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Optimization of the heat plant of district energy systems

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Abstract−This paper presents a scheme to achieve structural and operational optimization for the heat plant in a district energy system. A district energy system consists of energy suppliers and consumers, district heating pipelines and heat storage facilities in a region. Production and consumption of energy and transport of energy as well as storage of heat are taken into account in the model. The problem is formulated as a mixed integer linear programming (MILP) problem where the objective is to minimize the overall cost of the district energy system. Evaluation of the energy production cost is based on the daily operation for every season at the plant located at Suseo in Seoul, Korea. From the results of numerical simulations we can see that the district energy system is well approximated by the proposed model, and that the energy efficiency is improved by the application of the optimal operation conditions provided by the proposed model.

Key words: Mixed Integer Linear Programming, District Energy System, Optimal Operation, Energy Efficiency

INTRODUCTION

A district energy system is a complex system of energy suppliers and a large number of consumers, district heating pipelines and heat storage facilities in a region. A district energy system plays an important part in covering the heating demands in downtown and suburban areas. District energy systems 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 district energy systems has a huge economical potential. District energy systems fulfill a significant part of the energy demand, especially in Nordic countries including Iceland, Finland, Denmark, and Norway [1]. As a heat source of a district energy system, the CHP (cogeneration heat plant), PLB (peak load boiler), an incinerator and geothermal heat generation can be used. Korea began to employ district energy systems in 1987. In contrast to other countries, the heat source used in district energy systems mainly consists of fossil fuels in Korea. For this reason the energy supply by district energy system still suffers from economic and environmental contamination problems [2]. 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 district energy system with multiple heating plants and finding a feasible solution to the posed minimization problem will in most cases be very difficult due to the size of the problem. The optimization of the district energy system can be achieved by the optimization of the heat generation system and of the network distribution system followed by the integration of two separate optimal systems. More specifically, it is suggested to separate the optimization of the entire system into a scheduling between the different heat producing units followed by a control problem for the distribution network in order to make the solution of the optimization problem feasible. Because district energy systems fulfill a significant part of energy demand, especially in Nordic countries, the optimization problem has been subject to continued research activities for last few decades in those countries.

The main purpose in the optimization of the heat generation system is to minimize the production cost of the heat generation system while satisfying the constraints of the system as well as fulfilling heating demands from consumers. But, due to the existence of time delays in the heat supply during operation of a district heating system, the operation of a district energy system is highly dependent upon time-varying demands of customers and the energy distribution network. Moreover, the heat storage as well as the heart loss to the environment should be considered in the operation. To take into account all of these effects a "node" method was proposed to resolve the problem of determination of the supply temperature and/or the amount of the heat supply [3]. This method is based on the modeling of the heat generation system and the energy distribution network, and has been applied to simulate the heat flow and the temperature distribution in a district energy system.

A promising optimization scheme for a district energy system consists of modeling of the heat generation system and the energy distribution network and employment of the MILP algorithm [4]. Results of evaluation of manufacturing costs in a district energy system were reported to show the optimal heat generation and optimal operation of a heat distribution network [5]. Recently, many researchers tried to apply optimized models in the planning and scheduling of new district energy systems as well as in the operation of existing district energy systems [6]. They used an LP (linear programming) model in the planning and scheduling of district energy systems including CHP (cogeneration heat plant) to determine optimal operating costs while satisfying demands of heat and electricity of regional customers.

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In this work, the optimization problem is formulated by the construction of cost estimation models and constraints given by steady-state plant models as well as the application of the MILP method. The main objective of the proposed optimization model is to optimize the operation of the energy plant of the district energy system at Suseo in Seoul, Korea, with respect to operational cost. The optimization is performed every hour by selecting two days from each season to give heat generation costs. An MILP model is constructed for heat generation processes and related units in the heat generation system in the Suseo area in Seoul. The OPL Development Studio of ILOG is used as the computational tool. Results of numerical simulations are compared with actual operation data to evaluate the performance and energy efficiency of the proposed optimization model.

1. Plant Description (Suseo, Korea)

The district energy system considered in this work consists of a heat generation system including CHP and PLB, primary heat distribution networks and secondary heat distribution networks, as shown in Fig. 1. Connections to other regional district energy systems are included when larger energy distribution networks are considered. The heat generated from CHP or PLB is supplied to customers after elevation of temperature by heat exchangers and is returned to the system followed by elevation of temperature by heat exchangers again. Thus, the flow of heat forms a simple closed-loop heat distribution network. In the Suseo plant the heat generation plant consists of PLBs only and LNG (liquefied natural gas) is used as fuel. Two types of PLBs are used at the Suseo plant: two 34Gcal PLBs (PLB #1, PLB #2) and three 103Gcal PLB (PLB #3, PLB #4, PLB #5). The maximum and minimum heat generation capacity of the 34Gcal PLB is 34 Gcal and 11 Gcal, respectively, and that of the 103Gcal PLB is 103 Gcal and 31 Gcal, respectively. Each PLB has its own fuel pump which consumes electricity. The Suseo plant is a part of the metropolitan area energy network and energy is exchanged with the Bundang and Youngin energy plants. The sequence of energy flow among district energy systems can be determined from the energy distribution network system.

