.

If the value of every a_i is reduced to zero, then all the goals defined in the GP model must also be achieved.

However, since this ideal outcome may not be possible, the lexicographic minimum must be identified on the basis of an *achievement vector* $\mathbf{u}$, which is defined as follows:

$$\mathbf{u} = [\mathbf{c}^{(1)}\mathbf{a}^{(1)}, \mathbf{c}^{(2)}\mathbf{a}^{(2)}, \ldots, \mathbf{c}^{(K)}\mathbf{a}^{(K)}] \tag{40}$$

where $\mathbf{a}^{(k)}$ is the vector of achievement functions at priority level k and $\mathbf{c}^{(k)}$ denotes the vector of corresponding positive-valued weights. The achievement functions associated with hard goals are always included in $\mathbf{a}^{(1)}$ and their weights are all set to unity, i.e.

$$\mathbf{c}^{(1)} = [1, 1, \ldots, 1]. \tag{41}$$

On the other hand, the achievement functions at higher priority levels ($k \geqslant 2$) are usually corresponding to the soft goals and their precedence order is arranged according to the decision-maker's preference.

In this study, the hard goals are obtained from the rigid constraints of the MILP model formulated previously and the rest of the elements in the achievement vector are corresponding to the design objectives, i.e.

$$\mathbf{c}^{(1)}\mathbf{a}^{(1)} = \sum_{i=1}^{M} a_i \tag{42a}$$

$$\mathbf{c}^{(k)}\mathbf{a}^{(k)} = a_j \tag{42b}$$

$k = 2, 3, \ldots, R + 1$ and $j \in \{M + 1, M + 2, \ldots, M + R\}$.

Therefore, the standard form of a GP model can be written as

$$\operatorname{lexmin} \mathbf{u} \tag{43a}$$

s.t.

$$F_i(\mathbf{x}) + n_i - p_i = b_i, \quad i = 1, 2, \ldots, M + R \tag{43b}$$

$$\mathbf{x} \geqslant 0, \quad \mathbf{n} \geqslant 0, \quad \mathbf{p} \geqslant 0 \tag{43c}$$

where $\mathbf{n}$ and $\mathbf{p}$ denote the vectors of negative and positive deviation variables, respectively.

Finally, the concept of lexicographic minimum (lexmin) needs to be further clarified. Let us consider the achievement vector $\mathbf{u} = [u_1, u_2, \ldots, u_{R+1}]$. In searching for the solution to a GP problem, the one corresponding to a particular $\mathbf{u}'$ is preferred to another $\mathbf{u}''$ if $u'_k < u''_k$ and all higher-ordered terms (i.e. $u_1, u_2, \ldots, u_{k-1}$) are equal. Thus, if no other solution is preferred to the one associated with $\bar{\mathbf{u}}$, then $\bar{\mathbf{u}}$ is considered as a lexicographic minimum. On the basis of this concept, the following procedure can be adopted for solving eqs (43a)–(43c).

1. Let $k = 1$. Solve a single-objective optimization problem using a_k as the objective function and eqs (43b) and (43c) as the constraints.
2. Let $a_k^* = \min a_k$.
3. If $k \geqslant R + 1$, then a lexicographic minimum has been identified. Otherwise go to the next step.
4. Let $k = k + 1$. Solve the single-objective optimization problem using a_k as the objective function and eqs (43b), (43c) and

$$a_s = a_s^*, \quad s = 1, 2, \ldots, k - 1 \tag{43d}$$

as the constraints. Go to step 2.

Let us use a simple example to demonstrate the feasibility of the proposed multicriteria design technique.

Table 6. The solutions of multiobjective MILP model in example 2

Design no.	A	B
Cost (10^6 USD/yr)	10.49	9.93
CO_x rate (kg/h)	10,000.00	11,294.70
SO_x rate (kg/h)	− 99.60	− 95.30
NO_x rate (kg/h)	− 23.80	− 25.50
GTW (kW)	1015.60	—
GTF	Natural gas	—
BOF	Oil	Oil

Example 2: The problem stated in example 1 is solved again using the GP model. Let us assume that, after a careful study of the results presented in Table 5, the designer has decided that the appropriate aspiration levels of CO_x emission rate and annualized cost are 10,000 kg/h and 10 million U.S. dollars, respectively. Two designs have been obtained in this example. The first (design A) places more emphasis on environmental protection, i.e. the CO_2 emission rate is used as the first soft goal at the second level and the annualized cost is next at the third level. In design B, this priority order is reversed. A summary of these two designs is presented in Table 6. One can clearly see that, in each case, the first soft goal can be achieved satisfactorily and, although a slight deviation exists, the extent of violation in the second soft goal is still quite acceptable. One can also observe that, if economic performance is the main concern in designing a utility plant, then it is in general advantageous to produce power using a combination of steam turbines and boilers driven by the low sulfur diesel fuel. On the other hand, if the first priority in design is to reduce air pollution, natural gas is certainly the best choice for fuel. Also, the use of gas turbine should be considered to cut down the total consumption rate of fuel and, consequently, the gas emission rate can be reduced as well.

