Korean J. Chem. Eng., **20**(2), 200-206 (2003)

Optimal Operation of Utility Systems in Petrochemical Plants

Yeong-Koo Yeo†, Hang-Duk Roh*, In-Won Kim, Il Moon*** and Yonsoo Chung******

Department of Chemical Engineering, Hanyang University, Seoul 133-791, Korea
*SK Chemicals Co., Ltd., Suwon 440-300, Korea
**Dept. of Chemical Engineering, Konkuk University, Seoul 143-701, Korea
***Dept. of Chemical Engineering, Yonsei University, Seoul 120-749, Korea
****Dept. of Chemical Engineering, University of Seoul, Seoul 130-743, Korea
(*Received 22 March 2002 • accepted 10 September 2002*)

Abstract−Several operational modes can be used in the operation of utility plants for petrochemical plants. For the optimization system of a utility plant to be effective, all the possible operational modes should be taken into account. Moreover, due to the variable fuel cost and electricity cost, the objective function in the optimization system may take different forms depending on the utility management strategy. In this paper, we present a utility optimization system that is based on mixed integer linear programming and considers all possible operational modes and various types of objective functions to maximize the flexibility and the usefulness of the optimization system. The user can conveniently choose a suitable operation mode and a type of the objective function. Results of the optimization can be displayed both numerically and graphically.

Key words: Utility Plant, Optimization, Boiler, Steam Header, Operation Mode

INTRODUCTION

For optimal operation of energy management systems in a petrochemical plant, it is imperative to minimize the net cost of energy supplied to the plant. In general, energy requirements from process units in petrochemical plants are not constant. Especially, demands for energy change as production rates of individual units change. Many efforts have been devoted to the study of minimization and synthesis of energy integration and utility systems. A thermodynamic approach to utility systems design has been reported with some numerical design examples [Nishio et al., 1980]. A two-level approach determining the optimal supply and demand relationship of steam and power was proposed based on thermodynamic analysis of the system performance [Nishio et al., 1982]. Linear programming was employed to solve problems of driver allocation and selection of the header and power source [Petroulas and Reklaitis, 1984]. However, the linear objective function used in their work is not suitable to represent the utility cost, and fuel cost is not included in their work. Adaptation of thermodynamic viewpoint in the design and synthesis of the utility system can be found elsewhere [Chou and Shih, 1987]. Their work mainly concentrates on the maximum possible thermodynamic efficiency of the utility system and does not consider energy and fuel costs. The synthesis problem including both the utility system and chemical processes has also been addressed [Comenares and Seider, 1989]. The simulated annealing technique was used in the solution of the synthesis problem of the utility system [Hui and Ahmad, 1994; Maia, 1995]. Recently, the optimal multiperiod planning technique for utility systems was proposed considering variances in internal energy demand [Yi et al., 2000].

So far most of the operations concerning steam distribution have relied heavily on the heuristics of experienced engineers. In some cases they use various modeling and simulation software tools to make decisions. But changes in plant demands and operating conditions to minimize energy costs often require repetitive optimization computations within a very short period. Therefore, for the steam distribution system to be successful, use of a suitable optimization strategy as well as modeling and computational simulations for the energy distribution system is the essential prerequisite.

The utility plant considered in the present study consists of three different types of steam boilers: a coal boiler with a turbine generator, two oil boilers with a turbine generator and three small oil boilers without turbine generators. The choice of the type of boiler(s) to be used (i.e., the determination of the operation mode) to generate steam and electricity depends upon the operating conditions and utility demand (steam and electricity). Normally, the coal boiler is in charge of the production of most of the steam demand. If the steam demand increases beyond the capacity of the coal boiler, oil boilers join in the production of steam. Theoretically, it is very difficult to determine which type of boiler to use to fulfill a certain amount of steam demand. Depending on the operating mode, coal or oil is used as the fuel. Various operating mode and corresponding fuel types make the optimal operation of the utility plant very complicated problem.

The objective of the present work is to develop the optimal energy management system based on the steady-state steam distribution system. All the possible operation modes were considered in the optimization. Changes in the costs of fuel or steam production should be taken into account in the optimization. In the present study, a suitable objective function can be selected depending on the fuel costs and steam production cost as well as the operating mode.