2. Heat Production Cost

The total heat production $W_{Production}$ cost consists of fuel cost (W_{Fuel}), power (electricity) cost (W_{Power}) and water cost (W_{Water}) as shown in Eq. (1).

$$W_{Production}=W_{Fuel}+W_{Power}+W_{Water} \tag{1}$$

In Eq. (1), the fuel cost is obtained from Eq. (2) where U_{Fuel} denotes the amount of LNG consumed to produce 1 Gcal and C_{Fuel} represents the unit price of LNG.

$$W_{Fuel}=Q\times U_{Fuel}\times C_{Fuel} \tag{2}$$

The power cost in Eq. (1) is given by multiplication of the amount of the electricity consumed by the unit price of the electricity as shown in Eq. (3). Because of the difference in the unit price of electricity, the power consumed by the pump should be discriminated between daytime consumption and nighttime consumption.

$$W_{Power}=(P_{PLB.AM}+P_{Pump.AM})\times C_{Power.AM}+(P_{PLB.PM}+P_{Pump.PM})\times C_{Power.PM} \tag{3}$$

Compared to other costs, the water cost in Eq. (1) can be neglected and the fuel and power costs are considered in the total heat produc-

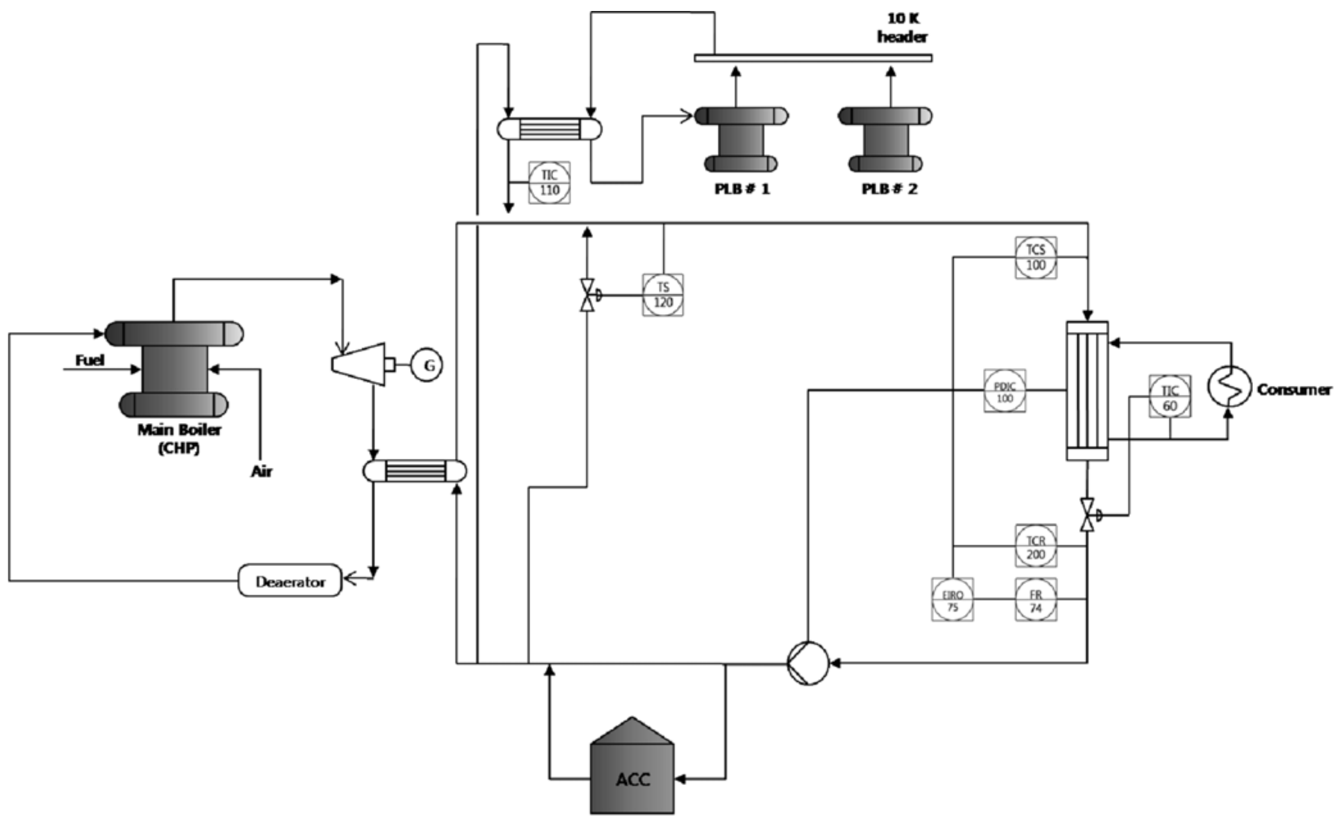


Fig. 1. Schematic of heat plants and grid of Suseo district heating system.

tion cost.

3. Formulation of the Optimization Problem

The operation data of the Suseo plant were used to develop the optimization model and to compare the total heat production costs between the Suseo plant and the optimal heat generation system model. The operation data during one year (from March 1, 2007 to February 29, 2008) were collected from the Suseo plant. Since the consumption of energy is highly dependent upon the season, the data were divided according to each season (spring (March-May), summer (June-August), autumn (September-November) and winter (December-February)) and data obtained during two days' operation were chosen for each season to compute the heat production cost. But, in the Suseo area, the district energy system is seldom used in summer and so the summer season was excluded from the optimization model.