AN ADDITIONAL EXAMPLE

In this section, an additional example is presented to show the effects of varying process requirements on the utility system design. Let us consider a chemical process in which three hot streams and three cold streams can be identified (see Table 7). Notice that cold stream C2 is originally a liquid which is vaporized at 119°C. The total electricity demand of this process is assumed to be 14,000 kW. The options for fuels are essentially the same as those adopted in example 1. The operating conditions and parameters of equipments in the utility system can be found in Table 3.

After carrying out the Problem Table Algorithm, the hot and cold pinch temperatures of this process have been found to be 139 and 119°C, respectively. From the heat deficits listed in Table 8, one can see that the first four temperature intervals require heat inputs. However, if the demand for heating utility in the first interval is to be satisfied with steam, then the saturated steam pressure must be higher than 500 bar. On the basis of safety and cost considerations, the steam header corresponding to the first interval is thus excluded in the superstructure. Three steam headers are used in this example. Their operating pressures are set to be the saturated steam pressures at the upper bounds of the second, third and fourth temperature intervals, i.e. 55, 17.5 and 3.5 bar, respectively. The discretized operating temperatures corresponding to 55 bar are 375, 400 and 425°C and those corresponding to 17.5 bar are 325, 350 and 375°C. Since the steam pressure of the third header is too low to drive a turbine, the operating temperature is fixed at 139°C.

As indicated before, the first step in design process is to solve several single-objective MILP problems. Four performance measures have been considered, i.e. the emission rates of CO_x, NO_x and SO_x and the annualized cost. A summary of the solutions is shown in Table 9. Contrary to the findings in example 1, a gas turbine is used in the minimum-cost design. The only difference between this design and those aimed at reducing gas emission is that the gas turbine in the former case produces less power. This result is obviously due to the fact the steam cannot be produced at very high temperatures. Also, one can see that appropriate fuel selection is critical in reducing the emission rate of a particular pollutant. Notice that the best fuel for minimizing NO_x emission is low-sulfur diesel oil but the choice for the other pollutants is natural gas. These selections are made apparently on the basis of fuel compositions. Accordingly to Smith and Delaby (1991), oil has the lowest nitrogen content and, on the other hand, the carbon and sulfur contents are lowest in natural gas.

After a review of the data given in Table 9, the priority order of the design objectives and the corresponding aspiration levels can be determined according to the designer's preference. Let us assume that these decisions have been made and the GP model has been solved according to Table 10. The final design of the utility plant is shown in Fig. 4. The corresponding grand composite curve can be found in Fig. 5. A summary of the design is listed in Table 11. One can see

Table 7. The stream data of the additional example (ΔT_{MIN} = 20°C)

Stream type and number	FC (kW/°C)	T_{IN} (°C)	T_{OUT} (°C)	Heat load (kW)
C1	40	185	414	9160
C2	—	119	119	25,200
C3	294	119	250	51,352
H1	126	205	60	24,360
H2	52	270	100	8840
H3	252	90	45	11,340

Table 8. The heat deficits of the temperature intervals in the additional example (T^H_{pinch} = 139°C, T^C_{pinch} = 119°C)

k	$T_{h,k}$ (°C)	$T_{c,k}$ (°C)	ΔT_k (°C)	$\sum(F_cC_c - F_hC_h)_k$ (kW/°C)	ΔH_k (kW)
0	434	414			
1	270	250	164	40	6560
2	205	185	65	380	24,700
3	139^+	119^+	66	172	11,352
4	139^-	119^-	—	—	25,200
5	125	105	14	– 220	– 3080
6	100	80	25	– 220	– 5500
7	90	70	10	– 168	– 1680
8	60	40	30	– 420	– 12,600
9	45	25	15	– 252	– 3780

Table 9. The solutions of single-objective MILP model in the additional example

Case no.	I	II	III	IV
Objective function	CO_x rate	NO_x rate	SO_x rate	Cost
Cost (10^6 USD/yr)	20.115	17.796	20.115	16.325
CO_x rate (kg/h)	2350.2	9903.4	2350.2	17581.8
SO_x rate (kg/h)	– 226.7	– 175.4	– 226.7	201
NO_x rate (kg/h)	17.2	– 46.9	17.2	53.8
GTW (kW)	8286.8	8296.8	8286.8	5007
GTF	Natural gas	Oil	Natural gas	Natural gas
BOF	Natural gas	Oil	Natural gas	Coal

Table 10. The priority order and aspiration levels used in the multi-objective MILP model of the additional example