OVERVIEW OF THE UTILITY PLANT

As mentioned, the utility system for a petrochemical plant basi-

†To whom correspondence should be addressed.
E-mail: ykyeo@hanyang.ac.kr

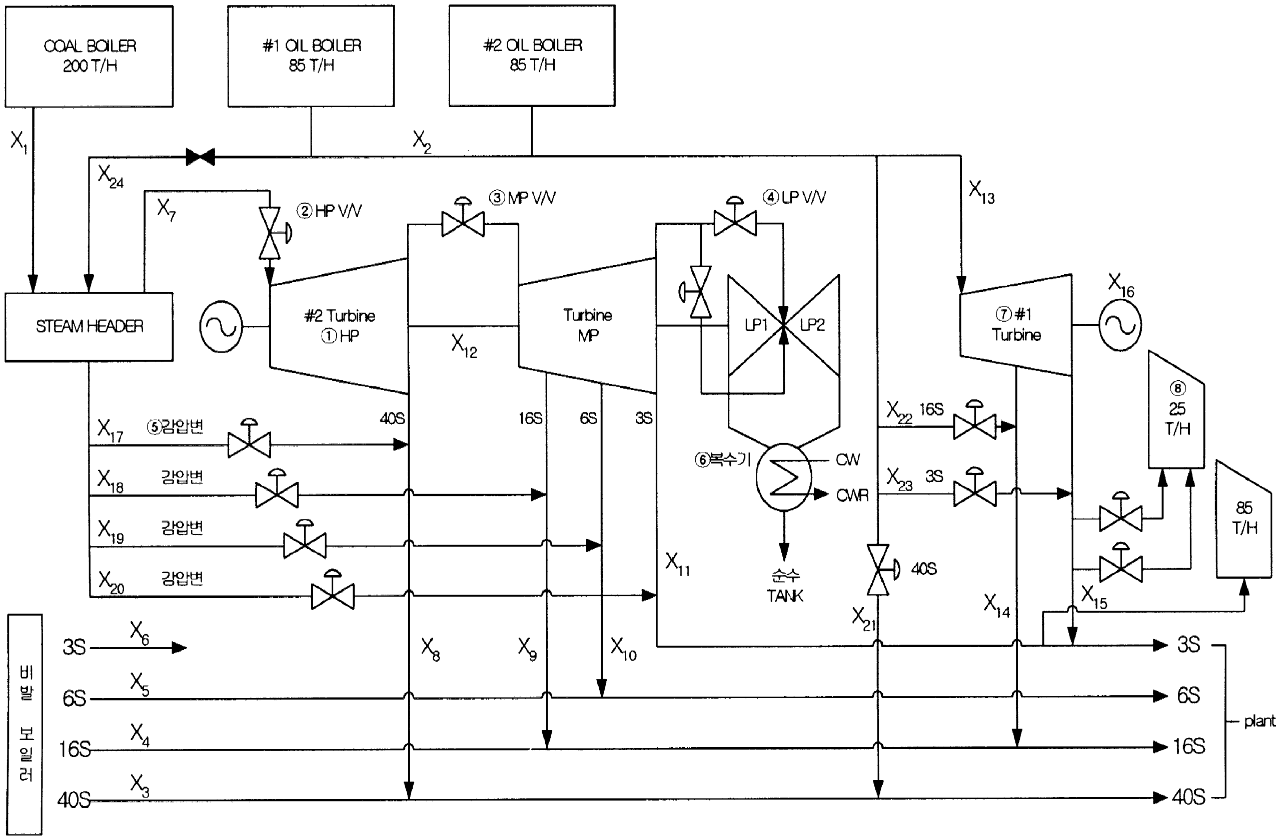

Fig. 1. Schematic of the utility plant.

Table 1. Operation range of typical variables

Variable	Typical operation range
X_1 (ton/hr)	$150<X_1<165$
X_2 (ton/hr)	$60<X_2<80$
X_3 (ton/hr)	$0<X_3<70$
X_4 (ton/hr)	$0<X_4<70$
X_5 (ton/hr)	$0<X_5<70$
X_6 (ton/hr)	$0<X_6<70$
X_7 (ton/hr)	$135<X_7<160$
X_8 (ton/hr)	$55<X_8<65$
X_9 (ton/hr)	$10<X_9<30$
X_{10} (ton/hr)	$15<X_{10}<45$
X_{11} (ton/hr)	$30<X_{11}<40$
X_{12} (MW/hr)	$20<X_{12}<23$
X_{13} (ton/hr)	$55<X_{13}<75$
X_{14} (ton/hr)	$30<X_{14}<50$
X_{15} (ton/hr)	$10<X_{15}<25$
X_{16} (MW/hr)	$3.5<X_{16}<5.5$
X_{17} (ton/hr)	$5<X_{17}<35$
X_{18} (ton/hr)	$0<X_{18}<5$
X_{19} (ton/hr)	$0<X_{19}<5$
X_{20} (ton/hr)	$0<X_{20}<5$
X_{21} (ton/hr)	$0<X_{21}<5$
X_{22} (ton/hr)	$0<X_{22}<5$
X_{23} (ton/hr)	$0<X_{23}<5$
X_{24} (ton/hr)	$0<X_{24}<5$