The data used in the optimization are classified as range data, equipment data, seasonal data and constant data. The range data consist of integer values denoting each hour, daytime and nighttime and each PLB as shown in Table 1. The equipment data consist of unit fuel consumption and minimum and maximum heat production for each PLB as shown in Table 2. The seasonal data, shown in Table 3, are the unit costs of fuel, daytime electricity and nighttime electricity for each season except summer. The constant data consist of the proportional coefficients A1, A2 and B (Table 4) and heat demands for each day (Table 5). The constants A1 and A2 represent the power consumption by the pumps attached to each PLB. The constant B denotes the power consumption by the supply pump used to distribute heat to customers. A1 and A2 were obtained from the regression of one year data for each PLB. Results of the regression for A1 and A2 are shown in Fig. 2 and 3 and those for B are shown in Fig. 4.

Table 1. Range data

Parameter	Range
Time [hour]	1…24
AM [hour]	8…22
PM [hour]	1…7, 23…24
Np [-]	1…5

Table 2. Equipment data

	PLB#1	PLB#2	PLB#3	PLB#4	PLB#5
U_{Fuel} [Nm^3/Gcal]	112.0027	112.0027	111.44	111.44	111.44
Q_{Max} [Gcal]	11	11	31	31	31
Q_{Min} [Gcal]	34	34	103	103	103

Table 3. Cost data for each season

	April	October	January
C_{Fuel} [won/Nm^3]	470.1	549.8	603.1
$C_{Power.AM}$ [won/kW]	45	45	50.7
$C_{Power.PM}$ [won/kW]	45	45	50.7

Table 4. Regression coefficients

Parameter	Value
A1 [-]	5.759
A2 [-]	4.106
B [-]	4.805

Table 5. Customer demand for each day [Gcal]

Time \ Date	4.3	4.5	10.27	10.28	1.7	1.8
1	102	115	64	68	240	274
2	90	110	60	68	228	274
3	84	110	54	68	207	274
4	102	110	54	68	225	274
5	103	110	54	68	240	274
6	102	114	25	68	240	274
7	100	137	25	61	240	274
8	102	137	17	45	220	274
9	40	86	0	0	220	274
10	0	27	0	0	215	274
11	0	0	0	0	150	248
12	0	0	0	0	150	160
13	0	0	0	0	150	160
14	0	0	0	0	120	160
15	0	0	0	0	120	162
16	0	0	0	0	120	170
17	0	0	0	0	180	206
18	55	0	0	25	236	246
19	110	60	0	60	274	276
20	127	103	25	103	274	300
21	136	103	54	103	258	279
22	137	103	56	103	258	275
23	136	103	56	103	258	275
24	130	103	68	103	258	275

The objective function is composed of the fuel cost and power cost for one day and is given by Eq. (4).

$$\text{Minimize}\sum_{i}^{Time}\left(\sum_{h}^{Np}Q(h,i)\times U_{Fuel}(h,i)\times C_{Fuel}\right)+\sum_{j}^{AM}\left\{\left(\sum_{h}^{Np}P_{PLB}(h,j)\right)+P_{Pump}(j)\right\}\times C_{Power.AM}+\sum_{k}^{PM}\left\{\left(\sum_{h}^{Np}P_{PLB}(h,k)\right)+P_{Pump}(k)\right\}\times C_{Power.PM} \tag{4}$$

The relations representing the amount of heat demands become the constraints to be satisfied. The total heat production at each PLB should meet the total heat demands from customers at the fixed interval as shown in Eq. (5):

$$D(i)\le \Sigma_{h}^{Np}Q(h,i) \tag{5}$$

where i=1…24 and h=1…5. The hourly heat production at each PLB, another constraint as shown in Eq. (6), should be in the range defined by the minimum and maximum heat production limits. The state of operation (on or off) is represented by the integer variable on(h, i) which takes 1 to denote operational state and 0 to denote non-operational state.

