Korean J. Chem. Eng., 26(6), 1484-1496 (2009)
DOI: 10.1007/s11814-009-0282-8

Optimization of district heating systems based on the demand forecast in the capital region

Tae Chang Park*, Ui Sik Kim*, Lae-Hyun Kim, Weon Ho Kim***, and Yeong Koo Yeo*,†**

*Department of Chemical Engineering, Hanyang University, Seoul 133-791, Korea
**Department of Chemical Engineering, Seoul National University of Technology, Seoul 135-743, Korea
***Infortrol, Inc., Yangchun-gu, Seoul 158-735, Korea
(*Received 20 March 2009 • accepted 18 May 2009*)

Abstract−A district heating system (DHS) consists of energy suppliers and consumers, heat generation and storage facilities and power transmission lines in the region. DHS has taken charge of an increasingly important role as the energy cost increases recently. In this work, a model for operational optimization of the DHS in the metropolitan area is presented by incorporating forecast for demand from customers. In the model, production and demand of heat in the region of Suseo near Seoul, Korea, are taken into account as well as forecast for demand using the artificial neural network. The optimization problem is formulated as a mixed integer linear programming (MILP) problem where the objective is to minimize the overall operating cost of DHS. The solution gives the optimal amount of network transmission and supply cost. The optimization system coupled with forecast capability can be effectively used as design and long-term operation guidelines for regional energy policies.

Key words: District Heating System, Optimal Operation, Demand Forecast, District Network, Mixed Integer Linear Programming

INTRODUCTION

A district heating system (DHS) usually consists of energy suppliers and a large number of consumers, district heating pipelines and heat storage facilities in a region. A DHS plays an important role in covering the heating demands in downtown and suburban areas. DHSs can be characterized by reduction of energy consumption, increase of energy efficiency and decrease of generation of pollutants. Hence the subject of optimal operation of DHSs has significant economical potential. In Korea DHSs take charge of about 10% of the energy consumption based on the total number of households in 2008. In contrast to other countries the heat source used in DHSs mainly consists of fossil fuels in Korea. For this reason the energy supply by DHS still suffers from economic and environmental contamination problems. To overcome these problems it is recommended to use waste materials as a heat source and to increase energy efficiency by the optimal operation of heat generation systems and heat distribution networks. The task of identifying a cost function for the operation of an entire DHS and finding a feasible solution to the posed minimization problem will in most cases be very difficult due to the size and constraints of the problem.

Recently, many researchers have tried to apply optimized models in the planning and scheduling of new district energy systems as well as in the operation of existing DHSs. But, in the operation of a DHS, demand for energy from local consumers changes frequently and application of the optimization system without demand forecast requires constant adjustment of optimization computations, which also results in heavy computational load. Thus, incorporation of prediction capability to the optimization system is necessary for efficient operation and scheduling. Based on the forecast for heat demand, the optimization system can construct future optional plans from which necessary resources for the production of energy can be estimated and prepared. Depending on the length of forecast periods, there are three types of forecast: long-term forecast, mid-term forecast and short-term forecast. Short-term forecast is most popular because of the accuracy. So far, various statistical forecast methods have been employed for short-term forecast. Among these methods the time series method [1,2] and regression scheme [3] have exhibited successful short-term predictions. But most of these methods are linear while load forecast is considered as a nonlinear problem in general. For this reason the artificial neural network can be effectively used in the short-term forecast once ample operation data are provided. As the input elements to the neural network, date, time, weather, and economical and environmental factors are typically used [4]. The amount of consumption of natural gas was predicted by using a multilayer neural network where date, weather and past consumptions were used as input elements [5]. Results on the prediction of the maximal short-term load were presented based on a multilayer neural network, which could be helpful in the electricity distribution [6]. Results on 1-hour predictions were reported where various date types such as holidays, Saturday and Sunday are considered as input elements [7]. In addition to the neural network forecast, predictions based on the moving average line are presented [1,8].

In the optimization many researchers use the linear programming (LP) model in the planning and scheduling of DHSs including cogeneration heat plant (CHP) to determine optimal operating costs while satisfying demands of heat and electricity of regional customers. But forecast for future demand is not taken into consideration in most of the optimization studies reported so far. In the formulation of a typical optimization problem, a DHS model can be divided into heat generation system, heat supply network and heat

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

consumption part, each of which should be optimized [9]. Especially, high weight should be given to the efficiency of heat supply and minimization of supply cost while heat demands from consumers are fulfilled. Thus it is imperative to get accurate measurement on the heat demand as well as to consider environmental temperature [10]. Moreover, the difference between the heat supplied to consumers and the heat actually consumed by the consumers should be measured [11]. The error in the heat supply temperature can be reduced if we get accurate heat loss through pipeline networks [12]. The overall optimization problem can be formulated as a mixed integer linear programming (MILP) problem, the solution of which gives the optimal heat generation and supply [13].

In this work, the optimization problem for a DHS located in the selected region is formulated based on short-term demand forecast by the multilayer neural network. In the forecast, time, the amount of past consumption and ambient temperature are used as input elements to generate 2-day, 3-day and 4-day predictions for demand from consumers. Accuracy of the forecast is estimated by comparing the predicted values with actual data. The optimization problem is then solved by branch-and-bound method. It is suggested that the long period problem can be effectively solved by using the generic algorithm approach method [14] where the graph theory approach can be used for the synthesis and optimization of energy distribution systems and networks [15]. The short-term forecast is paid much attention in this work because the predicted values can be used for the heat suppliers to adjust electricity generation facilities during operation. If the predicted values are small, several units are shut down in advance. In this situation, long-term predictions can hardly be used due to the low accuracy. Many regions in the metropolitan area are interconnected via energy transmission lines. Among the regions we select the DHS in the Suseo area, for which we forecast demand from consumers and compute optimal values of heat generation and demand followed by comparison of the results with measured data.

FORECAST FOR HEAT DEMAND BY NEURAL NETWORK

Fig. 1 shows the construction of the neural network used to forecast heat demand.

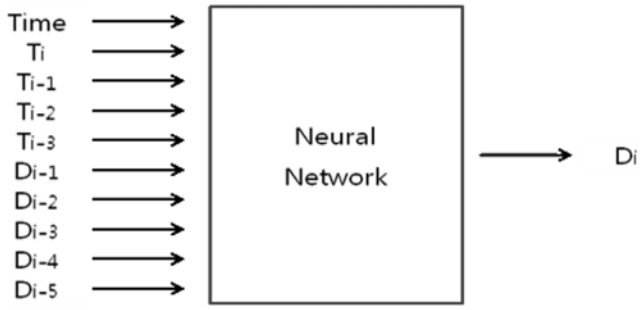

Fig. 1. The Neural Network for heat consumption forecasting of consumer.

The ten input neurons consist of the amounts of heat demand for five days prior to forecast (D_{i-1}, D_{i-2}, D_{i-3}, D_{i-4} and D_{i-5}), ambient temperatures for three days prior to forecast (T_{i-1}, T_{i-2} and T_{i-3}), the ambient temperature at the time of forecasting (T_i) and time (Time). The predicted demand (D_i) serves as the output neuron. For the purpose of training, heat demands and ambient temperatures during two months (January and February in 2007) and those values during 17 days (from February 1 to February 17, 2008) were used as input data and are shown in Table 1. The total number of input data is 2328, which represents data for 97 days. As usual, those input data should be scaled by using appropriate relations. The feedforward back-propagation prediction network consists of three layers and tan-sigmoid function is used as the transfer function. Ten neurons are used in the hidden layer.