Priority order	I	II	III	IV
Objective function	CO_x rate (kg/h)	SO_x rate (kg/h)	Cost (10^6 USD/yr)	NO_x rate (kg/h)
Aspiration level	8500	− 120	17.5	− 20

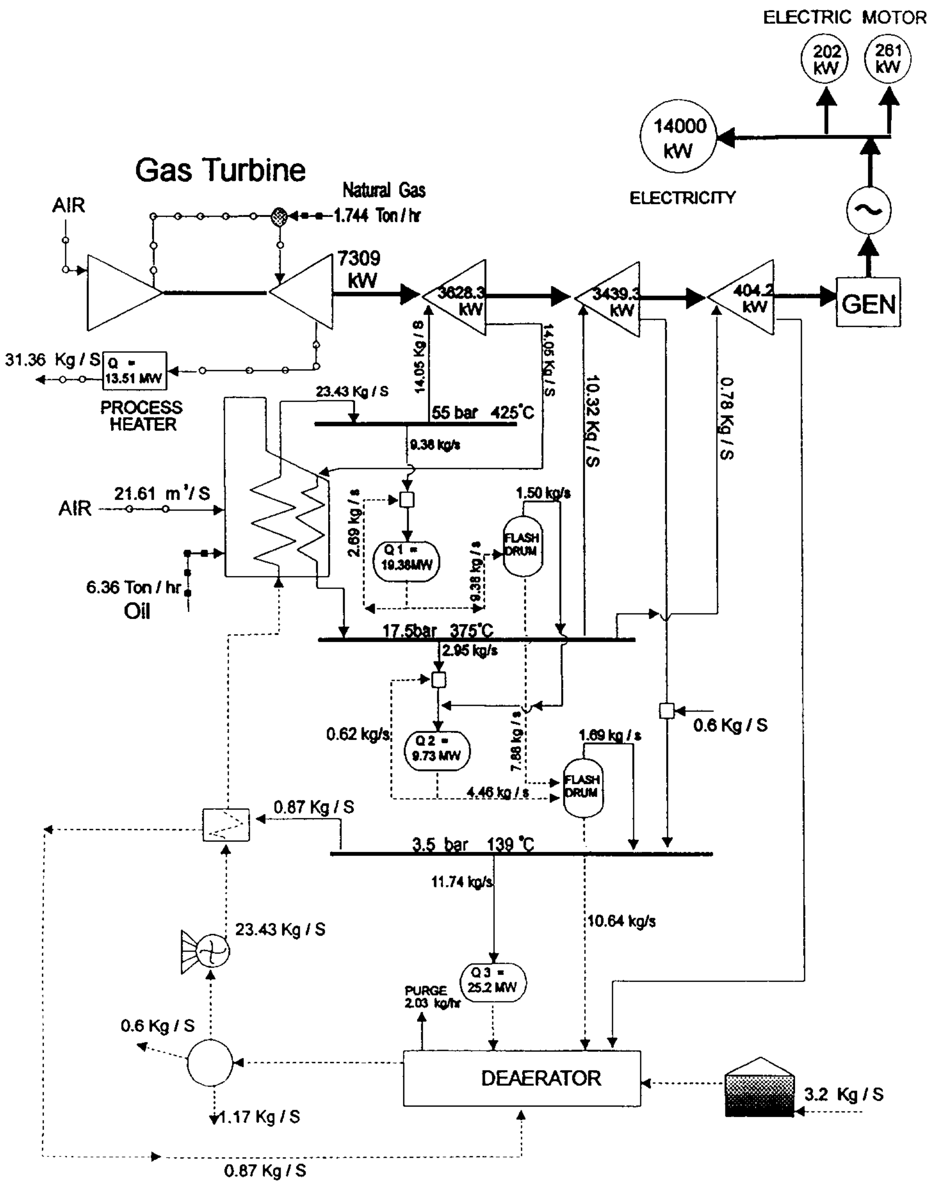

Fig. 4. The multiobjective design for the additional example.

that, other than the annualized cost, all design goals are achieved. Since the cost overrun is not significant, the system in Fig. 4 should be considered as a suitable solution when multiple conflicting criteria have to be considered in a single design.