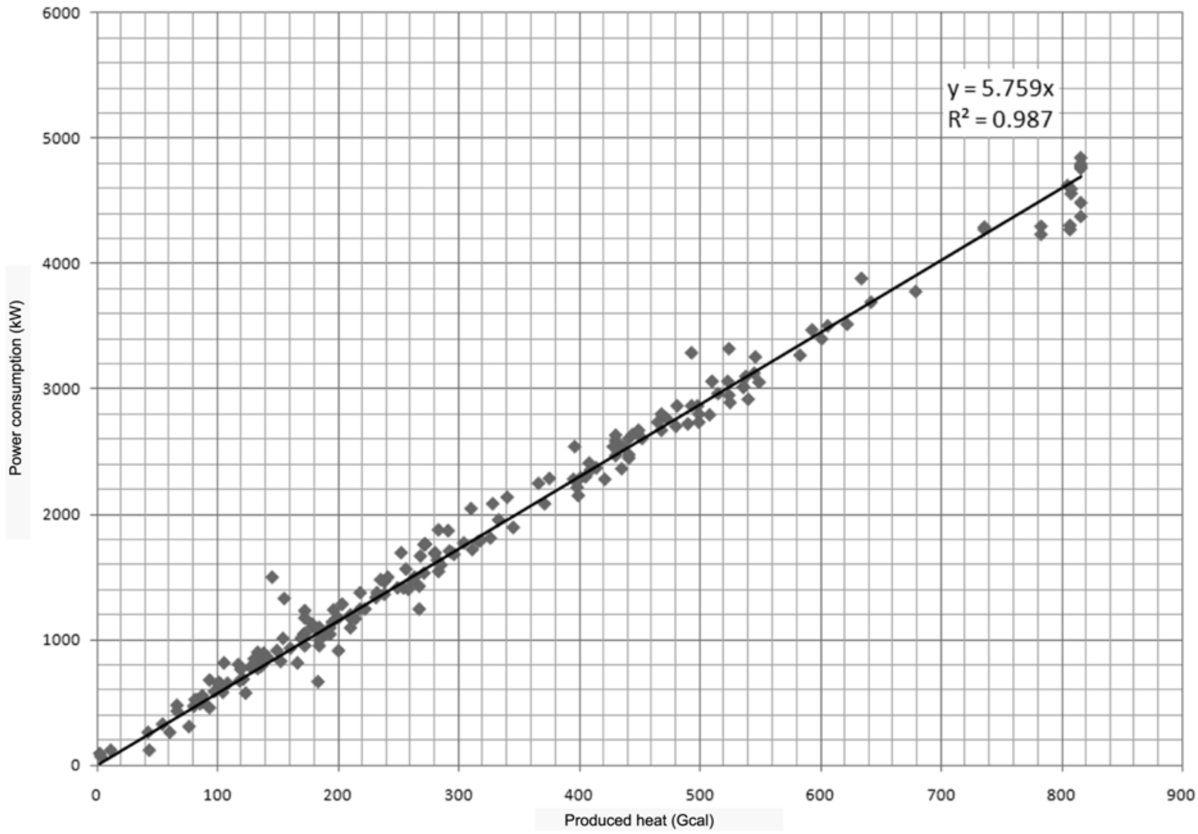


Fig. 2. Relationship between heat production and power consumption (PLB #1, 2).

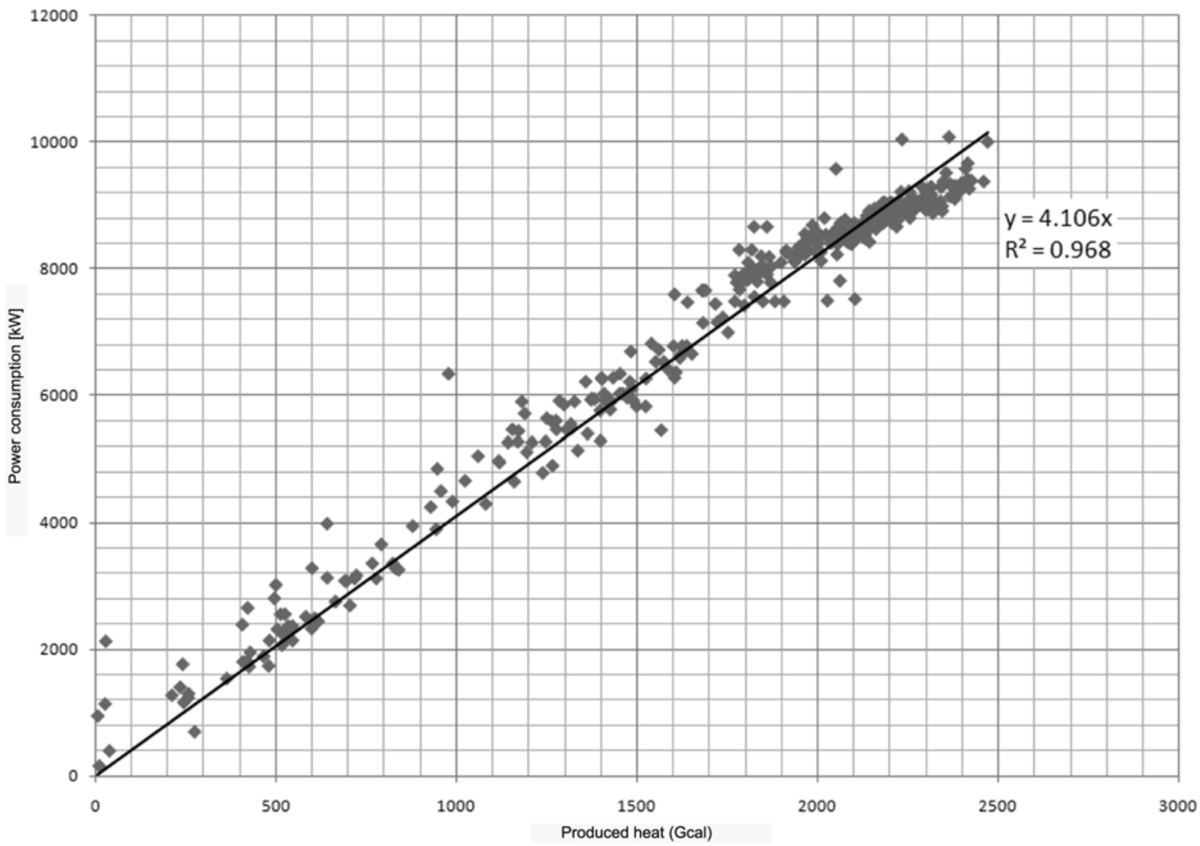


Fig. 3. Relationship between heat production and power consumption (PLB #3, 4, 5).