cally consists of boilers, turbine generators and a network of headers connecting the distribution system to the process units. Fig. 1 shows a utility system of a typical petrochemical plant. Major variables to be used in the utility optimization system are shown in Fig. 1, and the operation range of each variable is summarized in Table 1. The operational ranges shown in Table 1 can be displayed in the user interface as shown in Fig. 2. The user can change the operational range through the interface. The utility plant to be considered in the present study includes three types of steam generation units as mentioned before and seven desuperheaters. The steam headers consist of five headers: superheated steam (SS) header, high pressure steam (HS) header, medium pressure steam (MS) header, low pressure steam (LS) header and very low pressure steam (LLS) header. The pressure and temperature for each header are shown in Table 2.

A deaerator, which is not shown in Fig. 1, is used to separate gases from the boiler feed water (BFW). In the deaerator, oxygen, hydrogen and CO_2 dissolved in the water are removed by introducing LLS into BFW. In the desuperheater, a small amount of water is injected to lower the pressure of the inlet steam. The mass of the outlet steam in the desuperheater, m_{out}, can be easily obtained as

$$m_{out}=\left(\frac{H_{in}-H_w}{H_{out}-H_w}\right)m_{in} \tag{1}$$

where m_{in} denotes the amount of the steam to the desuperheater. In the steam-air heater, the combustion air is heated and fed into the air heater. Typical operation range of the air temperature is 15-20 °C for inlet and 80-85 °C for outlet. The MS used in the steam-air heat-