CONCLUSIONS

A practical utility system design must be evaluated with both economic and environmental criteria. To address this need, a multiobjective MILP model has been developed in our study. Not only the problem of cost minimization can be solved efficiently with the proposed superstructure, but also the concept of global emission can be incorporated in the model formulation. On the basis of goal programming (GP) philosophy, a satisfactory design can be generated according to the priority order given by the designer. From the results we have gathered so far in implementing

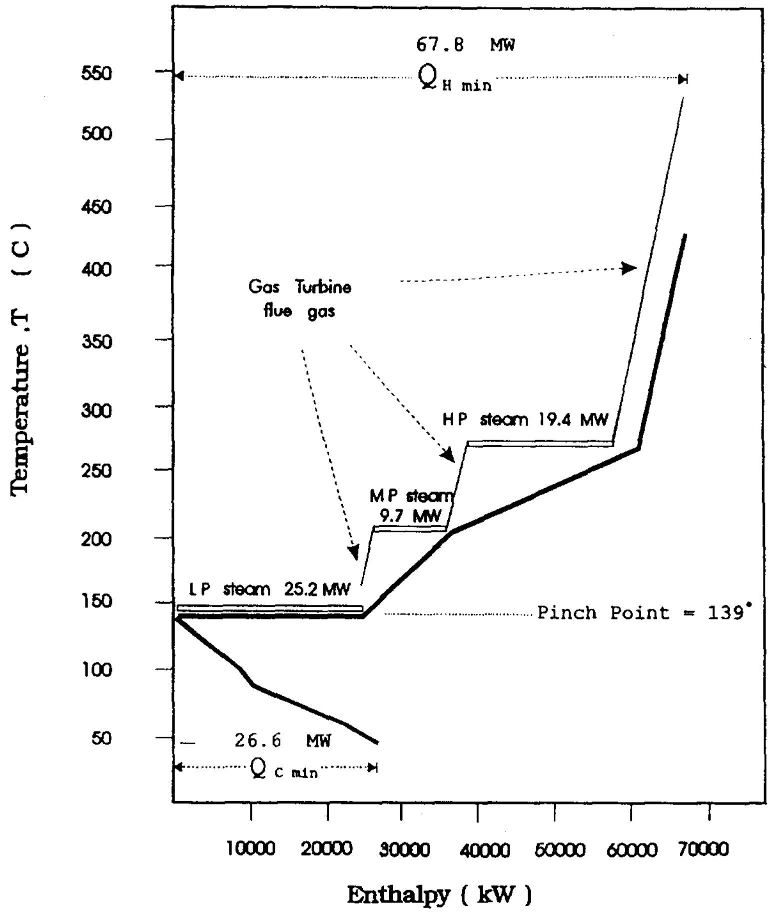

Fig. 5. The grand composite curve associated with the utility sytem design obtained in the additional example.

Table 11. The solution of multiobjective MILP model in the additional example

Cost (10^6 USD/yr)	18.02
CO_x rate (kg/h)	8500
SO_x rate (kg/h)	− 187.3
NO_x rate (kg/h)	− 30.1
GTW (kW)	7309.1
GTF	Natural gas
BOF	Oil

the proposed approach, one can conclude that the MILP model is suitable for the design of a wide variety of utility systems and, furthermore, the GP method is a natural and sensible design tool for establishing a compromise among conflicting objectives.

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NOTATION

C_{hk}^{HU}	the heat capacity of flue gas h in interval k
E_κ	the local emission rate of pollutant κ
E_κ^G	the global emission rate of pollutant κ
F^W	the mass flow rate of make-up water
F_{hk}^{HU}	the mass flow rate of utility h in interval k
$\tilde{F}_{zn}$	the mass flow rate of fuel z in unit n
G_n	the capacity of equipment n
G_{nm}	the discretized capacity of equipment n in range m
Q_n^{NF}	the heat absorbed by the utility stream in a fuel-burning unit n
Q_{hk}^S	the heat input from utility h to interval k
Q_{ik}^H	the heat input from hot stream i to interval k
Q_{jk}^C	the heat output from interval k to cold stream j
R_k	the residual heat from temperature interval k
T_{tft}	the theoretical flame temperature
T_{stack}	the stack temperature
W_m, W_n	the power produced by unit m in the chemical process and unit n in the utility system, respectively
$\hat{W}_m$, $\hat{W}_n$	the electricity consumed by motor m in the chemical process and motor n in the utility system, respectively

$\hat{W}_n^S$ the electricity generated by unit n in the utility system
$\hat{W}_O^D$ the electricity demand of the neighboring community
$\hat{W}^U$ the upper limit of electricity demand of the neighboring community
$\hat{W}_I^S$ the electricity imported from central power station

Greek letters

$\gamma_{\kappa z}$ the mass of pollutant κ generated after burning a unit mass of fuel z
ΔH_{hk} latent heat of steam h in interval k.
η_n the overall efficiency of a fuel-burning unit n
η_{mc} the conversion efficiency of a motor
η_{cps} the overall efficiency of generating and delivering electricity from power station to the end users
η_{eut} the overall efficiency of energy utilization of the utility system
η_{gen} the conversion efficiency of a generator
Ω_z the heat released by burning a unit mass of fuel z

Abbreviations

BFW boiler-feed water
BOF boiler fuel
GTF gas-turbine fuel
GTW power generated by the gas turbine
MP medium pressure

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