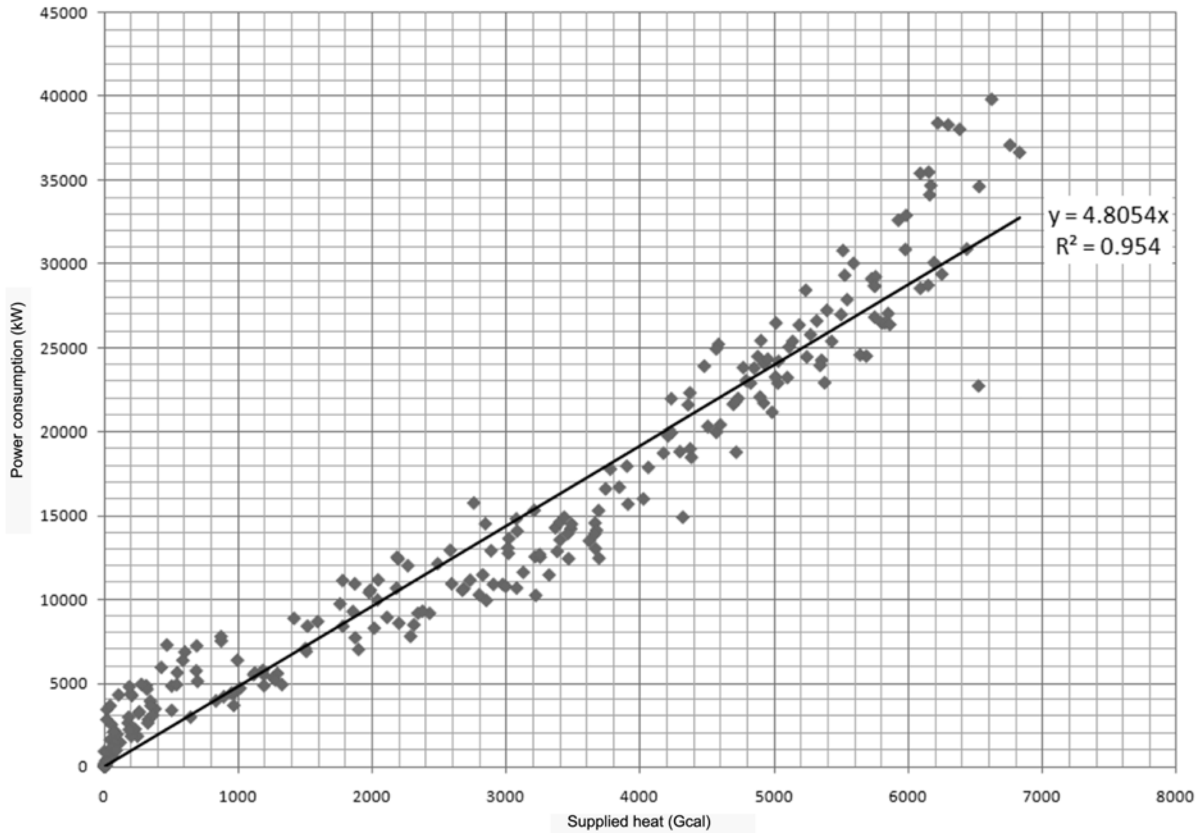
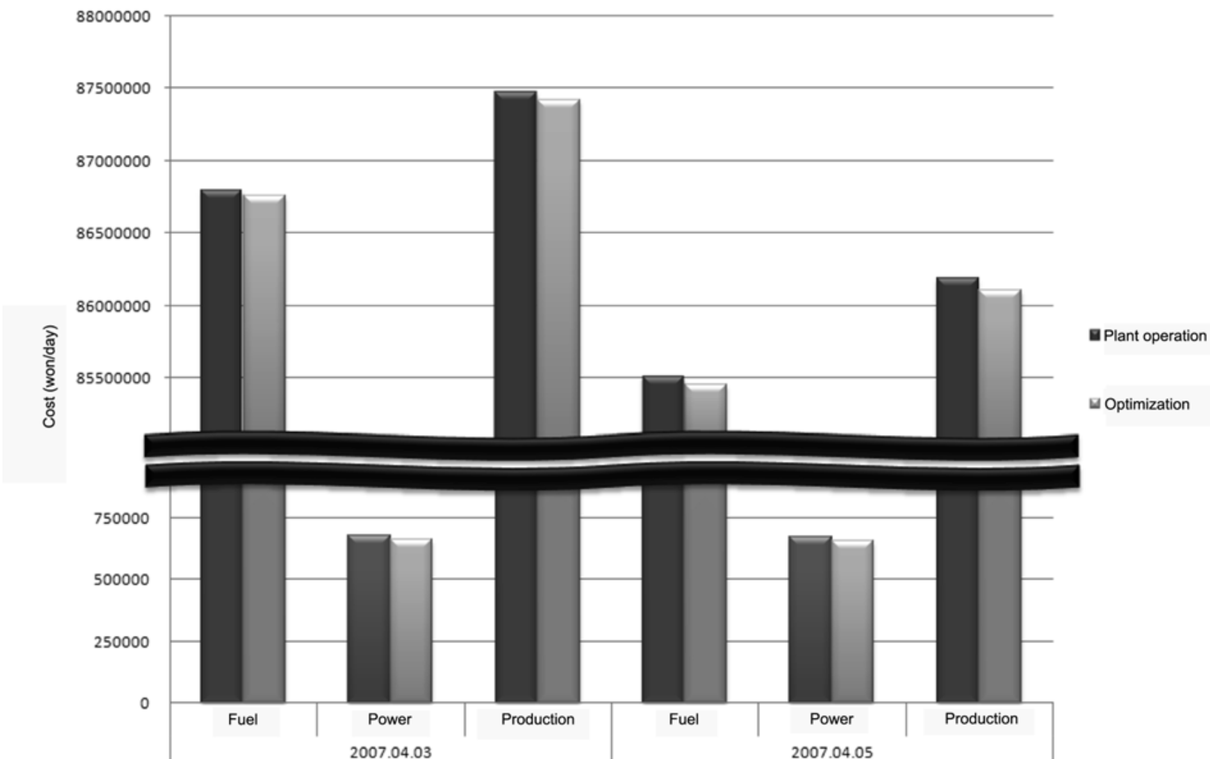
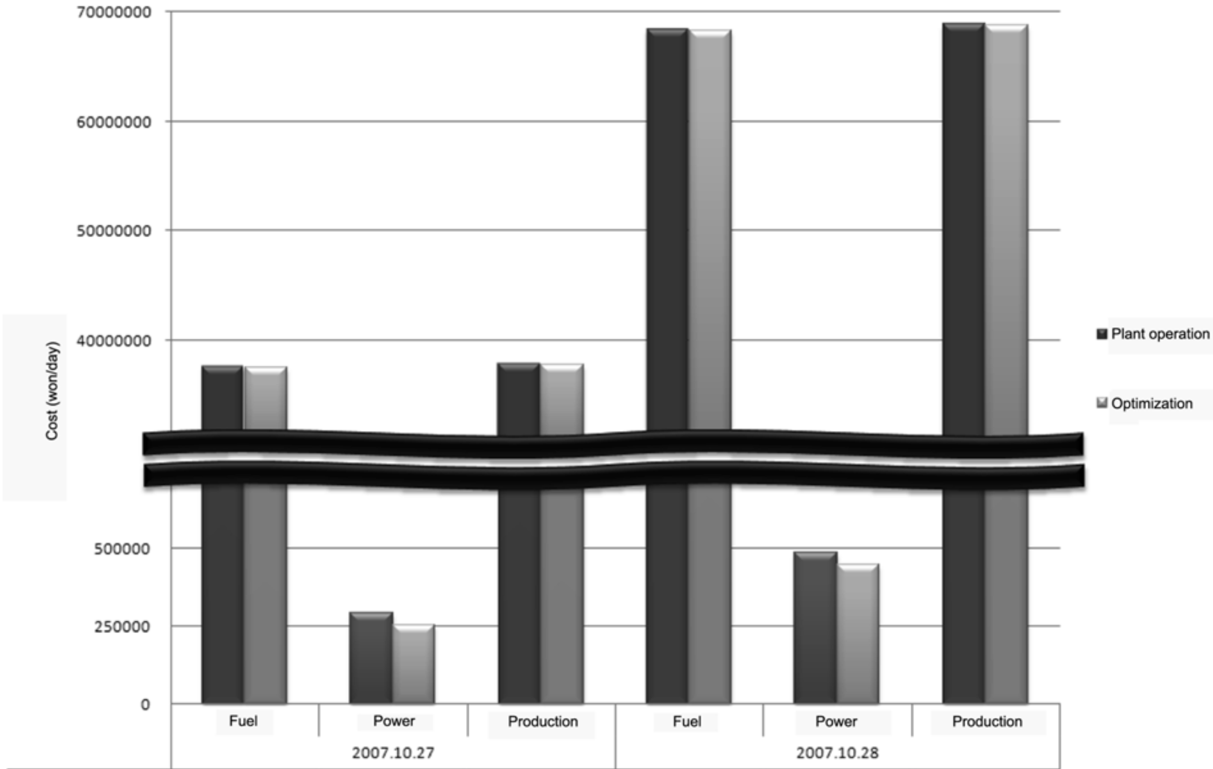