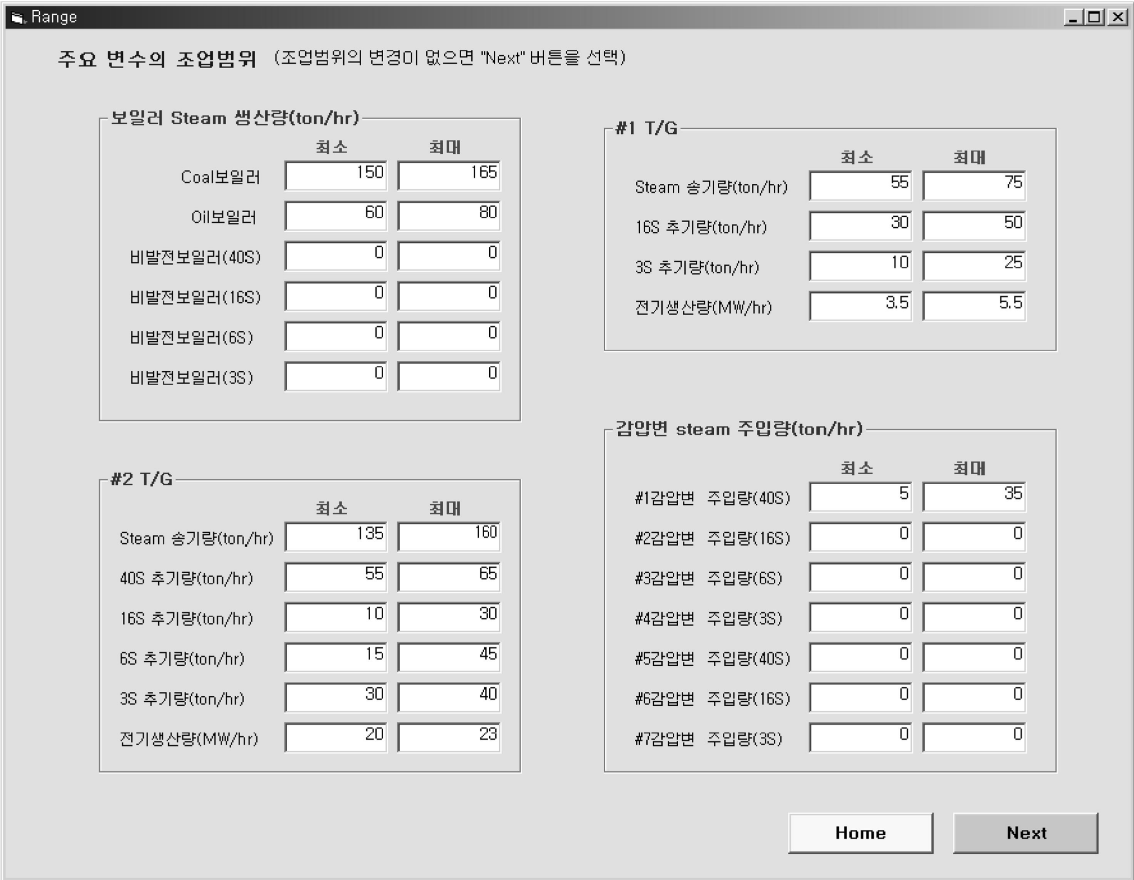

Fig. 2. Display of operation ranges for major variables.

Table 2. Steam headers

Header	Pressure (kg/cm^2)	Temperature (°C)	Enthalpy (kcal/kg)
SS	114	510	809.885
HS	41	300	708.409
MS	16	250	698.362
LS	6	180	670.734
LLS	3	165	667.598

er is condensed and returned to the deaerator.

OPTIMIZATION OF THE UTILITY PROCESS

Optimization of the utility plant is based on the steady-state modeling of the utility plant. Details on the modeling of boilers including the efficiency, heaters and other boiler units can be found elsewhere [Yi et al., 1998; Yoo et al., 1996]. Material balances for each steam header can be set up by considering steam demands from the production plants and the amount of the steam supply to turbine/generators. Header balances can be written as

$$\text{SS header}: x_1+x_2-x_7-x_{13}-x_{17}-x_{18}-x_{19}-x_{20}-x_{21}-x_{22}-x_{23}=0 \tag{2}$$

$$\text{HS header}: x_3+x_8+a_1(x_{17}+x_{21})=b_1 \tag{3}$$

$$\text{MS header}: x_4+x_9+x_{14}+a_2(x_{18}+x_{22})-a_3x_1-a_4x_2-a_5(x_3+x_4+x_5) -a_6(x_1+x_2)=b_2 \tag{4}$$

$$\text{LS header}: x_5+x_{10}+a_7x_{19}=b_3 \tag{5}$$

$$\text{LLS header}: x_6+x_{11}+x_{15}+a_8(x_{20}+x_{23})-a_9x_1-a_{10}x_2-a_{11}(x_3+x_4+x_5) -a_{12}(x_1+x_2)-a_{13}(x_1+x_2)=b_4 \tag{6}$$

For a typical operation, values of a_i are a_1=1.14813, a_2=1.1652, a_3=0.00291, a_4=0.1305, a_5=0.03756, a_6=0.000125, a_7=1.21494, a_8=1.220853, a_9=0.0641, a_{10}=0.1713, a_{11}=0.17365, a_{12}=0.13777 and a_{13}=0.00054. The b_i represent the amount of corresponding steam demand from each unit plant. Values of a_i depend on the operating temperature and pressure and operating mode being employed. Once the operating conditions and the operation mode are fixed, values of a_i are computed considering the efficiencies of utility units (i.e., the efficiencies of boilers, turbine generators and desuperheaters). Although not discussed in this paper, the efficiencies of major utility units are very important. Some results on the analysis and derivation of the efficiencies of major utility units including the coal boiler will be presented later.

From the generator, electricity is generated and steams of various grades are extracted and fed into the corresponding headers. The performance equation can be obtained from the model of the generator. It is very difficult to identify an analytical model for the generator. Empirical models can be obtained from the operational data and from the performance curve. In this work we used the neural network model developed by one of the authors [Yi et al., 1998]. Steady-state relations for the generators can be summarized as follows:

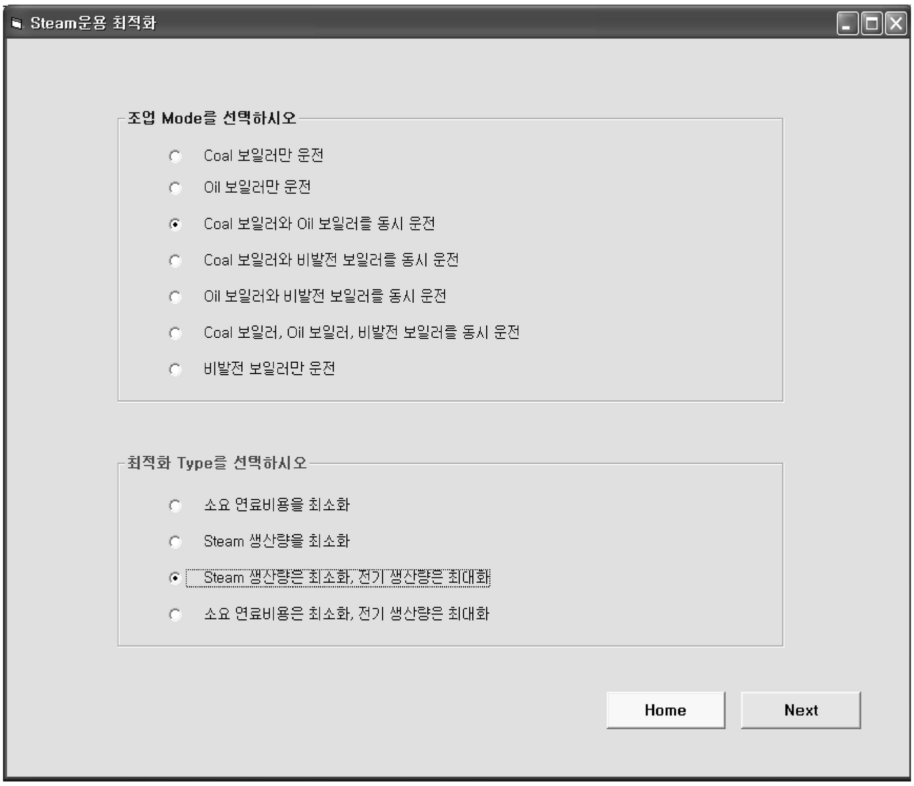

Fig. 3. Types of operations and optimization.

$$x_7-x_8-x_9-x_{10}-x_{11}-x_{25}=0 \qquad (7)$$

$$x_{13}-x_{14}-x_{15}-x_{26}=0 \qquad (8)$$

$$g_1x_{13}-g_2x_{14}+g_3x_{15}-x_{16}=0 \qquad (9)$$

$$g_4x_7+g_5x_8-g_6x_9-g_7x_{10}+g_8x_{11}-x_{12}=0 \qquad (10)$$

$$x_{13}+x_{21}+x_{22}+x_{23}+x_{24}=x_2 \qquad (11)$$

For a typical operation, values of g_i are g_1=0.14343164, g_2=0.0636767, g_3=0.01614416, g_4=0.126256, g_5=0.0508226, g_6=0.055969, g_7=0.02124 and g_8=0.02594. In the above relations, values of a_i and g_i depend upon the operation conditions.

The utility plant considered in the present work employs the coal boiler and the oil boilers as well as small scale oil boilers without electricity generation. For this reason, the optimization problem can be classified according to the operation type. The user can choose a suitable operation type as shown in Fig. 3. It is obvious that frequent change of the operation type is not permitted during the normal operation. But when one or two boilers need maintenance or when some operational faults or abnormal situations are detected during the normal operation, the optimal choice of operation type is imperative. The user can also choose the optimization type as shown in Fig. 3. For each optimization type, the corresponding objective function to be minimized can be defined as follows:

Minimization of fuel: f=(coal cost)(amount of coal)
+(oil cost)(amount of oil)
+(SS cost)(amount of SS generated) (12)

Minimization of steam production: f=(SS cost)
(amount of SS generated) (13)

Table 3. Results of optimization

Variable	Operation data	Optimization
X_1 (ton/hr)	163.1	161.445
X_2 (ton/hr)	64.8	80
X_3 (ton/hr)	0	0
X_4 (ton/hr)	0	0
X_5 (ton/hr)	0	0
X_6 (ton/hr)	0	0
X_7 (ton/hr)	143.8	160
X_8 (ton/hr)	30.9	55
X_9 (ton/hr)	9.9	17.063
X_{10} (ton/hr)	27.7	28.7
X_{11} (ton/hr)	36.8	31.962
X_{12} (MW/hr)	21.763	22.254
X_{13} (ton/hr)	57	75
X_{14} (ton/hr)	44.1	50
X_{15} (ton/hr)	12.9	25
X_{16} (MW/hr)	4.626	5.5
X_{17} (ton/hr)	24.2	6.4452
X_{18} (ton/hr)	0	0
X_{19} (ton/hr)	0	0
X_{20} (ton/hr)	0	0
X_{21} (ton/hr)	0	0
X_{22} (ton/hr)	1.0	0
X_{23} (ton/hr)	2.0	0
X_{24} (ton/hr)	4.8	5
Objective function (₩/hr)	4,163,561	3,939,036