1-day (24 hours) forecast was performed first for February 18, 2008. For the estimation of the accuracy of the forecast, the mean absolute percentage error (MAPE) criterion (Eq. (1)) was employed.

$$\mathrm{MAPE} = \frac{|C_{actual} - C_{forecasting}|}{C_{actual}} \times 100 \qquad (1)$$

In Eq. (1), C_{actual} represents actual heat consumption and $C_{forecasting}$ denotes predicted heat consumption. 1-day forecast was repeated three times to get the trend of forecasting errors. Table 2 shows prediction errors for each trial, and Fig. 2 exhibits trend of change in

Table 1. The input data for training

Time (h)	T_i (°C)	T_{i-1} (°C)	T_{i-2} (°C)	T_{i-3} (°C)	D_{i-1} (Gcal/h)	D_{i-2} (Gcal/h)	D_{i-3} (Gcal/h)	D_{i-4} (Gcal/h)	D_{i-5} (Gcal/h)
1	4.5	0.3	4.5	0.6	399	421	475	457	471
2	4.1	0	4.5	0.3	369	399	409	411	474
3	2	0	2.4	0	356	372	390	380	433
4	2.4	−0.8	1.3	0.3	368	403	425	411	454
5	2.8	−1.1	0.6	0.6	400	433	438	434	491
6	2	−1.1	0	1	415	452	427	424	446
7	2	−0.8	0	1	458	493	447	490	453
8	1.3	−0.8	−0.4	2	479	476	487	514	464
:	:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:	:
21	−3.5	−0.8	−3.2	−0.8	598	580	554	572	654
22	−4.6	−1.1	−3.9	−0.1	605	579	566	581	674
23	−5	−1.5	−4.6	0.3	598	674	557	577	666
24	−5.3	−2.2	−4.6	0.1	576	672	555	578	647

Table 2. The error of 1 day forecasting (2008.2.18)

Time (h)	Error of trial 1 (%)	Error of trial 2 (%)	Error of trial 3 (%)
1	1.14	0.50	1.68
2	1.85	5.00	0.13
3	2.16	0.55	7.90
4	1.14	2.18	6.82
5	1.68	5.23	7.66
6	6.23	7.31	8.17
7	6.44	9.66	14.85
8	10.88	9.16	4.61
9	0.12	1.92	1.11
10	0.66	4.00	1.77
11	8.27	8.62	6.14
12	4.40	6.07	3.91
13	1.17	0.72	0.16
14	4.44	7.17	2.81
15	3.79	0.35	5.33
16	3.86	0.43	5.41
17	7.68	5.42	12.01
18	8.92	10.79	7.62
19	6.31	6.95	6.37
20	0.26	0.96	2.07
21	5.26	4.22	1.69
22	3.32	3.07	0.80
23	6.20	4.82	3.43
24	5.64	4.13	4.59

errors. We can see that overall average errors for trials 1, 2 and 3 are 4.24%, 4.55% and 4.88%, respectively. Even with little discrepancy, these values exhibit consistent behavior as can be seen in Fig. 2. This fact validates that the forecasting model can be effectively used for prediction.

The trained neural network was used to perform 2-day prediction, i.e., values of heat demand after two days from now (February 19, 2008). Fig. 3 shows results of 2-day prediction as well as actual data on demand. We can see consistent tracking behavior in forecasted demand. The overall average forecasting error is 6.46% and hourly errors are shown in Table 3. The trained neural network was again used to perform 3-day prediction, i.e., values of heat demand after three days from now (February 20, 2008). Fig. 4 shows results of 3-day prediction as well as actual data on demand. Again we can see consistent tracking behavior in forecasted demand. The overall average forecasting error is 5.04% and hourly errors are shown in Table 4. Extension of the forecasting period to four days gives similar results as before. Fig. 5 shows results of 4-day (February 21, 2008) prediction as well as actual data on demand. Again, we can see consistent tracking behavior in the forecasted demand. The overall average forecasting error is 7.54%, and hourly errors are shown in Table 5.

FORMULATION OF THE OPTIMIZATION PROBLEM FOR DHS

1. Description on Regional DHSs

One of the main objectives in the operation of DHS is to achieve the minimum supply cost while satisfying heat demand from various consumers. Therefore, transmission of excess heat among regional DHSs should be considered elaborately based on the amount of heat generation and heat demand of neighborhood DHS. In other words, if heat is in short supply in one region, the heat supply from other nearby regions with excess heat should be considered first before heat generation in the region. In this work, heat demand from the Suseo area is forecasted, and the cost of the minimum heat supply from three nearby regional DHSs is optimized. As the possible source

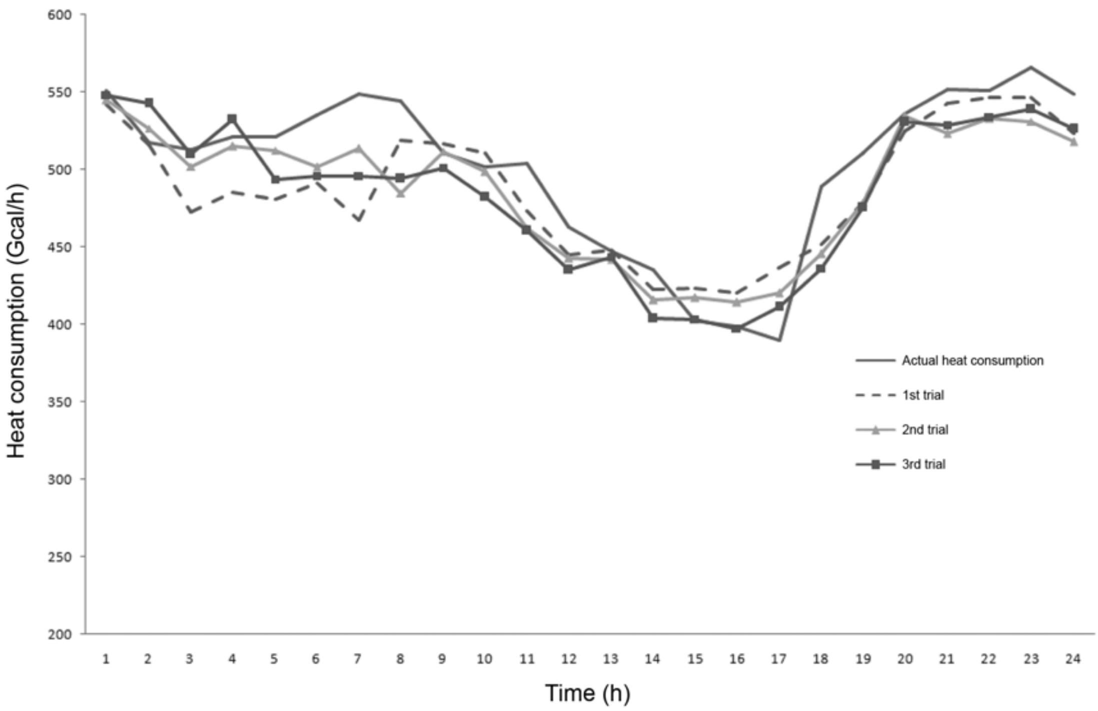

Fig. 2. Forecasted demand after 1 day (2008.2.18).