Fig. 4. Relationship between supplied heat and power consumption.



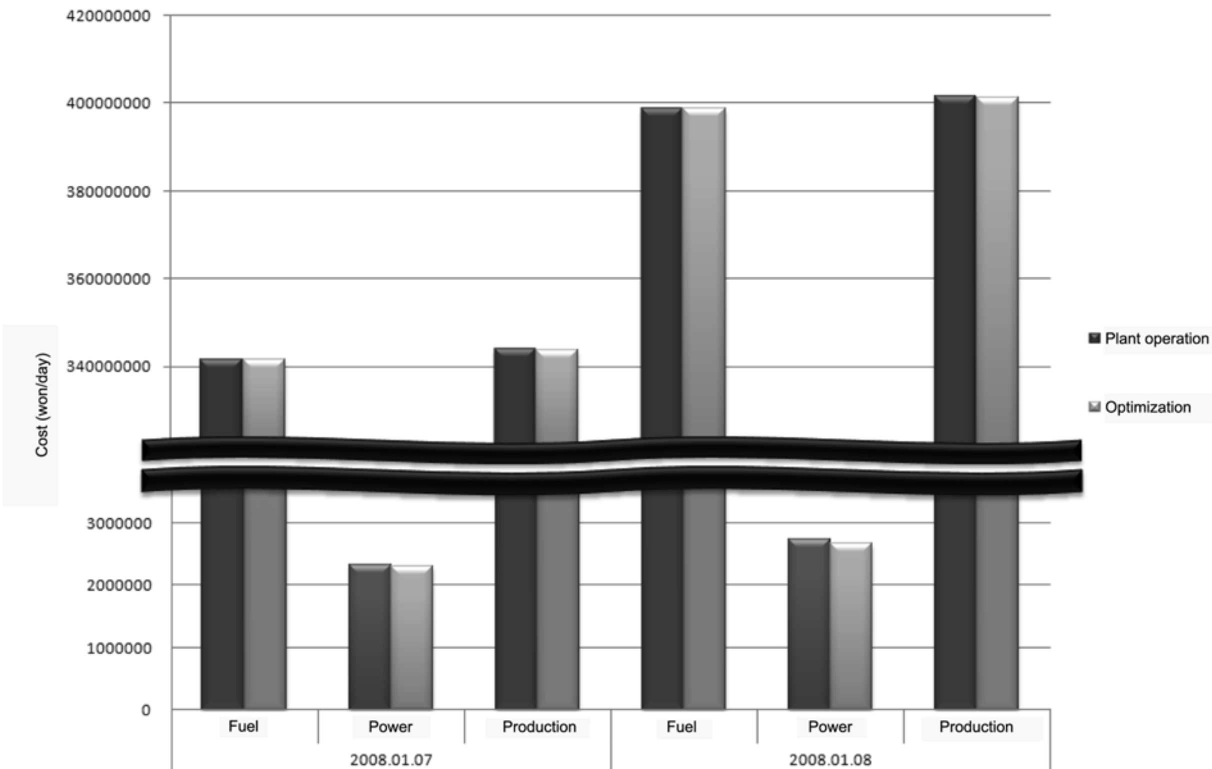
	2007.04.03 Fuel	2007.04.03 Power	2007.04.03 Production	2007.04.05 Fuel	2007.04.05 Power	2007.04.05 Production
Plant operation	86799140	676619	87475759	85515365	673884	86189249
Optimization	86754435	664048	87418483	85451879	656031	86107910