Minimization of steam production and maximization of electricity generation: f=(SS cost)(amount of SS produced)−(electricity cost)(electricity generated) (14)

Minimization of fuel and maximization of electricity generation:
f=(coal cost)(amount of coal)+(oil cost)(amount of oil)
−(electricity cost)(electricity generated)
+(SS cost)(amount of SS generated) (15)

A suitable mixed integer linear programming algorithm can be used in the optimization. Commercial optimization packages are available but they are expensive and lack flexibility and adaptability. Some commercial packages require use of specific computational tools, which in turn increases the overall installation cost. For this reason we developed the optimization system by using C++ to increase flexibility and adaptability of the system. As the mixed integer linear programming technique, we employed the well-known Gomorys cutting plane method [Rao, 1996].

Results of the optimization for the specific operation mode and the optimization type as shown in Fig. 3 are shown in Table 3 and Fig. 4. As can be seen in Table 3, the value of the objective function (cost function) at the optimization type in Fig. 3 shows approximately 6% decrease compared to that based on the operational data. Based on the results of Table 3, the hourly saving due to the optimization is 224,525 won/hr and the yearly saving reaches to 1,939,896,000 won/yr (the operation day is assumed 360 days/year) which is appreciable saving considering the highly competitive petrochemical market. It is obvious that the magnitude of the saving depends upon the operation mode and the optimization type that are again under unexpected change. Results of optimization calculation can be represented graphically for the convenience of the user as shown in Fig. 5 and Fig. 6.

Although frequent changes in the operating mode are not permitted in the actual operation, it will be interesting to figure out how the values of objective functions vary depending on various operating modes. Table 4 shows values of objective functions for various operating modes. It could be misunderstood that the actual operation should be based on the results shown in Table 4. For example, one may choose the operating mode based on the lowest value of the objective function. In the petrochemical plant considered in the present study, a single boiler cannot fulfill the steam demand. This fact means that the actual operation requires a combination of boiler types (see Table 4 and Fig. 3). If we want to identify the optimal operating conditions to maximize electricity generation and to minimize steam production while fulfilling the steam demand, we may choose the oil boiler considering the results shown in Table 4 (i.e., we choose the operating mode with the lowest function value). But the steam demand is usually greater than the capacity of the oil boiler and we have to identify the optimal combination of operating modes.

CONCLUSIONS

In the operation of utility plants for petrochemical plants there are several operational modes that can be used. Thus, in order for

Fig. 4. Results of the optimization.