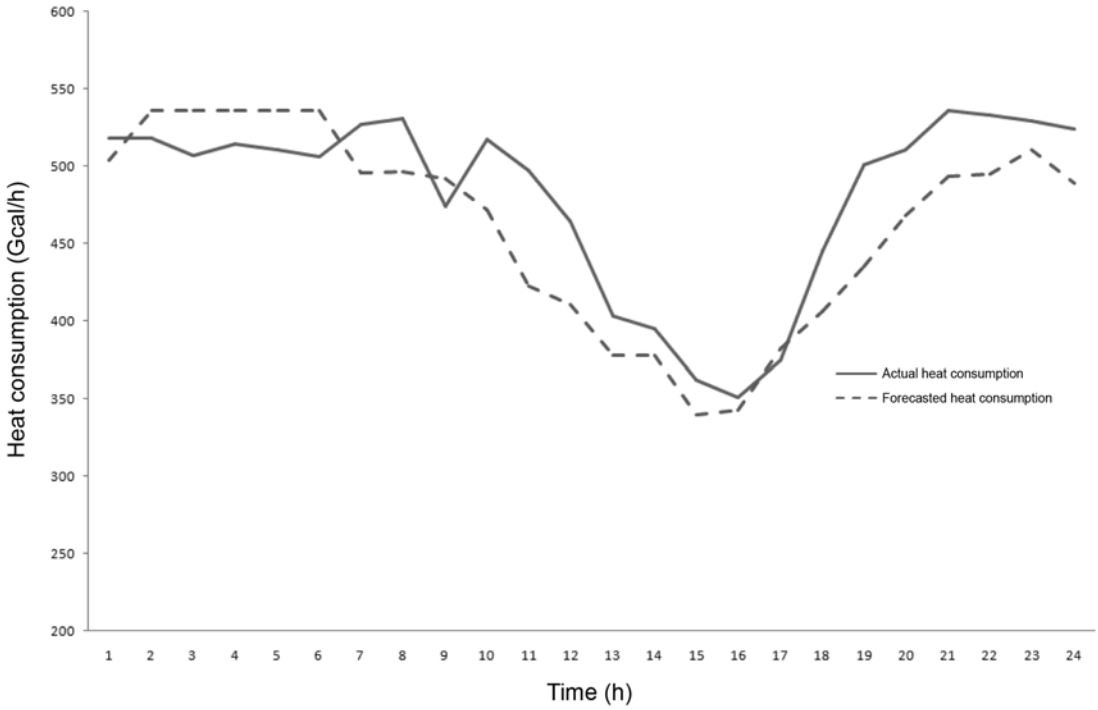

Fig. 3. Comparison of actual and forecasted demands after 2 days (2008.2.19).

Table 3. The error of forecasted heat consumption comparing actual heat consumption after 2 days (2008.2.19)

Time (h)	1	2	3	4	5	6	7	8	9	10	11	12
Error (%)	2.68	3.47	5.72	4.28	4.89	5.90	6.01	6.46	3.75	8.70	14.92	11.57
Time (h)	13	14	15	16	17	18	19	20	21	22	23	24
Error (%)	6.27	4.37	6.23	2.31	1.92	8.70	13.08	8.42	7.93	7.11	3.49	6.74

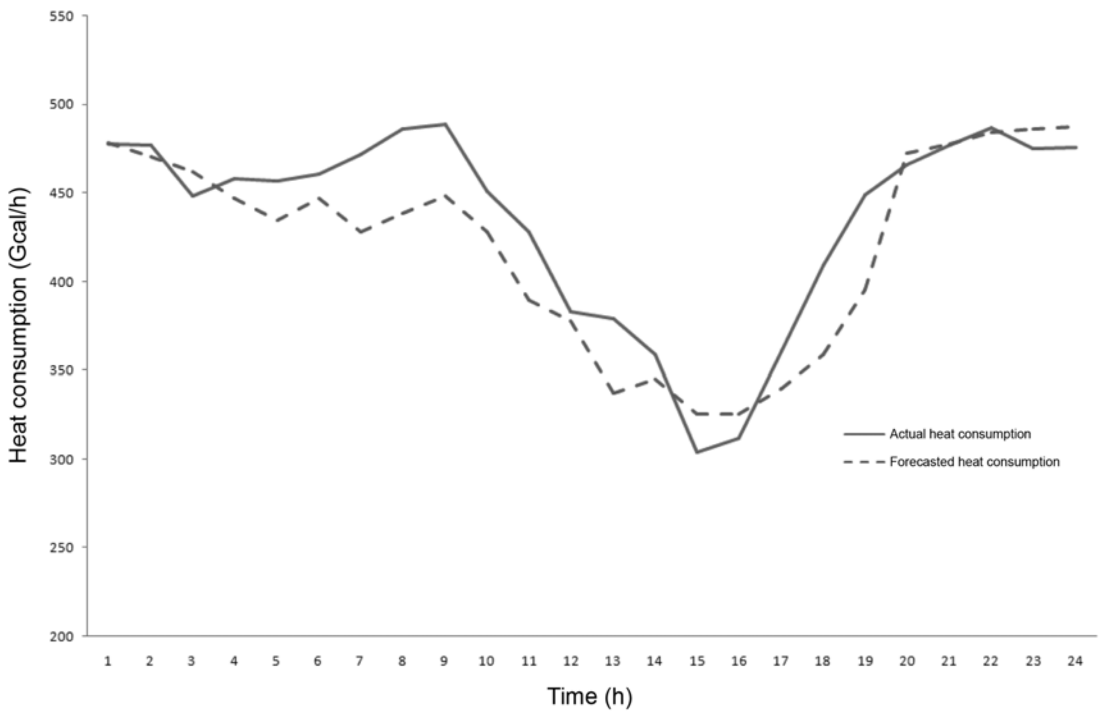

Fig. 4. Comparison of actual and forecasted demands after 3 days (2008.2.20).

Table 4. The error of forecasted heat consumption comparing actual heat consumption after 3 days (2008.2.20)

Time (h)	1	2	3	4	5	6	7	8	9	10	11	12
Error (%)	0.12	1.36	3.14	2.38	4.92	3.05	9.32	9.75	8.35	5.02	9.05	1.31
Time (h)	13	14	15	16	17	18	19	20	21	22	23	24
Error (%)	11.07	3.91	7.16	4.25	5.90	12.30	11.97	1.35	0.08	0.60	2.32	2.40

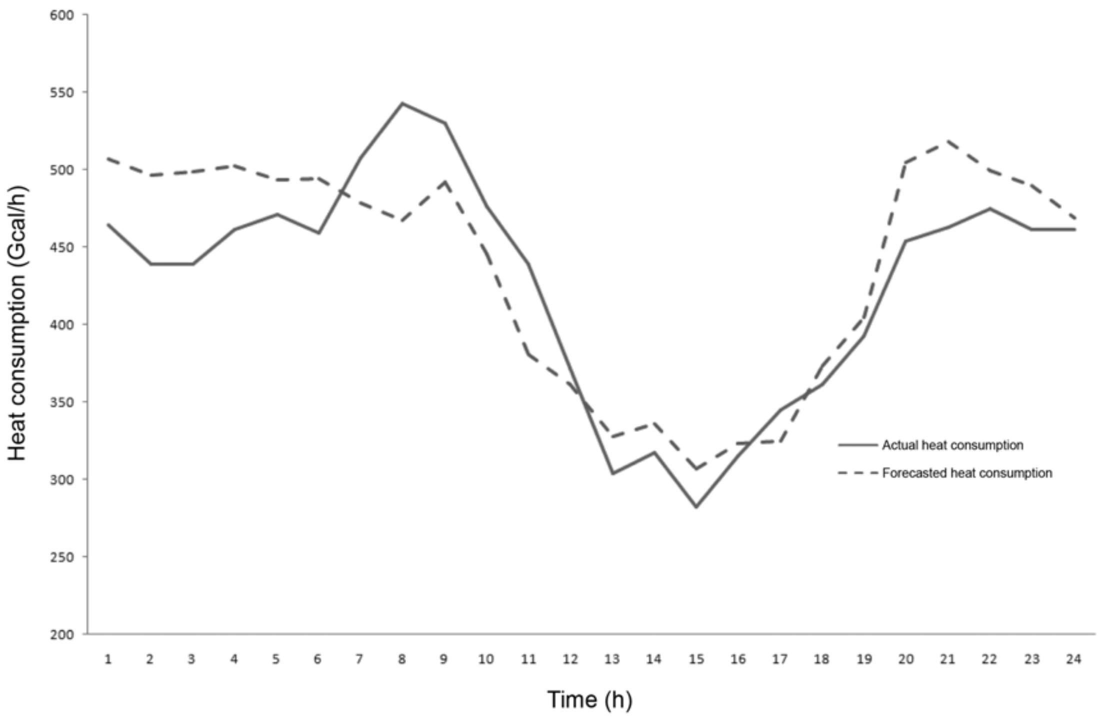

Fig. 5. Comparison of actual and forecasted demands after 4 days (2008.2.21).