Fig. 5. Comparison between plant operation and simulation (optimization) (April 2007).



	2007.10.27 Fuel	2007.10.27 Power	2007.10.27 Production	2007.10.28 Fuel	2007.10.28 Power	2007.10.28 Production
Plant operation	37686400	290933	37977332	68413477	484942	68898419
Optimization	37525526	252252	37777778	68262193	448568	68710762

Fig. 6. Comparison between plant operation and simulation (optimization) (October 2007).



	2008.01.07 Fuel	2008.01.07 Power	2008.01.07 Production	2008.01.08 Fuel	2008.01.08 Power	2008.01.08 Production
Plant operation	341639928	2332240	343972169	398931562	2740513	401672075
Optimization	341491287	2295533	343786820	398686540	2680005	401366545

Fig. 7. Comparison between plant operation and simulation (optimization) (January 2008).

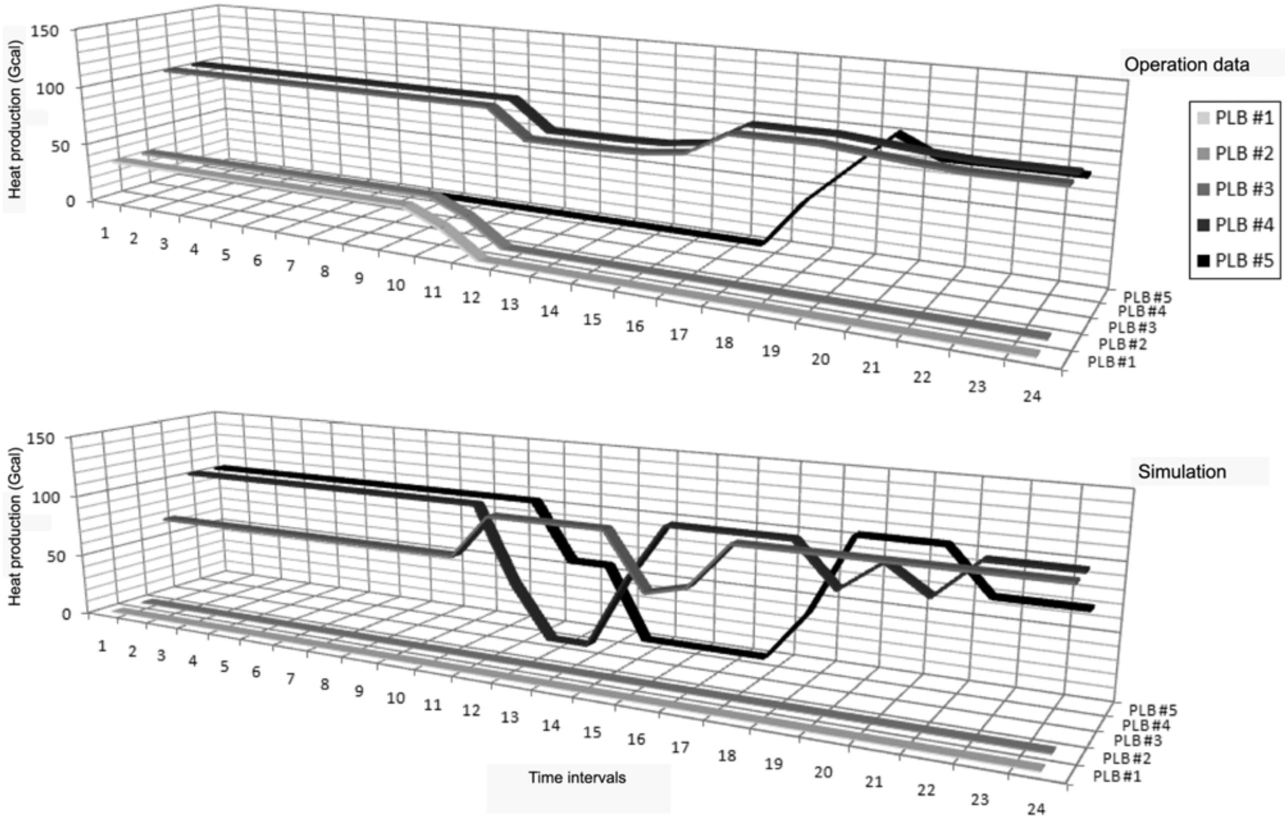


Fig. 8. Comparison between plant operation and simulation (optimization) of PLBs (2008.1.8).