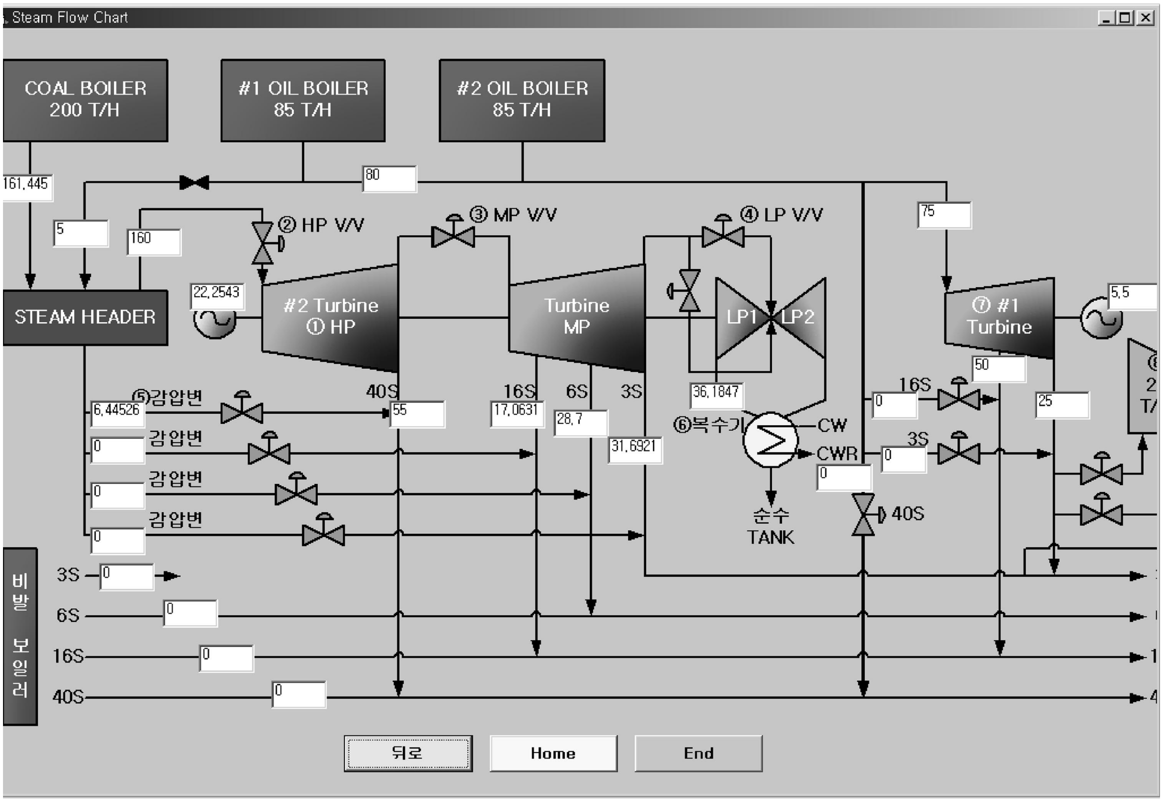

Fig. 5. Graphical representation of the optimization results (1).

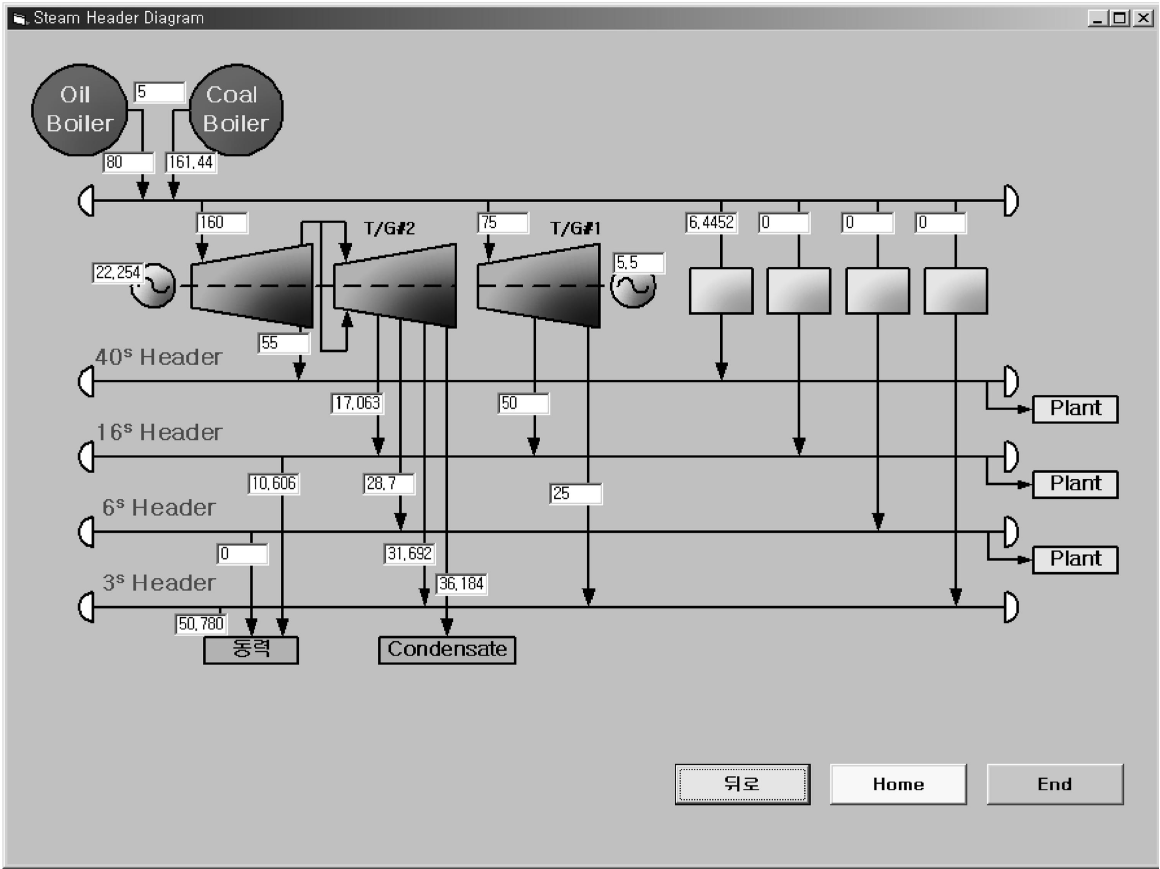

Fig. 6. Graphical representation of the optimization results (2).