Table 5. The error of forecasted heat consumption comparing actual heat consumption after 4 days (2008.2.21)

Time (h)	1	2	3	4	5	6	7	8	9	10	11	12
Error (%)	9.25	13.13	13.61	9.05	4.76	7.71	5.77	13.95	7.14	6.42	13.36	2.86
Time (h)	13	14	15	16	17	18	19	20	21	22	23	24
Error (%)	7.92	6.04	8.91	2.65	5.88	3.43	3.01	11.13	11.89	5.11	6.17	1.75

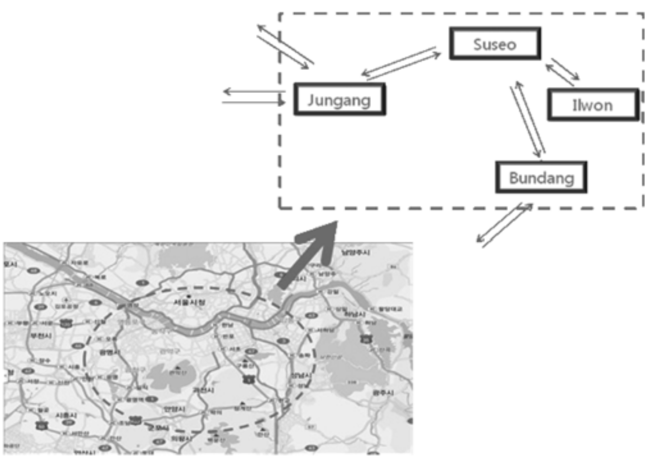

Fig. 6. Diagram of heat supply network near Suseo.

Table 6. Heat supply cost per energy (won/Gcal)

Date	Bundang to Suseo	Ilwon to Suseo	Jungang to Suseo
2007.3.22	31973	36000	34613
2007.4.01	30395	36000	28289

of heat supply DHSs, we consider three DHSs located in Bundang, Ilwon and Jungang area as shown in Fig. 6. Table 6 shows unit prices of heat supply and heat demand. The data were collected on March 22, 2007 and April 1, 2007. If we compare the prices at these two different points in time, we can see that the unit price of the heat supply from Bundang area to Suseo area is decreased from 31,973 won/Gcal on March 22, 2007 to 30,395 won/Gcal on April 1, 2007 and that from Jungang area to Suseo area is also decreased from 34,613 won/Gcal on March 22, 2007 to 28,289 won/Gcal on April 1, 2007. In actual operation, there is no heat supply from Ilwon to Suseo area. Thus, in the formulation of the optimization problem, we can assume that the heat supply from Ilwon to Suseo area is maintained at the minimum level.

2. Formulation of the Optimization Problem

In the formulation of the optimization problem, we can consider two operation types (to be called Type 1 and Type 2). In Type 1, the heat demand in the Suseo area exceeds the heat supply capability in that area. In this case, the heat deficit should be fulfilled by the supply from other regional DHSs (i.e., DHSs in Bundang, Ilwon and Jungang area). In this case, the objective function consists of the minimization of the heat supply costs from other DHSs while the fulfillment of heat demand from Suseo area being served as constraints. In Type 2, the generation of heat in Suseo area exceeds the heat demand in that area. Thus, the excess heat in Suseo area can be supplied to other DHSs (i.e., DHSs in Bundang, Ilwon and Jungang area). In this case, the objective function also consists of the summation of heat supply costs, while the fulfillment of heat demand from other areas being served as constraints. For each case, we can represent the objective function and constraints as follows.

Type 1: The objective function is given by

$$\mathrm{Min}[cb\ \ ci\ \ cj\ \ cs1\ \ cs2\ \ cs3]\begin{bmatrix} Q_{BS} \\ Q_{IS} \\ Q_{JS} \\ Q_{SB} \\ Q_{SI} \\ Q_{SJ} \end{bmatrix} \tag{2}$$

where Q_{BS}, Q_{IS} and Q_{JS} denote the amount of heat supply to Suseo from Bundang, Ilwon and Jungang area, respectively; Q_{SB}, Q_{SI} and Q_{SJ} denote the amount of heat supply from Suseo to Bundang, Ilwon and Jungang area, respectively. cb, ci and cj are heat supply cost from Bundang, Ilwon and Jungang area, respectively, and cs1, cs2 and cs3 are heat supply cost from Suseo to Bundang, Ilwon and Jungang area, respectively. As mentioned before, the sum of the amount of the heat available to be supplied from three regional DHSs (i.e., DHSs in Bundang, Ilwon and Jungang area) is greater than the amount of the heat demand from Suseo area, which is given by the difference between the amount of heat supply and that of heat demand in Suseo area. This criterion can be written as

$$D_S - P_S \le Q_{BS} + Q_{IS} + Q_{JS} \tag{3}$$

where D_S and P_S denote the amount of heat demand and generation in Suseo area, respectively.

For the heat supply from each regional DHS to be possible, the amount of heat generation should be greater than that of heat demand. If the amount of heat generation is greater than that of heat demand, we multiply +1 to the difference between the amount of heat generation and the amount of heat demand and multiply 0 otherwise. This constraint can be represented as Eq. (4).

$$0 \le Q_{ij} \le (P_i - D_i) \times Y_i \quad \text{where, } Y_i = 0 \text{ or } 1 \text{ integer} \tag{4}$$

where i and j denote regional DHS involving heat supply and heat demand, respectively. The amount of the heat available to be supplied in each regional DHS should be smaller than the difference between the amount of heat supply and that of heat demand in corresponding area as shown in Eq. (5).

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ -1 & -1 & -1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Q_{BS} \\ Q_{IS} \\ Q_{JS} \\ Q_{SB} \\ Q_{SI} \\ Q_{SJ} \end{bmatrix} \le \begin{bmatrix} P_B - D_B \\ P_I - D_I \\ P_J - D_J \\ -(D_S - P_S) \end{bmatrix} \tag{5}$$

where P_B, P_I and P_J represent the amount of heat generation in Bundang, Ilwon and Jungang area, respectively, and D_B, D_I and D_J denote the amount of heat demand in Bundang, Ilwon and Jungang area, respectively. If the sum of the amount of the heat available to be supplied from three regional DHSs to Suseo area is smaller than the amount of the heat demand from Suseo area, the constraint (5) can be rewritten as Eq. (6).