$$Q_{Min}(h)\times on(h,i)\le Q(h,i)\le Q_{Max}\times on(h,i) \quad (6)$$

The power consumptions by the PLB pump and heat supply pump given by Eq. (7) and (8), respectively, are additional constraints:

$$P_{PLB}(n, i)=A1\times Q(n, i) \qquad n=1\ldots2$$
$$P_{PLB}(o, i)=A2\times Q(o, i) \qquad o=3\ldots5 \quad (7)$$

$$P_{Pump}(i)=B\times\left(\sum_{h}^{Np} Q(h,i)\right) \quad (8)$$

The decision variables in the optimization of the district energy system at Suseo are hourly heat production at each PLB (Q(h, i)), the integer variable denoting the operational status (on(h, i)), the pumping cost at each PLB (P_{PLB}(h, i)) and the power cost of the heat supply pump to customers (P_{Pump}(i)).

RESULTS AND DISCUSSIONS

The primary objective of the optimization is to minimize daily heat production cost for the district energy system at Suseo area in Seoul, Korea. The optimization problem contains 384 decision variables and 408 constraints. The OPL Development studio IDE of ILOG, Inc. was used in the computation. The heat production cost is dominated by the cost of the electricity consumption by the PLB pumps. The supply temperature has direct impact on the pumping costs as flow rate, and thus pumping costs will increase with decreasing supply temperature. The optimization of the heat production cost is carried out under restrictions imposed by the distribution network and consumer installations. The restrictions are mainly due to maximum limits on the flow rates as well as requirements to a minimum inlet temperature at the consumer installations. In this work the power consumptions by the PLB pumps and the minimum and maximum heat production limits are considered as main constraints Limits on the flow rates and requirements to a minimum inlet temperature at the consumer installations are taken into account as additional constraints in the study of energy distribution networks not shown in this paper.

Results of the simulations based on the optimal model were compared with the operational data of Suseo plant. Figs. 5-7 show the seasonal heat production cost data obtained from the operation of Suseo plant, the optimal heat production cost computed from the optimization model developed in the present study as well as the profit that can be achieved by the application of the optimization model. As can be seen from the figures, the total heat production cost is decreased by employing the optimization model. Fig. 8 shows the results for January 8 when all the PLBs were under operational status for 24 hours to fulfill heat demands, while only three 103Gcal PLBs were used in the optimization model. The maximum profit can be found in the winter period (Fig. 7) when the difference between the operation and simulation was 305,530 won/day (January 8, 2008). The minimum profit can be found during the spring period (Fig. 5) when the profit was 57276 won/day (April 3, 2007).

CONCLUSIONS

The district energy system has main advantages of energy saving and reduction of pollutants over existing heating systems. The operation of district energy systems needs to be optimized in order to improve the economics and efficiency. To optimize the Suseo district energy plant, an MILP model was developed and the effectiveness of the model was investigated. In the optimization the total heat production cost is minimized while heat demands from customers are satisfied. From the results of numerical simulations, it was found that the total heat production cost is decreased by employing the optimization model. The maximum saving can be achieved in the winter period when the difference between the operations and simulations was 305,530 won/day. The minimum saving can be achieved during spring period when the profit was 57276 won/day.

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NOMENCLATURE

AM : daytime [-]
A1 : regression coefficient between 34Gcal PLB pump and used power [-]
A2 : regression coefficient between 103Gcal PLB pump and used power [-]
B : regression coefficient between supply pump and used power [-]
C_{Fuel} : unit cost of fuel (LNG) [won/Nm^3]
$C_{Power.AM}$: unit cost of power in the daytime [won/kW]
$C_{Power.PM}$: unit cost of power in the nighttime [won/kW]
D : the total heat demands from customers [Gcal]
Np : the number of PLB in heat plant [-]
on : the on/off signals of PLB [-]
P_{PLB} : power consumption of PLB [kW]
$P_{PLB.AM}$: the amount of the electricity consumed by PLB in the daytime [kW]
$P_{PLB.PM}$: the amount of the electricity consumed by PLB in the nighttime [kW]
P_{Pump} : power consumption of supply pump [kW]
$P_{Pump.AM}$: the amount of the electricity consumed by supply pump in the daytime [kW]
$P_{Pump.PM}$: the amount of the electricity consumed by supply pump in the nighttime [kW]
PM : midnight [-]
Q : the heat production of PLB [Gcal]
Q_{Max} : the maximum production of PLB [Gcal]
Q_{Min} : the minimum production of PLB [Gcal]
U_{Fuel} : the amount of fuel consumed when producing heat [Nm^3/Gcal]
W_{Fuel} : the fuel cost [won/day]
W_{Power} : the power (electricity) cost [won/day]
$W_{Production}$: the total heat production cost [won/day]
W_{Water} : the water cost [won/day]

REFERENCES

1. District Heat in Europe, 2005 Survey, *Euroheat & Power*, Unichal, Bruxelles (2005).
2. Korea District Heat Corp.'s web site, http://www.kdhc.co.kr.
3. A. Benonysson, B. Bohm and H. F. Ravn, *Energy Conversion and Management*, **36**, 297 (1995).
4. R. Aringhieri and F. Malucelli, *Annals of Operations Research*, **120**, 173 (2003).
5. Jörgen Sjödin and Dag Henning, *Appl. Energy*, **78**, 1 (2004).
6. N. A. Tibi and H. Arman, *Clean Technologies and Environmental Policy*, **9**, 235 (2007).