Table 4. Values of objective functions for various operating modes

Operating mode	Values of objective functions (won/hr)			
	Min. fuel	Min. steam	Min. steam and max. electricity	Min. fuel and max. electricity
Coal boiler	1,319,070	3,120,304	2,657,712	856,478
Oil boiler	1,745,706	1,456,000	1,342,535	1,632,241
Coal and oil boilers	2,610,492	4,511,608	3,939,036	2,037,920
Coal and no-electricity boilers	1,524,264	3,650,600	3,207,336	1,080,999
Oil and no-electricity boilers	1,977,203	2,012,600	1,899,135	1,863,738
Coal, oil and no-electricity boilers	2,808,994	5,015,600	4,445,932	2,239,325

the optimization system of the utility plant to be effective, all the possible operational modes should be taken into account. Moreover, due to the variable fuel cost and electricity cost, the objective function in the optimization system may take different forms depending on the utility management strategy. The utility optimization system developed in the present work considers all possible operational modes and various types of objective functions to maximize the flexibility and the usefulness of the optimization system. The user can conveniently choose a suitable operation mode and a type of the objective function. Results of the optimization can be displayed both numerically and graphically. For a typical operating condition, the optimization system developed in the present work was shown to be able to achieve approximately 6% saving in the operation cost.

ACKNOWLEDGMENT

This work was supported by grant No. R01-2001-00409 form the Korea Science & Engineering Foundation and in part by Hanyang University.

NOMENCLATURE

a : constant
b : steam demand from unit plants [kg/hr]
g : constant
H : enthalpy [kcal/kg]
m : mass rate [kg/hr]
x : typical operation variable

Subscripts

i : variable index
in : inlet
out : outlet
w : water

REFERENCES

Chou, C. C. and Shih, Y. S., "A Thermodynamic Approach to the Design and Synthesis of Plant Utility Systems," *Ind. Eng. Chem. Res.*, **26**, 1100 (1987).

Colmenares, T. R. and Seider, W. D., "Synthesis of Utility Systems Integrated with Chemical Processes," *Ind. Eng. Chem. Res.*, **28**, 84 (1989).

Hui, C. W. and Ahmad, S., "Total Site Heat Integration Using the Utility System," *Computers Chem. Engng.*, **18**(8), 729 (1994).

Maia, L. O. A., Vidal de Carvalho, L. A. and Qassim, R. Y., "Synthesis of Utility Systems by Simulated Annealing," *Computers Chem. Engng.*, **19**(4), 481 (1995).

Nishio, M., Itoh, J., Shiroko, K. and Umeda, T., "A Thermodynamic Approach to Steam-Power System Design," *Ind. Eng. Chem. Proc. Des. Dev.*, **19**, 306 (1980).

Nishio, M., Shiroko, K. and Umeda, T., "Optimal Use of Steam and Power in Chemical Plants," *Ind. Eng. Chem. Proc. Des. Dev.*, **21**, 640 (1982).

Petroulas, T. and Reklaitis, G. V., "Computer-Aided Synthesis and Design of Plant Utility Systems," *AIChE J.*, **30**, 69 (1984).

Rao, S. S., "Engineering Optimization," John Wiley & Sons, New York (1996).

Yi, H. S., Han, C. H. and Yeo, Y. K., "Optimal Multiperiod Planning of Utility Systems Considering Discrete/Continuous Variance in Internal Energy Demand Based on Decomposition Method," *J. Chem. Eng. of Japan*, **33**(3), 456 (2000).

Yi, H. S., Yeo, Y. K., Kim, J. K. and Kang, S. S., "A Rule-Based Steam Distribution System for Petrochemical Plant Operation," *Ind. & Eng. Chem. Res.*, **37**(3), 1051 (1998).

Yoo, Y. H., Yi, H. S., Yeo, Y. K., Kim, M. K., Yang, H. S. and Chung, K. P., "Modeling and Simulation of Energy Distribution Systems in a Petrochemical Plant," *Korean J. Chem. Eng.*, **13**, 384 (1996).