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ -1 & -1 & -1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Q_{BS} \\ Q_{IS} \\ Q_{JS} \\ Q_{SB} \\ Q_{SI} \\ Q_{SJ} \end{bmatrix} \le \begin{bmatrix} P_B - D_B \\ P_I - D_I \\ P_J - D_J \\ -(P_B - D_B + P_I - D_I + P_J - D_J) \end{bmatrix} \tag{6}$$

Type 2: The objective function is also defined as the minimization of the supply cost as given by Eq. (2) with different constraint from Type 1. If the amount of heat available to be supplied to three regions is greater than the sum of all the heat demands in the three regions, the constraint can be written as Eq. (7).

$$D_B - P_B + D_I - P_I + D_J - P_J \le Q_{SB} + Q_{SI} + Q_{SJ} \tag{7}$$

The heat available for supply should be less than the difference between the heat demand and heat generation at each regional DHS. This condition can be summarized as Eq. (8).

$$\begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -1 & -1 & -1 \end{bmatrix} \begin{bmatrix} Q_{BS} \\ Q_{IS} \\ Q_{JS} \\ Q_{SB} \\ Q_{SI} \\ Q_{SJ} \end{bmatrix} \le \begin{bmatrix} D_B - P_B \\ D_I - P_I \\ D_J - P_J \\ -(D_B - P_B + D_I - P_I + D_J - P_J) \end{bmatrix} \tag{8}$$

If the amount of heat available to be supplied to three regions from Suseo is smaller than the sum of all the heat demands in the three regions, the constraint is given by Eq. (9).

$$\begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -1 & -1 & -1 \end{bmatrix} \begin{bmatrix} Q_{BS} \\ Q_{IS} \\ Q_{JS} \\ Q_{SB} \\ Q_{SI} \\ Q_{SJ} \end{bmatrix} \le \begin{bmatrix} D_B - P_B \\ D_I - P_I \\ D_J - P_J \\ -(P_S - D_S) \end{bmatrix} \tag{9}$$

3. Heat Transmission Among Regional DHSs

The operation of the DHSs can be classified into three cases (to

Table 7. Heat product and demand of regions in case 1 (Gcal/h)

Time (h)	S* region		B region		I region		J region	
	Product	Demand	Product	Demand	Product	Demand	Product	Demand
1	260	348	300	234	40	19	200	186
2	260	327	300	249	40	18	200	182
3	260	326	300	260	40	17	200	180
4	260	326	300	262	40	19	200	182
5	260	353	300	245	40	20	200	179
6	260	355	300	240	40	19	200	177
7	260	356	300	235	40	17	200	171
8	260	356	300	234	40	20	200	172
9	260	359	300	248	40	18	200	168
10	260	340	300	252	40	18	200	165
11	260	304	300	261	40	17	200	139
12	260	280	300	262	40	17	200	156
13	260	285	300	257	40	19	200	195
14	260	285	300	248	40	17	200	166
15	260	276	300	247	40	17	200	175
16	260	265	300	251	40	18	200	178
17	260	274	300	253	40	17	200	172
18	260	273	300	244	40	17	200	171
19	260	289	300	228	40	19	200	177
20	260	315	300	226	40	18	200	179
21	260	314	300	238	40	18	200	182
22	260	324	300	243	40	19	200	180
23	260	324	300	236	40	19	200	182
24	260	318	300	235	40	19	200	186

*B: Bundang, S: Suseo, I: Ilwon, J: Jungang

Table 8. Heat product and demand of regions in case 2 (Gcal/h)

Time (h)	S* region		B region		I region		J region	
	Product	Demand	Product	Demand	Product	Demand	Product	Demand
1	260	348	300	234	40	19	250	186
2	260	327	300	249	40	18	250	182
3	260	326	300	260	40	17	250	180
4	260	326	300	262	40	19	250	182
5	260	353	300	245	40	20	250	179
6	260	355	300	240	40	19	250	177
7	260	356	300	235	40	17	250	171
8	260	356	300	234	40	20	250	172
9	260	359	300	248	40	18	250	168
10	260	340	300	252	40	18	250	165
11	260	304	300	261	40	17	250	139
12	260	280	300	262	40	17	250	156
13	260	285	300	257	40	19	250	195
14	260	285	300	248	40	17	250	166
15	260	276	300	247	40	17	250	175
16	260	265	300	251	40	18	250	178
17	260	274	300	253	40	17	250	172
18	260	273	300	244	40	17	250	171
19	260	289	300	228	40	19	250	177
20	260	315	300	226	40	18	250	179
21	260	314	300	238	40	18	250	182
22	260	324	300	243	40	19	250	180
23	260	324	300	236	40	19	250	182
24	260	318	300	235	40	19	250	186

*B: Bundang, S: Suseo, I: Ilwon, J: Jungang

Table 9. Heat product and demand of regions in case 3 (Gcal/h)

Time (h)	S* region		B region		I region		J region	
	Product	Demand	Product	Demand	Product	Demand	Product	Demand
1	400	348	200	234	10	19	100	186
2	400	327	200	249	10	18	100	182
3	400	326	200	260	10	17	100	180
4	400	326	200	262	10	19	100	182
5	400	353	200	245	10	20	100	179
6	400	355	200	240	10	19	100	177
7	400	356	200	235	10	17	100	171
8	400	356	200	234	10	20	100	172
9	400	359	200	248	10	18	100	168
10	400	340	200	252	10	18	100	165
11	400	304	200	261	10	17	100	139
12	400	280	200	262	10	17	100	156
13	400	285	200	257	10	19	100	195
14	400	285	200	248	10	17	100	166
15	400	276	200	247	10	17	100	175
16	400	265	200	251	10	18	100	178
17	400	274	200	253	10	17	100	172
18	400	273	200	244	10	17	100	171
19	400	289	200	228	10	19	100	177
20	400	315	200	226	10	18	100	179
21	400	314	200	238	10	18	100	182
22	400	324	200	243	10	19	100	180
23	400	324	200	236	10	19	100	182
24	400	318	200	235	10	19	100	186

*B: Bundang, S: Suseo, I: Ilwon, J: Jungang

be called Case 1, Case 2 and Case 3). Both in Case 1 and 2, the DHSs in Bundang, Jungang and Ilwon area can supply heat to Suseo area. The difference between Case 1 and Case 2 is that Case 1 is based on the demand and cost data on March 22, 2005, while Case 2 is based on the data measured on April 1, 2007. In Case 3, the DHS in Suseo can supply heat to all the three other DHSs (i.e., Bundang, Jungang and Ilwon).

Case 1: heat supply possible from Bundang, Jungang and Ilwon to Suseo(1).

Table 7 shows hourly values of heat generation and demand in Suseo, Bundang, Jungang and Ilwon areas on March 22, 2005. It is obvious that the amount of heat generation is greater than that of heat demand in Bundang, Jungang and Ilwon area; heat can be supplied to Suseo area from these regional DHSs.

Case 2: heat supply possible from Bundang, Jungang and Ilwon to Suseo(2).

Table 8 shows hourly values of heat generation and heat demand in Suseo, Bundang, Jungang and Ilwon areas on April 1, 2007. All the heat generated in three DHSs can be supplied to Suseo after fulfillment of heat demand in those areas.

Case 3: heat supply possible from Suseo to Bundang, Ilwon and Jungang.

We could not find any operation history that heat was supplied from Suseo to Bundang, Ilwon and Jungang. But it is quite natural that the DHS in Suseo can supply heat to Bundang, Ilwon and Jungang areas. Thus, we assumed an operational scenario as shown in Table 9 constructed based on Table 8. It was assumed that heat demand in Bundang area increased to the amount of +100 Gcal, while that in Ilwon area was decreased to the amount of −10 Gcal. We further assumed that the DHS in Suseo could supply heat to all the three regions (Bundang, Ilwon and Jungang areas) to give Table 9.

RESULTS AND DISCUSSION

For the three possible operation cases described above, the values of interconnected heat supplies and demands among four regions as well as the minimal supply costs were estimated based on the amount of heat generation and demand in each region area. The optimization problem can be solved easily by using an optimization tool such as ILOG CPLEX. Results obtained from the optimization problem were compared with operational data to evaluate the model proposed in the present study. The key point in this study is to develop a reliable optimization model to be used in DHSs in capital regions.

(1) Case 1: Table 10 shows the optimal heat supply to Suseo from Bundang, Ilwon and Jungang areas. Heat is supplied from Bundang to Suseo first because the supply cost from Bundang to Suseo is the lowest (31,973 won/Gcal). Then the DHS in Jungang supplies heat to Suseo because the supply cost (34,613 won/Gcal) is lower than that from Ilwon (36,000 won/Gcal). If additional heat is required in Suseo, the DHS at Ilwon is employed to heat supply to Suseo. Fig.

Table 10. Optimum heat supply in case 1 (Gcal/h)

Time (h)	Optimum heat supply		
	B*→S	I→S	J→S
1	66	8	14
2	50.9996	0	16.0004
3	39.9998	6.0009	19.9994
4	38	10	18
5	55	17	21
6	59.9998	12.001	22.9993
7	64.9994	2.0012	28.9994
8	65.9997	2.0005	27.9998
9	51.9997	15.0012	31.9991
10	47.9991	0.0001	32.0009
11	38.9883	0.0036	5.0082
12	20	0	0
13	25	0	0
14	25	0	0
15	16	0	0
16	5	0	0
17	14	0	0
18	12.9979	0.0004	0.0019
19	28.9978	0.0015	0.0008
20	55	0	0
21	53.9994	0.0001	0.0005
22	57	0	7
23	63.9852	0.006	0.0095
24	58	0	0

*B: Bundang, S: Suseo, I: Ilwon, J: Jungang

Table 11. Optimum heat supply in case 2 (Gcal/h)

Time (h)	Optimum heat supply		
	B*→S	I→S	J→S
1	24	0	64
2	0.0001	0	66.9999
3	0.0379	0.0004	65.9618
4	0.0003	0.0001	65.9996
5	22.0228	0.0004	70.9769
6	22.03	0.0004	72.9697
7	17	0	79
8	18.003	0.0001	77.9969
9	17	0	82
10	0.0001	0	79.9999
11	0	0	44
12	0	0	20
13	0	0	25
14	0	0	25
15	0.0015	0	15.9986
16	0	0	5
17	0.0006	0	13.9995
18	0.0001	0	13
19	0	0	29
20	0	0	55
21	0.0001	0	53.9999
22	0	0	64
23	0	0	64
24	0.007	0.0001	57.9929

*B: Bundang, S: Suseo, I: Ilwon, J: Jungang

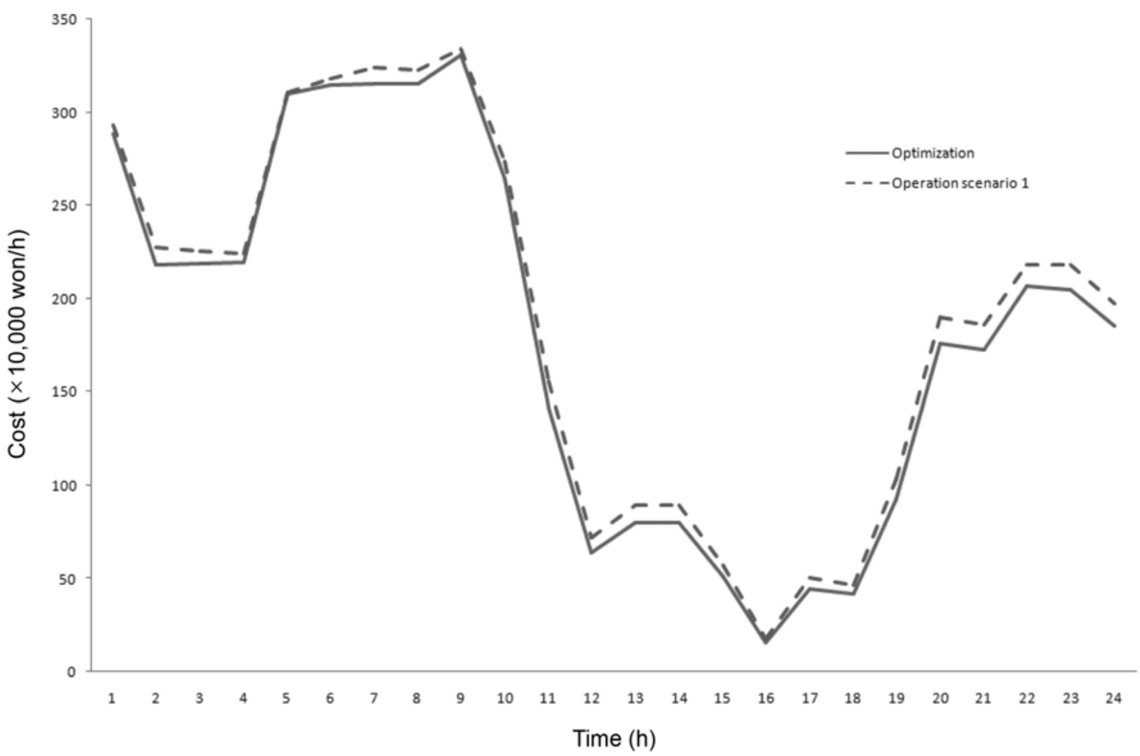

Fig. 7. Heat supply cost of optimization and operation scenario 1 in case 1.

7 shows hourly optimal costs as well as the costs of operation scenario 1. We can see that a reduction of 5.6% in operating cost is achieved.

(2) Case 2: Table 11 shows the optimal heat supply to Suseo from Bundang, Ilwon and Jungang areas. Heat is supplied from Jungang to Suseo first because the supply cost from Jungang to Suseo is the lowest (28,289 won/Gcal). Then the DHS in Bundang supplies heat to Suseo because the supply cost (30,395 won/Gcal) is lower than that from Ilwon (36,000 won/Gcal). If additional heat is required in Suseo, the DHS at Ilwon is employed to heat supply to Suseo as in Case 1. Fig. 8 shows hourly optimal costs as well as the costs of operation scenario 2. We can see that reduction of 11.8% in operat-

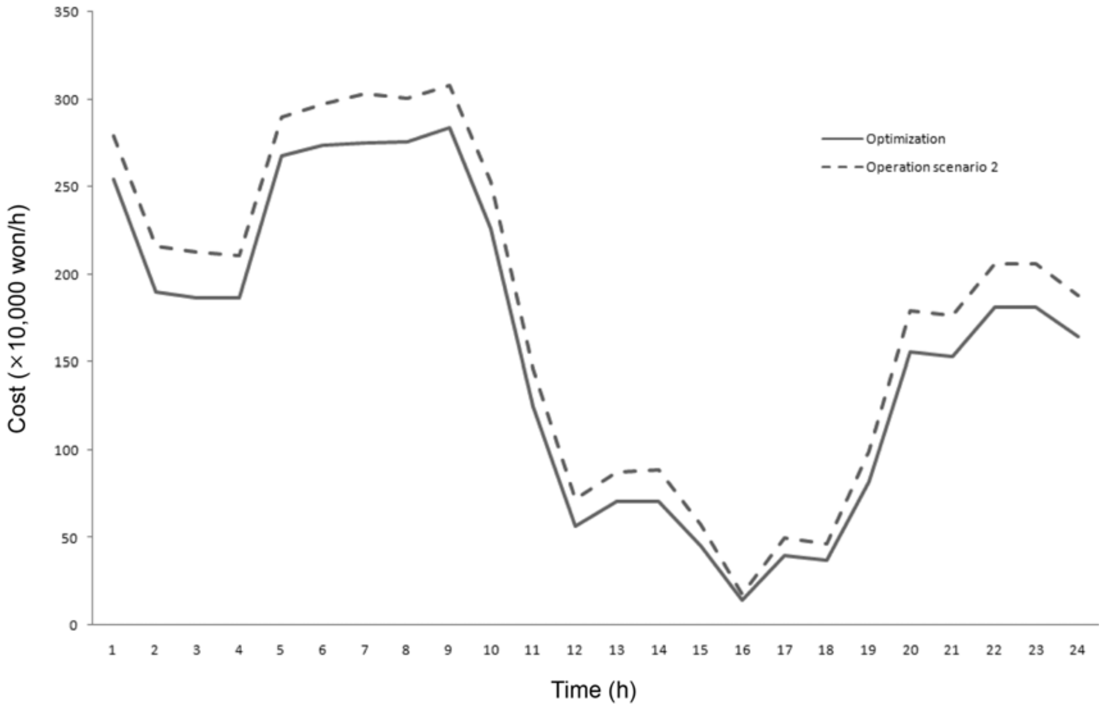

Fig. 8. Heat supply cost of optimization and operation scenario 2 in case 2.

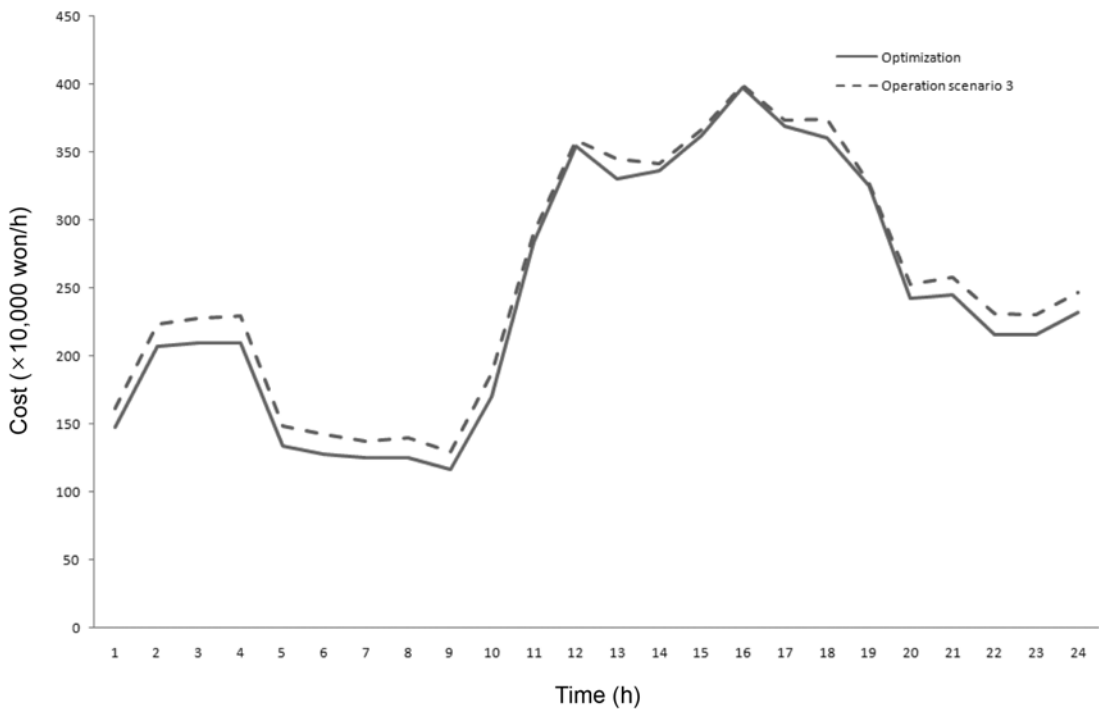

Fig. 9. Heat supply cost of optimization and operation scenario 3 in case 3.

Table 12. Optimum heat supply in case 3 (Gcal/h)

Time (h)	Optimum heat supply		
	B*→S	I→S	J→S
1	0	0	52
2	0.0034	0.0001	72.9966
3	0.0001	0	73.9999
4	0.0001	0.0011	73.9995
5	0	0	47
6	0	0	45
7	0	0	44
8	0	0	44
9	0.0001	0.0009	40.9997
10	0	0	60
11	57.002	0.0001	38.9979
12	61.992	2.0232	55.9854
13	20	0	95
14	48	1	66
15	47	2	75
16	51	6	78
17	53	1	72
18	44.0003	6.9999	71.0001
19	27.9999	6.0001	77
20	5.9999	0.0016	78.9986
21	4.002	0.0013	81.9968
22	0.0001	0.0011	76.0001
23	0	0.0007	75.9998
24	0.003	0	81.9972

*B: Bundang, S: Suseo, I: Ilwon, J: Jungang

ing cost is achieved.

(3) Case 3: Table 12 shows the optimal heat supply from Suseo to Bundang, Ilwon and Jungang areas. According to data on the supply cost based on April 1, 2007, the supply cost from Suseo to Bundang, from Suseo to Ilwon and from Suseo to Jungang is 30,395 won/Gcal, 36,000 won/Gcal and 28,289 won/Gcal, respectively. Thus, it is quite natural that the heat deficit at Jungang area is fulfilled first followed by heat supply to Bundang and Ilwon. Fig. 9 shows hourly optimal costs as well as the costs of operation scenario 3. We can see that a reduction of 4.6% in operating cost is achieved.

The differences among the supply costs are not large and they are often ignored in computations. The optimization for Case 2 was performed again based on the assumption of negligible supply cost differences. Fig. 10 shows results of the optimization for the heat supply from Bundang to Suseo, and Fig. 11 shows those from Jungang to Suseo. Results of numerical simulations are also displayed in these figures to be compared with those of optimization. From Figs. 10 and 11, we can see that negligible differences among the supply costs cause variations in the amount of heat transmission.

CONCLUSION

A model for operational optimization of the DHS in the metropolitan area is presented by incorporating forecast for demand from customers. In the model, production and demand of heat in the region of Suseo near Seoul, Korea, are taken into account as well as forecast for demand by using the artificial neural network. Based on the heat deficit or excess heat in DHSs at target areas, three operation cases are considered according to the pattern of heat transmission. For each case, the optimization problem is formulated as a

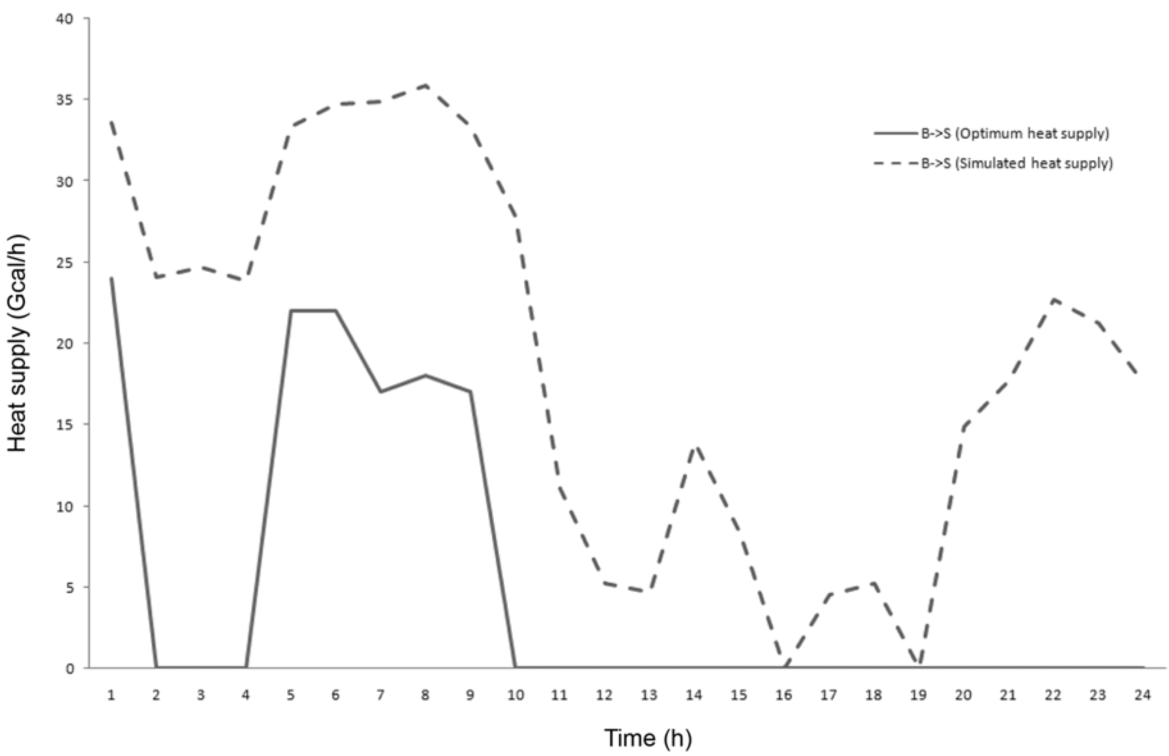

Fig. 10. Optimum and simulated heat supply from Bundang to Suseo in case 2 (B: Bundang, S: Suseo).

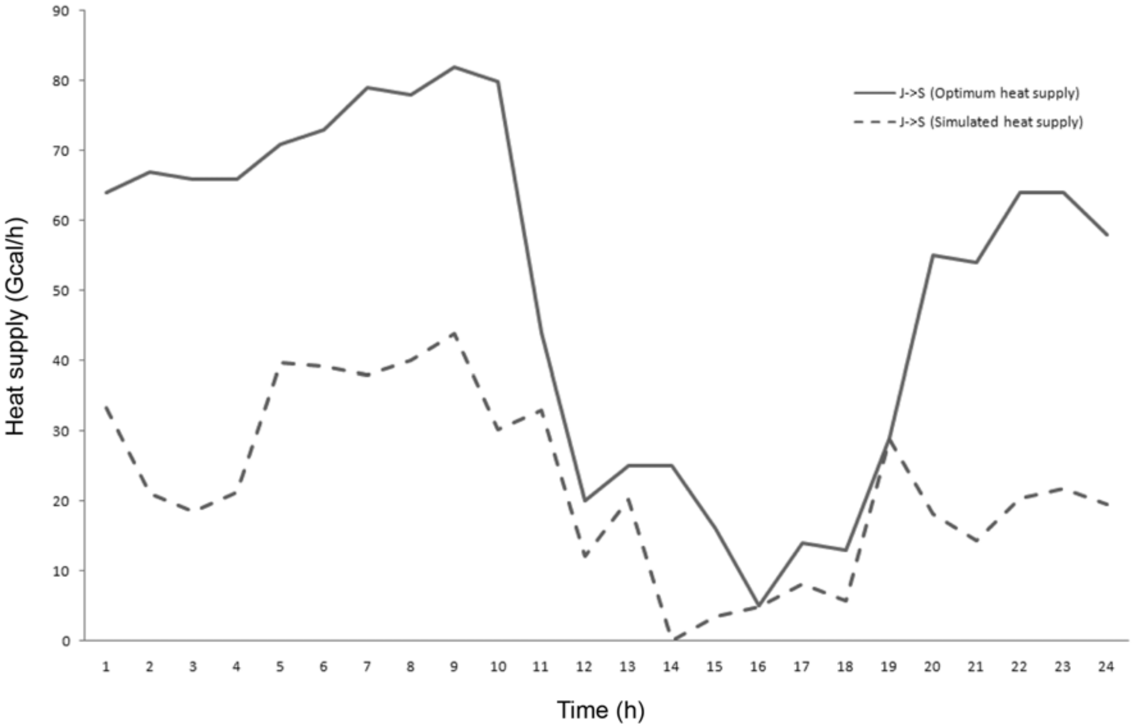

Fig. 11. Optimum and simulated heat supply from Jungang to Suseo in case 2 (J: Jungang, S: Suseo).

mixed integer linear programming (MILP) problem where the objective is to minimize the overall operating cost of DHS. The solution gives the optimal amount of network transmission and supply cost. Results of the optimization show 5-8% reduction in overall operating costs. The optimization system coupled with forecast capability can be effectively used as design and long-term operation guidelines for regional energy policies.

ACKNOWLEDGMENTS

This work was sponsored by the Ministry of Knowledge Economy, Republic of Korea, as a part of the research project titled "Constitution of energy network using District heating energy" (Project No: 2007-E-ID25-P-02-0-000). The authors wish to thank them for their support.

NOMENCLATURE

C : heat consumption [Gcal/h]
D : heat demand [Gcal/h]
P : heat product [Gcal/h]
Q : heat supply [Gcal/h]
cb : heat supply cost from Bundang to Suseo [Won/Gcal]
ci : heat supply cost from Ilwon to Suseo [Won/Gcal]
cj : heat supply cost from Jungang to Suseo [Won/Gcal]
cs1 : heat supply cost from Suseo to Bundang [Won/Gcal]
cs2 : heat supply cost from Suseo to Ilwon [Won/Gcal]
cs3 : heat supply cost from Suseo to Jungang [Won/Gcal]

Subscripts

B : region of Bundang [-]
I : region of Ilwon [-]
J : region of Jungang [-]
S : region of Suseo [-]
BS : from Bundang to Suseo [-]
IS : from Ilwon to Suseo [-]
JS : from Jungang to Suseo [-]
SB : from Suseo to Bundang [-]
SI : from Suseo to Ilwon [-]
SJ : from Suseo to Jungang [-]
i : heat supply region [-]
j : heat demand region [-]

REFERENCES

1. M. Ibrahim and R. Saifure, *IEEE Trans. Power Syst.*, **4**(4) (1989).
2. K. Lru, S. Subbarayan, R. R. Shoults, M. T. Manry, C. Kwan, F. L. Iewis and J. Naccarino, *IEEE Trans. Power Syst.*, **11**(2) (1996).
3. D. Alex and C. Timothy, *IEEE Trans. Power Syst.*, **5**, 1535 (1990).
4. B. Jie, B., *Short-term load forecasting based on neural network and moving average*, Iowa State University (2002).
5. I. Dejan, *FME Transactions*, **34**, 165 (2006).
6. T. Yalcinoz and U. Eminoglu, *Energy Conversion and Management*, **46**, 1393 (2005).
7. A. J. Al-Shareef, E. A. Mohamed and E. Al-Judaibi, *One hour ahead load forecasting using artificial neural network for the western area of saudi arabia*, International Journal of Electrical Systems Science and Engineering (2006).
8. J. Y. Fan and J. D. McDonald, *IEEE Trans. Power Syst.*, **9**, 988 (1994).
9. D. Erik, *Appl. Energy*, **73**, 277 (2002).
10. F. Jovic, V. Rajkovic, Z. Jagnjic and D. Vuksanovic, *Information*

Technology Interfaces, **1**, 325 (2001).
11. K. Çomaklı, B. Yüksel and Ö. Çomaklı, *Appl. Thermal Eng.*, **24**, 1009 (2004).
12. G. Sandou, S. Font, S. Tebbani, A. Hiret and C. Mondon, *Decision and Control*, **44**, 7372 (2005).
13. J. Söderman and F. Pettersson, *Appl. Thermal Eng.*, **26**, 1400 (2005).
14. J. Söderman, *Appl. Thermal Eng.*, **27**, 2665 (2007).
15. C. Weber, I. Heckl, F. Friedler, F. Marechal and D. Favrat, *Network synthesis for a district energy system: A step towards sustainability*, 16*th* European Symposium on Computer Aided Process Engineering and 9*th* International Symposium on Process Systems Engineering, 1869-1874 (2006).